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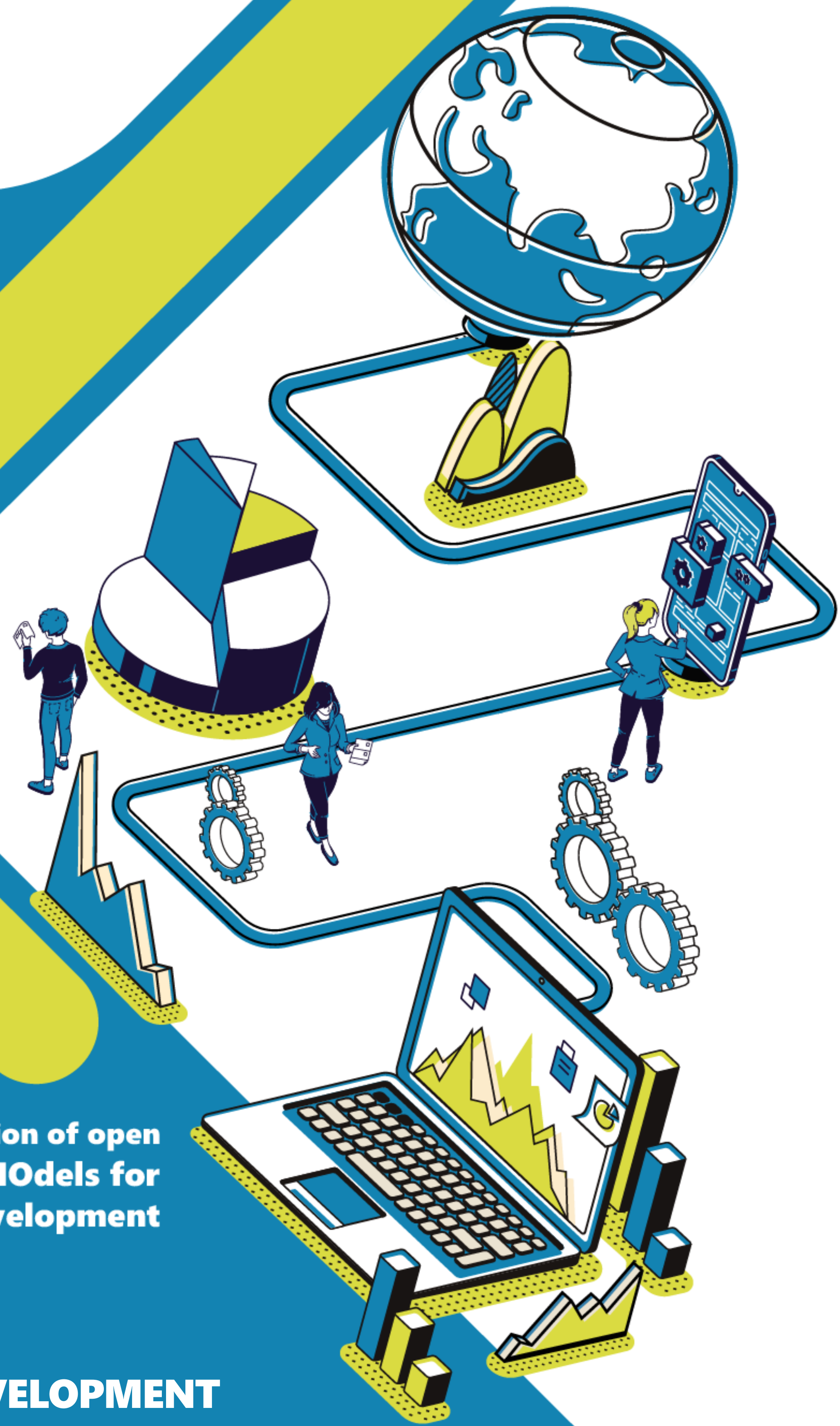

Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development

D3.2 – MODEL DEVELOPMENT STRATEGY – UPDATE 1

WP3 – Update & Upgrade

Funded by the European Union

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

The deliverable is intended for policymakers and the broader stakeholder community of DIAMOND and other IAM-related projects to showcase the capabilities and simple descriptions of the models in the armoury of the project. It is also intended for the scientific community of IAMs to present the added capabilities, expansions, and integrations that are performed in DIAMOND.

3. Short summary of results (<250 words)

Integrated Assessment Models (IAMs) have historically been the dominant tools in mitigation policy assessment and the analysis of the implications of global and/or regional scenarios. In DIAMOND, a coordinated effort is undertaken to update, upgrade, expand, and integrate six different economy-wide IAMs. In a previous stage (D3.1), different modelling teams outlined initial development plans for their models. To enhance the broad application of the models, these plans must be updated to reflect stakeholder needs. This deliverable presents the updated model development strategies, incorporating progress and adjustments based on stakeholder feedback obtained in a dedicated workshop. Each IAM team completed an updated internal survey, showing progress and describing the integration of stakeholders' insights in development strategies. Survey outputs show that all models plan to expand their geographical and sectoral/technological coverage. The models have updated their plans to improve the geographical detail in the EU and/or expand coverage in the rest of the world. In terms of technological coverage, the updated development strategies align with the higher technoeconomic detail demanded by stakeholders, particularly improving the representation of hydrogen and electricity storage technologies. In terms of policy representation, a large part of newly developed capacity will focus on trade policies, while all models will also be improved in terms of behavioural measures, such as transport modal shifts. Since the updated survey also highlighted data requirements for different input assumptions used by the models, this report provides a preliminary model harmonisation strategy that can be used in model development and future model intercomparison studies.

4. Evidence of accomplishment

This report and the corresponding Zenodo dataset (https://zenodo.org/records/14216491) including the updated surveys for all models.

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Preface

DIAMOND will update, upgrade, and fully open six Integrated Assessment Models (IAMs) that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. It will further enhance modelling capacity to assess the feasibility and desirability of Paris-compliant mitigation pathways, their interplay with adaptation, circular economy, and other SDGs, their distributional and equity effects, and their resilience to extremes, as well as robust risk management and investment strategies. This will be done via integration of tools and insights from psychology, finance research, behavioural and labour economics, operational research, and physical science. The project will develop a transdisciplinary scientific approach to legitimise the implementation process and co-create research questions that stretch the frontiers of climate science, as well as establish vibrant communities of practice to transparently open model enhancements and to develop capacities, thereby lowering the entrance barriers to the established IAM community.

ICCS	INSTITUTE OF COMMUNICATIONS AND COMPUTER SYSTEMS	EL
BC3	ASOCIACION BC3 BASQUE CENTRE FOR CLIMATE CHANGE - KLIMA ALDAKETA IKERGAI	ES
CESAR	KRATENA KURT	AT
CICERO	CICERO SENTER FOR KLIMAFORSKNING	NO
CYI	THE CYPRUS INSTITUTE	CY
E4SMA	ENERGY ENGINEERING ECONOMIC ENVIRONMENT SYSTEMS MODELING AND ANALYSIS SRL	IT
HOLISTIC	HOLISTIC IKE	EL
COMILLAS	UNIVERSIDAD PONTIFICIA COMILLAS	ES
ISINNOVA	ISTITUTO DI STUDI PER L'INTEGRAZIONE DEI SISTEMI (I.S.I.S) - SOCIETA'COOPERATIVA	IT
SEURECO	SEURECO SOCIETE EUROPEENNE D'ECONOMIE SARL	FR
UM	UNIVERSITEIT MAASTRICHT	NL
ESMIA	ESMIA CONSULTANTS INC.	CA
USMF	THE UNIVERSITY OF MARYLAND FOUNDATIION INC	US
UMD	UNIVERSITY SYSTEM OF MARYLAND	US
EPFL	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	CH
ETH	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	CH
UNIBAS	UNIVERSITAT BASEL	CH
Imperial	IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	UK
Oxford	THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD	UK
UCL	UNIVERSITY COLLEGE LONDON	UK

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Executive Summary

Integrated Assessment Models (IAMs) have historically been the dominant tools in climate change mitigation policy assessment and the analysis of global and/or regional scenarios. While IAMs have largely contributed to global and regional policymaking and decarbonisation strategies, scientific literature has pointed out some weaknesses or areas of improvement that should be considered for the robustness of future IAM applications. First, IAMs do not represent socioeconomic and political barriers associated with the implementation of alternative policies. Second, there is misrepresentation of certain dynamics that can in turn lead to misinterpretation of derived outcomes, such as the common practice of using economy-wide carbon prices as an oversimplified proxy for global climate policies. One of the main aspects to be improved is achieving finer temporal and geographical scales to assess the distinct region-/country-specific solution space. Finally, another area of improvement for IAMs is to address the current lack of transparency and detailed documentation. IAMs have frequently been considered as “black boxes”, with opaque input assumptions that do not allow a full understanding of the uncertainties embedded in the produced outputs.

In this context, DIAMOND aims to enhance six multi-sectoral IAMs by integrating stakeholder input and connecting them with sector-specific models, overcoming current limitations to ensure robust, reliable, and socially relevant outcomes. As outlined in the initial development plan (D3.1), the six IAMs within DIAMOND have heterogenous development plans, due to their systematically different modelling structures, including the geographical, temporal, and sectoral coverage, the representation of different variables and policy mechanisms, or input requirements. These model-specific development plans must be refined and updated to accurately reflect the needs and priorities of stakeholders, ensuring they remain practical, aligned with real-world objectives and problems, and impactful. The aim of this report is to update the initial model development plans, based on ongoing development efforts in the project so far, as well as drawing from suggestions for new capabilities and features provided by different stakeholders in the Requirements Workshop, hosted as part of the project’s transdisciplinary approach. Finally, this update also introduces a recommended data harmonisation protocol as a preparatory step towards model use within the project (WP5) as well as beyond.

In order to gather the main information of the updated plans of the models, each IAM team has updated the internal surveys presented in D3.1, providing a comprehensive overview of their progress and detailing how they have incorporated stakeholders' insights into their development strategies. In terms of geographical coverage, the consulted stakeholders stressed the need for increasing the spatial granularity of models. As a response, different modelling teams have finetuned their plans to improve their representation of the European Union (EU) (e.g., by individual member states) and their coverage in the rest of the world. In terms of sectoral and technological coverage, different stakeholders demanded improving the level of technoeconomic detail, including aspects such as technological readiness or costs associated with storage technologies. Additionally, stakeholders highlighted the need for greater sectoral disaggregation, distinguishing between areas such as passenger versus freight transport or more detailed breakdowns of labour markets, particularly based on skill levels. Stakeholders also called for more accurate representation of trade policies and behavioural measures, such as transport modal shifts. The updated model development strategies align better with the stakeholders’ suggestions for increased technoeconomic and policy representation, with a focus on improving the representation of hydrogen and electricity storage systems and preparing models for scenarios focusing on behavioural change and trade policies.

Finally, the updated internal survey includes information on the data sources for different input assumptions used by the different models. This deliverable includes early-stage insights for a **model harmonisation strategy**, which can assist modelling teams during the development stage, and which could also be applied in future project activities for participating or coordinating model inter-comparison exercises, a non-trivial process that is crucial for improving the consistency and robustness of scenario results. The steps outlined in this harmonisation strategy could also serve as a framework for future modelling exercises beyond the scope of this project.

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1 INTRODUCTION

Integrated Assessment Models (IAMs) have historically been the dominant tools in climate change mitigation policy assessment and the analysis of the implications of alternative global and/or regional scenarios (van Beek et al., 2020). These models are designed to explore alternative "what if"-type scenarios and to evaluate the interdependencies between the economy, energy, agriculture, forestry, and land use (AFOLU), water or climate systems. Due to their flexibility, they have been largely used in several global and regional scenario analyses and policymaking. Some representative examples are the scenarios within the different assessment reports by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022), the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014), or the U.S. strategy to reach net zero emissions in 2050 (Horowitz et al., 2022).

While these models have largely contributed to global and regional policymaking and climate change mitigation strategies (Weyant, 2017), scientific literature has pointed out some weaknesses or areas of improvement that should be considered for the robustness of future IAM applications. First, IAMs do not represent socioeconomic and political barriers that different policymakers face for the implementation of alternative policies (Peng et al., 2021). In order to improve the trustfulness and social acceptance of the model outcomes and the effective translation of results to real policy action, it is essential to incorporate the views of a wide range of stakeholders at different levels, including international experts, cross-regional organisations, national governments, regional institutions, local agents, and citizens (Miller and Wyborn, 2020; Galende-Sánchez and Sorman, 2021). While IAM modellers commonly rely on stakeholder inputs to enhance model parameters and identify weaknesses or potential improvements, the concept of model co-development is still relatively underrepresented in the scientific discourse (Nikas et al., 2023).

Second, IAMs usually misrepresent certain dynamics that can lead to misinterpreting model-produced outcomes. The implementation of global climate policies in IAMs are usually oversimplified (Keppo et al., 2021), The use of a universal carbon price, for example, is a common approach, which nonetheless does not represent real-world policies (Sognnaes et al., 2021). The models also have limited spatiotemporal and sectoral granularity (Mulugetta et al., 2022; Peng et al., 2021). Historically, IAMs work at annual or multi-year time-steps (i.e., 5-year periods), implying disruptive events or seasonality within-year dynamics could not be captured. These events may be particularly relevant for some sectors, such as the power sector (Wise et al., 2019). Furthermore, IAMs do not incorporate within-region inequality considerations to capture the contribution of different socioeconomic groups to global warming, or the impacts of global change to the different groups within each region, which is becoming essential for the design and assessment of the decarbonisation strategies (Sampedro, 2021; UNFCCC, 2016). Similarly, IAMs do not model the finance system or the capital markets, thus failing to capture different perceptions of investors (e.g. banks or funds) that play an essential role in the energy transition rarely captured the projected alternative socioeconomic and/or technological pathways (Battiston et al., 2021). Hence, different studies have highlighted that the way of representing the epistemic and structural uncertainties can lead to misinterpretations of the model results (Beck and Krueger, 2016; Pindyck, 2017).

Finally, another area of improvement for IAMs is the lack of transparency and detailed documentation. IAMs have frequently been considered as "black-boxes", with opaque input assumptions that do not allow a full understanding of the uncertainties embedded in the produced outputs (Pindyck, 2013; Van der Sluijs, 2002). Likewise, the lack of peer review for these models can reduce their credibility (Rosen, 2015). Increasing model transparency has become a high priority for the IAM community, particularly for improving the reliability of the scenarios analysed in the IPCC reports (Robertson, 2021; Skea et al., 2021). Recent multi-model intercomparison studies have emphasised the need for comparing modelling assumptions, in order to reduce the heterogeneity of model responses (Giarola et al., 2021; Krey et al., 2019). Similarly, the IAMC community is actively promoting different open-access tools to explore the alternative IPCC scenarios and improve their transparency and re-use, such as the AR6 scenario explorer (Byers et al., 2022), the 1.5ºC scenario explorer (Huppmann et al., 2018), the *pyam* package (Gidden and Huppmann, 2019), or the I^2AM PARIS platform (Nikas et al., 2021). Nevertheless, the adoption of open science practices varies significantly among different IAM teams and is frequently limited by multiple challenges, which can slow scientific progress, restrict the reporting and reuse of research findings, and undermine the reliability of models representing complex real-world systems (Pirani et al., 2024; Wilson et al., 2021). Therefore, improving the documentation of model input parameters, assumptions, and uncertainties becomes essential for increasing the relevance and acceptance of model results.

Considering inter alia these critiques, the model development strategy and its updates within DIAMOND aim to start making inroads towards the development of models that improve the representation of such dimensions. In a previous deliverable (D3.1), we presented a strategy to coordinate the initial model development activities in DIAMOND in order to improve six multi-sectoral IAMs. These initial strategies were designed to address the identified limitations, ensuring open access, transparency, and the capacity of the models to tackle key research to better inform policy debate. The current deliverable (D3.2) builds upon previous work (D3.1) by **presenting updated model development plans** for the various IAMs, detailing both the progress made thus far and the planned future activities. **These plans are now enriched with valuable information and insights gathered from a diverse group of stakeholders**, which were obtained during a dedicated workshop. This workshop was an integral part of the transdisciplinary process undertaken throughout the project, specifically within the framework of WP2-related activities. The incorporation of stakeholder perspectives into the updated strategies guarantees that the model development is more aligned with real-world needs and research priorities.

In addition, this document includes a **preliminary model harmonisation strategy** that could be used to develop multi-model comparison studies with the six IAMs in the consortium. Putting together all the different data sources used by the modelling teams helps towards potential harmonisation of data across different models, which will be useful for high-impact, model intercomparison studies as they can provide robust insights for alternative scenario analysis.

2 UPDATING THE MODEL DEVELOPMENT STRATEGY

The main objective of this deliverable is to update the model development strategy, which details the steps to improve the capabilities and the political and social relevance of the consortium's IAMs [Work Package (WP) 3],and connect them with sectoral models (WP4) to widen the scope of the potential research questions they can analyse (WP5). The updated strategy builds on the initial development plan and incorporates the various adjustments made by the IAMs teams based on stakeholder feedback (WP2). This section provides a summary of the initial development plan (section 2.1), the process to incorporate stakeholder insights into the updated development plans (section 2.2), and the updated representation of policies and measures (section 2.3).

2.1 Initial development plan (D3.1)

The first step to enhance the IAMs within DIAMOND was the preparation of an initial development plan, which formed the core of deliverable D3.1. The six IAMs have different modelling structures, including geographical, temporal, and sectoral coverage, the representation of different variables (exogenous or endogenous), input requirements, the implementation of policy mechanisms, or solver methods/algorithms. Therefore, we needed a common documentation space that gathers the main information about the six different models. Each modelling team prepared a preliminary model development strategy (MS5) that described: 1) the refinement of the geographical and temporal scales (e.g., more detailed regional disaggregation); 2) the planned improvements in terms of dynamics, capabilities, or sectoral coverage, as well as the potential actions to improve transparency (e.g., improving the documentation or opening the source-code under an appropriate open source license); and 3) the potential interconnections with the additional sectoral models within the DIAMOND consortium. For that purpose, **we created a survey that gathered the main features of each model** in terms of regional coverage, resource and technology representation, the end-use demands and demand drivers, the socioeconomic structure, the (lack of) incorporation of different climate feedbacks, the way of implementing alternative climate policies, or broader policy mechanisms (see Table 1). The survey also included data sources for different input assumptions that are read in by the different models. This common documentation space facilitated the communication between the global and sectoral modelling teams in an efficient way, ensuring that all teams take advantage of the possibilities that will emerge during the model development efforts. Furthermore, the addition of data sources used by the different models into the survey is a co-benefit for the update and upgrade of the IAMs: each team becomes able to use the data sources originally intended for the rest of the models to develop new modelling capabilities that were not originally captured in their plans.

Table 1. Overview of the contents of the initial survey

Sheet	Description
Model Info	Model general information and short description
Integration & Expansion	Possible links with WP4 modules and their objectives
Regions	List of the model regions and geographical aggregations
Sources & Potential	List of fossil fuels resources and renewable potentials, including the modelling function
Technologies	List of technologies included in the model and preferred data source
Demand drivers	List of energy demands, including units and demand drivers
Socio-Economics & Prices	List of endogenous/exogenous socio-economic parameters, including energy prices, used by the model
Emissions	List of endogenous/exogenous emissions
Policies	List of policies that can be modelled
Measures	List of endogenous/exogenous measures that can be modelled
Climate Impacts	List of endogenous/exogenous climate impacts covered by the model

The different IAM modelling teams in the consortium filled the survey for their models. All the surveys with the information on the six IAMs, including their regional, sectoral, policy coverage, as well as the calibration data and input assumptions are publicly available on Zenodo[1].

2.2 Incorporating stakeholder insights

The incorporation of stakeholder insights into the model development strategy of each model is essential to ensure that the **models developed in the project address the diverse needs, preferences, and expectations of a broad audience**. Communicating with a wide range of stakeholders with varying backgrounds allows to evaluate how the initial development plans resonate with stakeholder needs and guides the modelling teams towards refining their strategies based on stakeholder insights. The initial development strategy (D3.1) indicated that, for an effective and efficient integration of stakeholder information[2], the modelling teams need to:

- Identify the topics and themes that stakeholders want to be addressed through the models.

[1] The initial version of the surveys can be found here, and the updated version here.
[2] More details on the stakeholder engagement strategies can be found in the different Tasks in WP2, concretely in Task 2.1 ("*Developing an innovative stakeholder engagement plan*"), Task 2.2 ("*Phase 1 – Towards mutual understanding*"), and Task 2.3 ("*Phase 2 – Towards knowledge co-production*").

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- Discuss how the models can be applied for supporting policymakers in the design and assessment of different policy packages.
- Use stakeholder information to identify the most crucial aspects to be improved, including:
    - Geographical and temporal scales
    - Sectoral coverage
    - Input information and assumptions
    - Misrepresented dynamics and uncertainties
    - Potential interconnection with additional sectoral models (to widen the modelling scope)

Within this context, on September 13, 2024, the DIAMOND team conducted a "Requirements Workshop", coordinated by ISINNOVA (as part of the activities in T2.3.1). The workshop aimed to gather feedback from various stakeholders within the following themes: high-level and cross-sectoral; residential and transport; power (including upstream); industry; and water, land, and other sectors. During the workshop, the participants were guided through a structured process to reflect on and discuss proposed research themes, in 5 breakout rooms using a Mural board, where the participants could post their comments. As a first step, the participants were asked to review the proposed themes and provide feedback on their relevance to their policy needs. They were encouraged to assess the themes' pertinence and suggest improvements where necessary. Then the moderator initiated a round discussion, where participants explained their comments, allowing for group feedback and further reflections. The goal was to evaluate how modelling capacities align with stakeholder expectations. The participants were also invited to suggest other relevant research themes they felt were important, posting their suggestions on Mural board for further exploration. The session concluded with an opportunity for participants to explain their suggested themes and receive feedback, with the possibility of delving deeper into these ideas in the second session. The rationale behind these actions was to foster individual reflections followed by collective discussions, ensuring the proposed research themes addressed real-world policy concerns and identifying any gaps or new themes worth considering. More on the process followed during the workshop can be found in the report of MS6.

In summary, stakeholders identified some key aspects to be considered by the different models in their development strategies, which include improving the spatiotemporal granularity, and the level of technological and sectoral detail. They also underscored the critical importance of incorporating emerging technologies and addressing uncertainty in climate models by integrating both physical and transition risks, as detailed in MS6. Due to the systematic differences across the IAMs in the consortium, the information provided by the stakeholders in the workshop was then processed by the different teams and tailored to fit the specific structures and capabilities of each model. Table 2 compiles the information that will support the IAM teams in their model-specific development plans.

Table 2. Summary of the stakeholder information processed by different modelling teams

Topic	GCAM-Europe	OMNIA	CLEWS-EU	GEMINI-E3-EU	NEMESIS-WORLD	OPEN-PROM
High-level and cross-sectoral	- Reflect differentiated levels of technological readiness, infrastructure and other hidden costs by EU member state based on existing data and estimations	- Consider internally in the model infrastructure costs for power grid transmission - General review of the cost of technologies and infrastructure	-	- Introduction of Hydrogen in the model will be based on technological readiness—specifically, the point at which a given technology can feasibly be integrated into the model framework. - More detailed regional representation: able to capture the inter-regional agreements and cross-border policies, as well as relevance in burden sharing and distributional aspects.	- To represent shocks from climate change, NEMESIS will include estimated climate damage functions by type of damage for each EU country. These functions link an economic indicator of the extent of the damages (pt of GDP, labour productivity, etc.) and the change in global/local temperature.	- Consider different climate policy scenarios (NDC, 2C, 1.5C) and uncertainty (SSPs). - Better Regional representation will be more relevant to burden sharing and distributional aspects. - Spatial Disaggregation is crucial to understand local specificities.
Residential and Transport	- Represent international intra-EU transport demand and options and consumer preferences (e.g. high-speed rail). - Implement scenario design by household groups (e.g., income) to model differentiated policy impacts.	- Type of transport vehicle Breakdown by Fuel: Data were used to detail the share of energy consumption for different types of vehicles (e.g., cars, buses, passenger planes etc) by fuel type. - Residential End-Use Breakdown by Fuel: Data were used to detail the share of energy consumption for different end uses (e.g., heating, cooling, lighting) by fuel type. - Residential Region Segmentation by Energy Intensity: Regions are split	As traditional cost-optimisation models fail to capture behavioural aspects, a relevant module is developed by UNIBAS and will be integrated in CLEWs-EU to assess how behaviour affects choices on vehicle technologies and building insulation.	Modifying the model to include different type of Households (based on income) to capture different demand services.	- Represent households by income group, which will be feasible for the EU. - Extend the employment results by sector and by educational level, types of jobs and gender.	- Make transparent assumptions for travel/transport demand - Address how/if technology shift (required investments) will increase the inequality gap - Model both private and public transport, as well as shipping of goods

Topic	GCAM-Europe	OMNIA	CLEWS-EU	GEMINI-E3-EU	NEMESIS-WORLD	OPEN-PROM
		into high- and low-intensity zones based on heating and cooling demands. Temporal demand profiles aligned with OMNIA's time slices capture hourly and seasonal variations, improving the model's accuracy.				
Power and Upstream	- Explicitly model intra-EU trading of energy commodities and grid electricity, separated from extra-EU trade. - Include storage technologies in the electricity sector.	- Implement different CCS retrofit technology options in the supply chain: refineries, fossil fuel power plants. Make sure all CCS options in the upstream sector are included. - Run sensitivities on hydrogen pipeline cost to study hydrogen transportation uncertainties. Add the option of existing natural gas pipeline retrofit into hydrogen pipelines. - Run sensitivities on extra-EU trades to study a less dependent EU for energy supply. - Add new integrated storage technologies to power system modelling	- Future technology options for electricity and heat generation included in the model will include fossil- and biomass-fired combustion employing Carbon Capture and Storage (CCS) to assess the future importance of CCS (e.g., BECCS, gas with CCS). - Different storage options will be included in the model (e.g., batteries, pumped-hydro, green hydrogen production) to assess the importance and role of various means of storage in the energy transition. - The level of detail on cross-border electricity interconnections will be improved to allow projections on intra-EU electricity trade across scenarios.	Potential implementation of CCS and BECCS plants in the model will be monitored to avoid over-utilisation of these abatement technologies in simulations.	-	- Model CCS technologies such as BECCS and fossil fuel CCS plants - Model the need to have dispatchable energy sources available to support the system, such as GAS with CCS. - Model Storage in the power sector - Model which storage technologies are best suited for different countries/regions. In terms of cost and/or impacts on land use (e.g., for pumped hydro)
Industry	- Include DRI and H2 trade (at least intra-European) as an alternative option to industrial allocation.	- Ensuring that the energy intensive sectors we are focusing on are represented in sufficient detail to provide insights on the role of CCS, material efficiency	- Future technology options for industry included in the model will include fossil- and biomass-fired combustion employing Carbon Capture and Storage (CCS).	Sectoral reclassification: enable more reliable modelling of trade policies (taxes, duties, mandates and regulation) especially for hard to abate sectors.	- In terms of capital restrictions, some policies acting on the cost of (imported) capital could be implemented in the NEMESIS model, but it	- Model how circular economy policies impact decarbonisation and cost of mitigation in the cement sector - Model the

Topic	GCAM-Europe	OMNIA	CLEWS-EU	GEMINI-E3-EU	NEMESIS-WORLD	OPEN-PROM
	– Add material circularity options in steel, aluminum, cement. - Endogenously model efficiency costs in industry (potentially).	and trade dynamics. We will also ensure that the OMNIA-ENGAGE model linkage is fit for purpose and able to address the important issues they raised.	- The relevant technology options will be expanded to include biomass, solar thermal and green hydrogen to assess what the future role of renewable fuels will be in the industrial sector.		means designing complete scenarios. - Disaggregate the results of employment by sector, educational level, types of jobs and gender, to model the potential winners and losers from energy transition. - To better represent financial aspects NEMESIS currently improved the modelling of capital in the EU version of the model by including several layers related to capital markets: central bank monetary rule, public. Nevertheless, so far it does not concern technologies per se.	decarbonisation of Chemical and Petrochemical Sector (and reflect on the issue of data availability) - Model the role of renewable fuels in the industrial sector (i.e. Biofuels and Hydrogen).
Water, land and other sectors	-	-	- Detail in the model will be improved to capture climate change impact on crops and to assess impacts across the sectors on energy-water-land interlinkages. - In order to account for climate uncertainty, use of the FAO GAEZ tool will be adopted to derive different crop yield under different climate scenarios. - The level of detail in the land module will be improved to allow representation of energy content and CO2 emissions of different biomass options.	-	-	- Modelling of Climate change impact on crops and to what extent the energy-water-land loop is completed in the models. - Representation of energy content and CO_2 emissions of biomass.

Apart from the direct feedback to be use by the different teams to improve their models (WP3), stakeholders also raised some relevant feedback that could be further explored in WP4, which focuses on integrating IAMs with sectoral or bottom-up models to broaden the overall scope of analysis. In terms of high-level and cross sectoral research themes, several stakeholders outlined the importance of incorporating climate feedbacks into the models, particularly into the power sector, and into the projections of future crop yields and water availability. Integrating potential climate feedbacks is a recognised research priority for the integrated assessment community (Khan et al., 2021; Seneviratne et al., 2024), and is planned to be explored by the different modelling teams in WP4. The stakeholders also highlighted the need to consider the health impacts of air pollution, and the potential health co-benefits of decarbonisation. While it is not explicitly considered in this project, it is an active research line for some of the modelling teams (Sampedro et al., 2023) and could be further explored during the course of the project. For the residential and transport sectors, some modelling teams are planning to expand the model representation of different transportation modes to be able to capture the environmental implications of modal shifts (e.g., in WP5), which is an important option, considering the existing barriers for decarbonising the transport sector. Regarding the power sector, the consulted stakeholders showed their interest on improving temporal granularity (to better capture benefits of storage); modelling decentralised electricity systems, including energy communities; and representing intra-EU electricity trade and changes in the interconnector capacity. Stakeholders also provided feedback on the industry sector that could be explored by the modelling teams during the project, including the explicit consideration of carbon transportation costs or modelling additive manufacturing. Finally, on the land and water sectors, the consulted stakeholders showed interest on the potential integration of nutritional values of the different food sources into the models, as well as the representation of multifunctional land uses (e.g., agroforestry), wildfires, or biodiversity impacts.

The Requirements Workshop was the key vessel for our stakeholder engagement approach to directly influence the model development strategy. However, as more engagement activities are planned for the next period, more insights may be useful for model development. The modelling teams will monitor these discussions and are prepared to further adapt this strategy based on potential feedback received. Any further such changes will be reported in the next update of the model development strategy.

2.3 Representation of policies and measures

As part of the initial development plans, the different modelling teams also described the climate policies and broader energy, land and demand-side measures that could be represented with the models in the consortium. The implementation of different policies into the models is relevant for WP5, which focuses on exploration of alternative scenarios. **Stakeholder input, as described in the previous section, is designed to steer the definition of policies in WP5, and therefore this information is crucial for the potential representation of policies and measures in the models in the context of WP3**. Considering that IAMs are explicitly designed to analyse the effects and impacts associated with alternative climate policies, the original versions of the models within DIAMOND are already able to directly represent a suite of climate policies without any further modification, such as carbon prices, emission quotas, climate targets, energy tax/subsidies, or land protection policies. In addition, IAMs can also represent a wide range of economy-wide measures that are essential in a transition towards a carbon neutral economy. These measures include the use of cleaner or more efficient fuels or technologies in different end-use sectors (buildings, industry, transport, and agriculture), or additional mitigation options such as direct air capture, afforestation, or behavioural changes. The original models can also usually represent some of these options either endogenously or exogenously. The current development strategies included detailed plans for the improvement of the representation of alternative climate policies (Table 3) and additional energy-land-demand side measures (Table 4).

Table 3. Overview of the climate policies represented in each model.

Category	Policy measure	GCAM-Europe	OMNIA	CLEWS-EU	GEMINI-E3-EU	NEMESIS-World	OPEN-PROM
Emissions mitigation	Tax						
	Emissions target / quota						
	Regulations (emissions standards, etc…)						
	Global Temperature / Radiative Forcing target						
	Financial supports (negative emissions, CDMs, Green Climate Fund)						
Energy	Tax						
	Subsidy						
	Energy mix target						
	Efficiency target						
	Regulations (thermal regulation in buildings, banning of diesel cars in urban areas, etc…)						
Land	Protected lands						
	Production quotas						
	Carbon sink pricing / Land use change emissions tax						
	Afforestation targets						
Trade	Carbon border tax on imports						
	Carbon border supports on exports						
	Regulations policies (certifications, Best-available technologies, standards, etc…)						

Policy not applicable in original or updated model	Policies that could be directly implemented in the original model version	Policies that could be implemented with the original version of the model, but with some modifications	Policy is planned to be represented in the updated model version	Option to implement the policy in the updated model version, but it still needs to be decided

Table 4. Overview of the energy, land and end-use demand measures represented in each model.

Category	Policy measure	GCAM-Europe	OMNIA	CLEWS-EU	GEMINI-E3-EU	NEMESIS-World	OPEN-PROM
Buildings	Fuel switch/energy mix						
	Technology substitution						
	Efficiency improvement						
Industry	Fuel switch/energy mix						

Category	Policy measure	GCAM-Europe	OMNIA	CLEWS-EU	GEMINI-E3-EU	NEMESIS-World	OPEN-PROM
	Technology substitution						
	Efficiency improvement						
	CCS						
Combined heat and power	Fuel switch/energy mix						
	Technology substitution						
	Efficiency improvement						
	CCS						
Transport	Fuel switch/energy mix						
	Technology substitution						
	Efficiency improvement						
	Modal shifts						
Agriculture	Fuel switch/energy mix						
	Technology substitution						
	Efficiency improvement						
	Land practices						
	Agroforestry						
	Animal husbandry practices						
Direct Air Capture	Direct Air Capture						
Land Use, Land-Use Change and Forestry (LULUCF)	Afforestation						
Behavioural Changes	Behavioural Changes						

The measure is not represented in the original or updated model version	The measure is represented endogenously in the original model version	The measure is exogenous in the original version of the model	The measure is planned to be incorporated or endogenised in the updated version of the model	The representation or endogenisation of the measure in the original model version needs to be decided

3 UPDATED MODEL DEVELOPMENT STRATEGIES

Table 5 summarises the planned model developments, and the following subsections detail the strategies of the six global models in the consortium.

Table 5. Summary of model developments

Original model	New model	Model type
GCAM	GCAM-Europe	Partial equilibrium
TIAM	OMNIA	Partial equilibrium
Global CLEWS/GLUCOSE	CLEWS-EU	Linear optimisation
GEMINI-E3	GEMINI-E3 EU	Computable general equilibrium (CGE)
NEMESIS	NEMESIS-World	Macroeconomic/Econometric
PROMETHEUS	OPEN-PROM	Partial equilibrium

Regarding the timeline, each modelling team has started the development of the model enhancements in Month 4 (M4), as indicated in D3.1. Likewise, the exploration of potential interconnection options with additional bottom-up models (WP4) for some research areas (e.g., representation of labour/finance dynamics) has started at the very early stages of the project (M1). The following sections outline the updated model-specific development strategies per model (sections 3.1-3.6), which now incorporate stakeholder insights and suggestions from the dedicated "stakeholder requirements" workshop. This process ensures that the models will capture their needs and therefore will be relevant for policymaking.

3.1 From GCAM to GCAM-Europe

3.1.1 Overview

GCAM (Global Change Analysis Model) is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. Regional population and labour productivity growth assumptions drive the energy, land-use and water systems employing numerous technology options to produce, transform, and provide energy services as well as to produce agricultural and forest products, and to determine land use and land cover. The model has been used to explore the potential role of emerging energy supply technologies and the impact on greenhouse gas emissions of specific policy measures or energy technology adoption including; carbon dioxide (CO_2) capture and storage, bioenergy, hydrogen systems, nuclear energy, renewable energy technology, and energy demand in buildings, industry and the transportation sectors. Outputs of the model include projections of future energy supply and demand and the resulting greenhouse gas emissions, radiative forcing and climate effects of 16 greenhouse gases, aerosols and short-lived species, implications for future land cover and water use, contingent on assumptions about future population, economy, technology, and climate mitigation policy. Through separate modules, results in terms of emissions and water use can be used to estimate pre-mature mortality and water shortages by region.

For the development of GCAM-Europe, geographical disaggregation is increased for the European continent. GCAM by default divides the world in 32 regions, and the European continent is divided in five different regions: 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 (see Figure 1 and Table 6). Having this level of detail will enable us to explore the country-level effects of European policy packages or transformational strategies, as well as the potential international effects (e.g., carbon leakage) for a representative set of non-European regions (27) over the world.

In terms of sectors, the model expands (for the newly created European countries, and there may be differences by country based on data availability) in various dimensions (Figure 2). The representation of electricity grids and regional trade, as well as demand segments, allows to have more sectoral detail in the power sector by reflecting energy storage. In final energy demand, predominantly in building energy demand, new demand categories are included as well as new technologies like heat pumps, driven by high data availability for European countries. Behind the overall sectoral representation, there is a further deep-dive in terms of consumer group representation, which is highlighted in section 3.1.5.

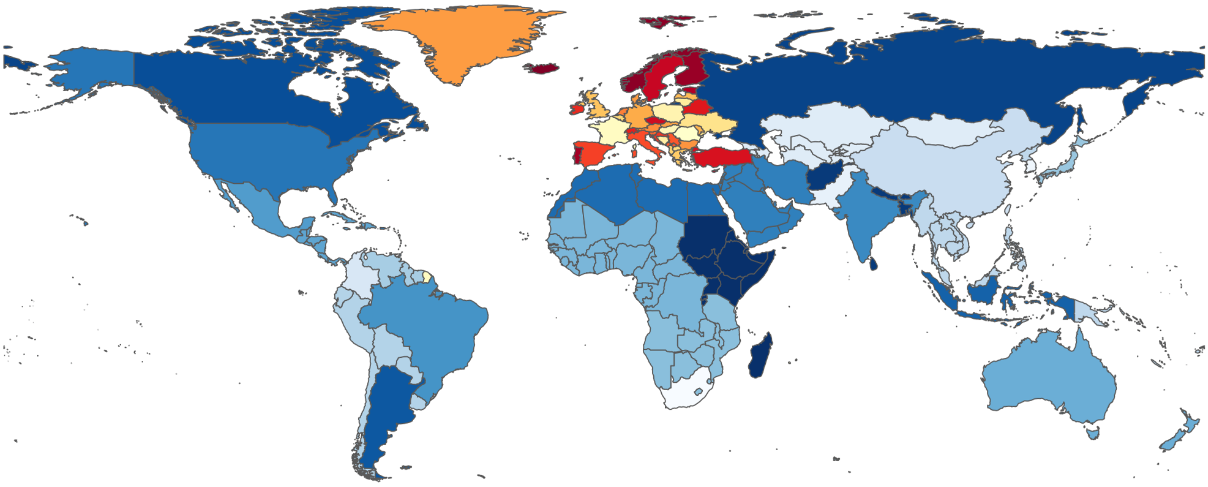

Figure 1. Regional disaggregation in GCAM-Europe.

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.

Table 6. List of model regions in GCAM-Europe

Model region (default)	Model region (new)	Model region (new)
Africa_Eastern	Albania	Lithuania
Africa_Northern	Belarus	Luxembourg
Africa_Southern	Belgium	Macedonia
Africa_Western	Bosnia and Herzegovina	Malta
Argentina	Bulgaria	Moldova
Australia_NZ	Croatia	Netherlands
Brazil	Cyprus	Norway
Canada	Czech Republic	Poland
Central America and Caribbean	Denmark	Portugal
Central Asia	Estonia	Romania
China	Finland	Serbia and Montenegro
Colombia	France	Slovakia

India	Germany	Slovenia
Indonesia	Greece	Spain
Japan	Hungary	Sweden
Mexico	Iceland	Switzerland
Middle East	Ireland	Turkey
Pakistan	Italy	United Kingdom
Russia	Latvia	Ukraine
South Africa		
South America_Northern		
South America_Southern		
South Asia		
South Korea		
Southeast Asia		
Taiwan		

Funded by
the European Union

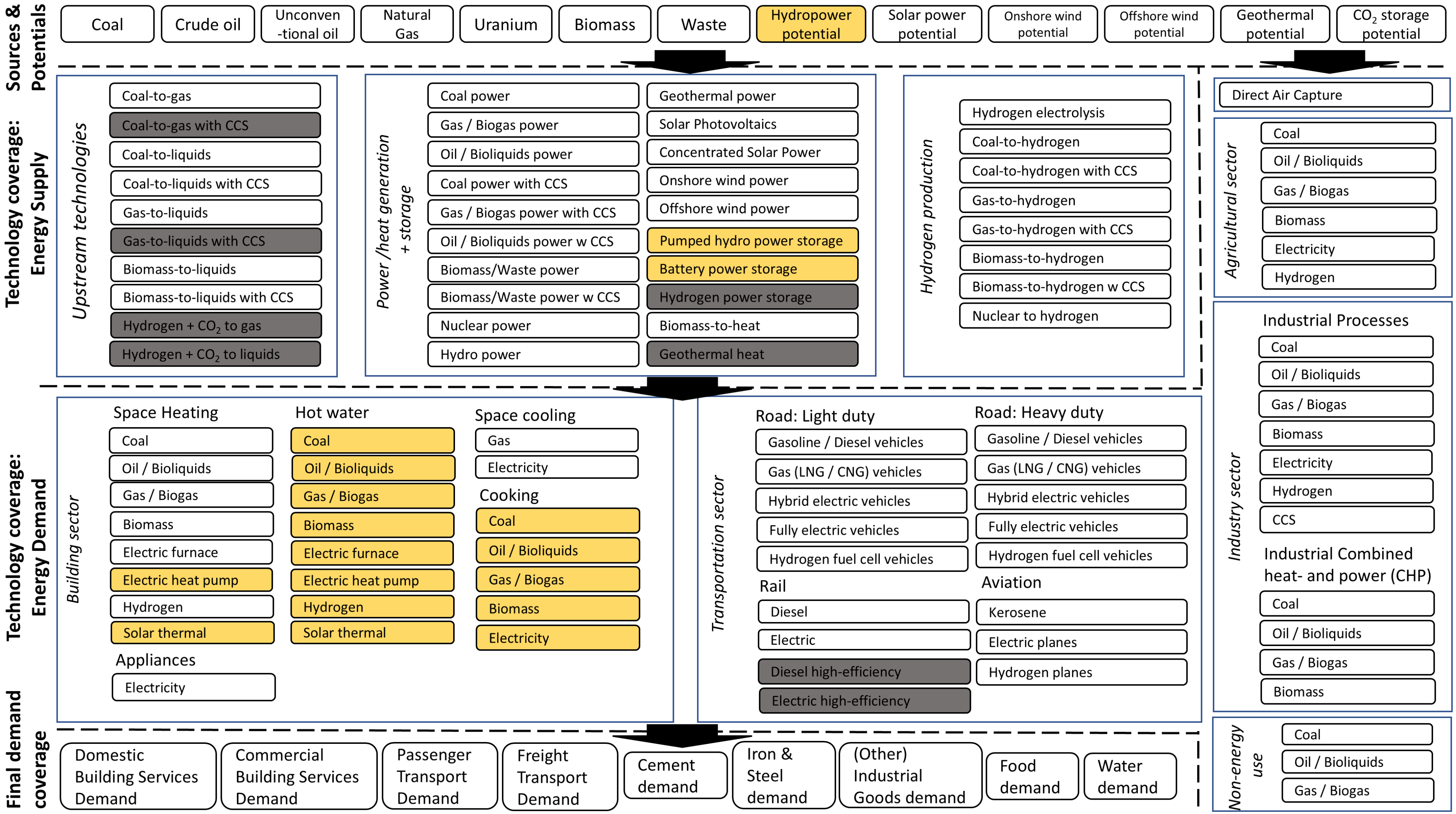

Figure 2. Summary of the resource, technology, and end-use demand representation in GCAM-Europe.

White boxes indicate features already part of the original model. Grey boxes indicate features not part of the core nor the updated model. Dark yellow boxes indicate the features that will be explicitly developed for GCAM-Europe in the DIAMOND project, and which are not in the core version of the model

3.1.2 Development timeline

- January 2024: Working “alpha” version with all countries as separate regions within global core structure
- December 2024: Updated version (GCAM-Europe 7.1-Beta)
    - All data replaced by specific European data sources where available (Eurostat, ENTSO-E)
    - Grid regions for electricity trade between countries, based on openTEPES assumptions
    - Basic sectoral expansions based on data availability (e.g. building services and technologies, transport fuels)
    - Adapted commodity trade structure to represent EU trading block
    - Updated with GCAM core improvements (GCAM 7.1)
    - Open-source access through Github and technical description of model to be written and published in Q1 2025 in peer-reviewed journal and the I^{2}AM PARIS Platform
- June 2025: Updated version with initial expansions / WP4 links:
    - Household consumption based on actual HBS data for household groups (e.g. income levels)
    - Improvements in industry coverage and structure (ENGAGE)
    - Electricity module further updated emulating open-TEPES interactions
    - Other relatively straightforward potential improvements as listed in section 3.1.6.3
    - Updated with GCAM core improvements (including potential base year update)
- December 2025: Further updated version with deeper expansions / WP4 links:
    - Behavioural change aspects incorporated throughout model (UNIBAS)
    - Potential links with labour/financial modules (UM)
    - More challenging potential improvements as listed in section 3.1.6.3
    - Updated with GCAM core improvements
- June 2026: Final version (GCAM-Europe 7.X):
    - Potential bug / consistency fixes relative to previous version
    - Updated with GCAM core improvements
    - Full documentation (contents TBD) written down in D3.6 and academic publication
    - Open access branch ready through GitHub

3.1.3 Meetings (internal modelling team and external)

The development of GCAM-Europe is a gradual process in which the European region is being disaggregated within the global version of the model through a step-by-step process. Largely, the structure of the model will follow that of the global version, with several additional deep-dives in sectors and sector-links based on data availability, similarly as in GCAM-USA (Binsted et al., 2021) and GCAM-China (Cui et al, 2021), among other regional GCAM versions. To coordinate efforts and gather input from developers at BC3, ICCS, and UMD, while considering stakeholder feedback (guided by ETH I the context of WP2 activities), a GCAM-Europe kick-off meeting was held at BC3 in Bilbao on May 18, 2023.

Table 7. GCAM-Europe kick-off meeting agenda

Thursday, May 18, 2023, BC3 Offices (all times in CEST/local)			
09:30 – 10:00	*Arrival, coffee, get together*		
10:00 – 10:10	I.1	**Welcome**	BC3
10:10 – 10:30	I.2	**Aspirations for GCAM-Europe** • Geographical coverage • Module integration • Policies covered	ICCS, BC3
10:30 – 11:00	I.3	**Technical Aspects** • Github Repositories • GCAMdata • Development Practices	BC3, Holistic
11:00 – 11:15	*Coffee break*		
11:15 – 11:30	I.4	**Lessons learnt from GCAM-USA**	UMD
11:30 – 13:45	I.5	**From GCAM to GCAM-Europe** • Member-State disaggregation • International Impacts (Trade policies) • Integration with additional modules • Technology expansion • Sectoral Expansion	BC3, ICCS, UMD, Holistic
13:45 – 14:45	*Lunch break*		
14:45 – 16:15	I.6	**Joint Problem Framing Workshop** Coordination with WP2 to explore topics to take forward in the next workshops/stakeholder engagement	ETH
16:15 – 16:30	I.7	**Concluding Remarks**	ICCS, BC3

During this meeting, several details have been agreed on, such as the work process in collaboration with the different partners, the initial steps to follow, and the aimed regional disaggregation based on several factors, such as data availability and model coherency.

Since this meeting, there have been a large amount of internal BC3 and external meetings to guide the development of GCAM-Europe, including connections with different WP4 module teams (see Table 8).

Table 8. GCAM-Europe meetings

Type of meeting, description and dates		**Date**
Physical (Bilbao)	**Weekly internal meetings** Discuss progress in past week, forthcoming tasks and divide efforts between team members	Weekly every Thursday 11:00-12:00
Online	**WP4 link - Behaviour** Discussion with UNIBAS team on modelling the impact of household heterogeneity (HH) on technology uptake	3th October 2023
Physical (Bilbao)	**WP4 link – Household Heterogeneity** Discussion with Kurt Kratena (CESAR) on implementation of household heterogeneity in GCAM-Europe	10th January 2024
Online	**WP4 link - Electricity** Discussion with Comillas team about the	12th June 2024

	workflow to emulate openTEPES electricity model within GCAM-Europe	
Online	**WP4 link – Demand/Circularity** Discussion with UCL team about ENGAGE developments on assumptions on demand projections	18th June 2024
Physical (Bilbao)	**WP4 link – Finance** 2-week stay of Prescott Morley (UM) at BC3 with regular meetings about the representation of household financial constraints in GCAM-Europe	9-20th September 2024
Online	**Heat pump integration** Exploring conversation with Alvaro Campos (UPV/EHU) on representation of heat pumps in GCAM-Europe	15th October 2024
Online	**WP4 link - HH** Discussion with CESAR, EPFL and SEURECO teams about data/timeline issues around household heterogeneity	21st October 2024
Online	**WP4 link - Electricity** Follow-up discussion with Comillas team about updated data on electricity modelling in GCAM-Europe	14th November 2024
Online	**WP4 link - Household Heterogeneity** Follow-up discussion with CESAR, EPFL and SEURECO teams about data/timeline issues around household heterogeneity	14th November 2024

3.1.4 Completed development steps

The development of GCAM-Europe was initially aimed to be strongly guided by earlier regional model developments within the GCAM context, such as GCAM-USA and GCAM-China (see project DOW and Deliverable 3.1). However, these regional versions have no representation of several systems and sectors on the subnational level, such as land, agriculture, water and energy extraction. An important difference between GCAM-Europe with these earlier examples is that the disaggregation in the case of Europe is based on independent countries that are individually represented in many input data used for GCAM, such as the IEA energy balances (energy), FAOSTAT (agriculture and food), and the CEDS database (emissions). To exploit this opportunity and to ensure that the full GCAM system and sector representation refers to each European country individually, the process towards GCAM-Europe has started by disaggregating all European countries within the default model and based on the default input datasets, and then overwriting much of the (mostly energy) data by more detailed Europe-specific data sources. This first step in the development process, on top of GCAM core version 7.1, aims to create an initial workable version of GCAM-Europe 7.1-Beta).

As such, in the current version a notable difference from the global GCAM-core is the regional disaggregation, covering all European countries as individual regions. In the global version, these countries are aggregated into 5 energy-economy regions: EU-12, EU-15, European Free Trade Association, Europe_Eastern, and Europe_non_EU. This disaggregation in GCAM-Europe makes a version with 66 separate energy-economy regions (see section 3.1.2).

3.1.4.1 Replacing energy data by Eurostat data

The subsequent step was to replace data sources step-by-step for all newly created European countries for which Europe-specific data is available. The coverage of some key Eurostat energy databases has been checked and is outlined in Table 9. In the case a country is not covered with some of these data, other sources need to be found, where the most straightforward is to return to the default GCAM data (i.e. IEA for energy data). Less straightforward is the treatment of cases where the coverage in European data sources changes with time, such as in the case of the United Kingdom (UK). While more detailed Europe-specific data would be preferred for the UK, the apparent stop of this data after 2019 could be a problem for updating the model when the base year will get updated beyond 2019 (currently 2015).

Table 9. Country coverage of Eurostat data

	Complete Energy Balances (nrg_bal_c)	Disaggregated final household energy consumption (nrg_d_hhq)	Heat pumps, captured heat (nrg_ind_ahbtc) and technical data (nrg_ind_hptctc)
EU-27 member states	(green = fully covered)		
United Kingdom	**Until 2019, strategy after base year update to be decided.**		
Switzerland	**Not covered, IEA data used**	**Not covered, detail not covered in model**	
Norway			
Non-EU Balkan countries			
Turkey		**Data from 2022, disaggregation not covered**	
Ukraine + Moldova			
Iceland			
Belarus	**Treated as regular GCAM region based on IEA energy data**		

3.1.4.2 Electricity grid regions

Like in other regional GCAM versions (GCAM-USA, GCAM-China), 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 3 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[3], 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 will act as standalone grids without interconnection, as real-world interconnection with other European countries is insignificant. For Turkey, grid interconnection with the rest of Europe is represented.

[3] https://energy.ec.europa.eu/data-and-analysis/market-analysis_en#gas-and-electricity-market-reports

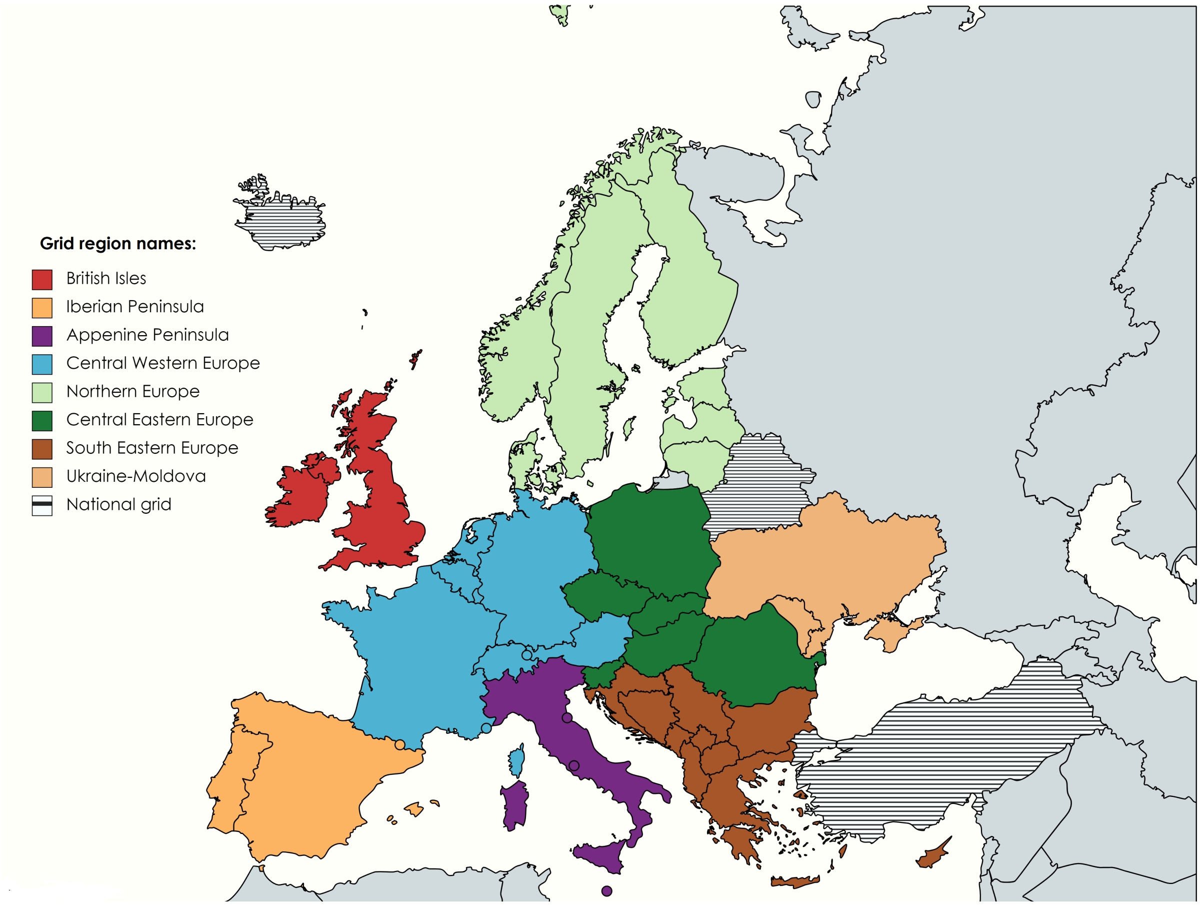

Figure 3. Planned electricity grid regions GCAM-Europe

The approach for representing the electricity system in GCAM-Europe is designed in collaboration with the Comillas team and the openTEPES model (DIAMOND task 4.7). Both teams agreed that the representation of the electricity system will be 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), representing a "reference" scenario for grid investment and electricity demand in Europe (ENTSOE, 2024).

While this development is currently undergoing (by November 2025), Figure 4 reflects the workflow of openTEPES for providing inputs to GCAM-Europe to support development. Figure 5 provides some preliminary estimates of load clusters and technology representation by identified cluster from the abovementioned workflow. The purpose of the integration of the electricity system in GCAM-Europe is to meaningfully represent European electricity trade dynamics within an integrated assessment model with relatively low detail in terms of timesteps (5 years) and geographical representation (country level). The different demand clusters, despite relevant differences for each of the grid regions in Figure 3, are identified equally throughout all regions to correctly represent potential trade possibilities between grid regions. In GCAM-Europe, electricity in every grid region and cluster will have a separate market, where the price likely is lowest in off-peak demand, and highest in peak demand. Cost differences between clusters may encourage electricity storage investments, while cost differences between grid regions may encourage electricity trade.

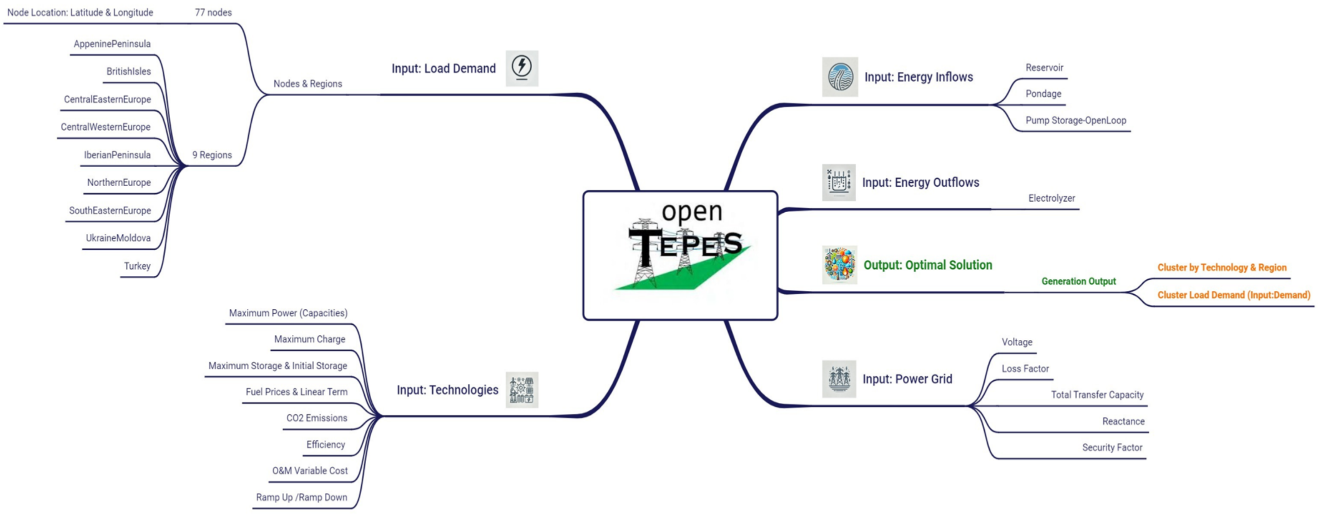

Figure 4. Work scheme for openTEPES to provide input parameters consistent with GCAM-Europe structure.

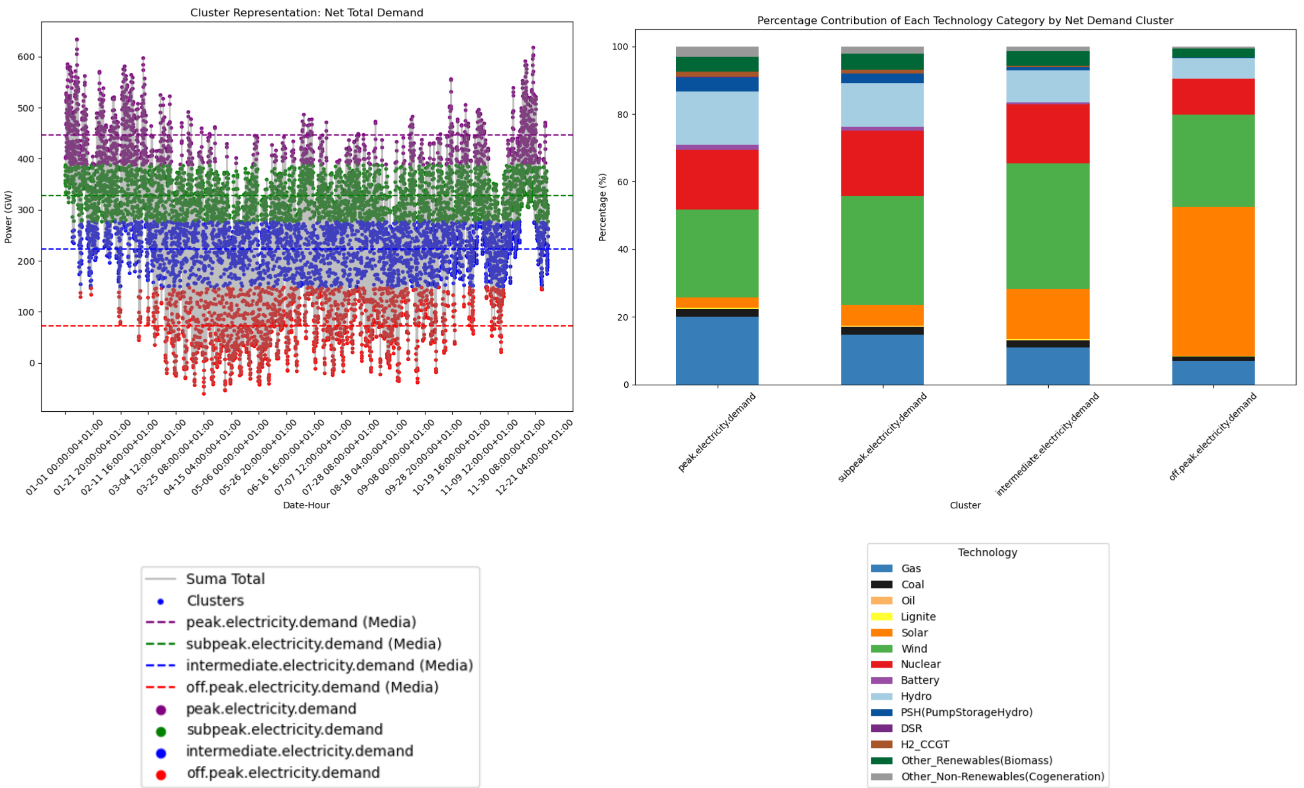

Figure 5. Net Demand (subtracting intermittent electricity supply) cluster representation (left) and technology contribution by cluster (right) based on openTEPES outputs

3.1.4.3 Adapted commodity trade structure for European Economic Area (EEA)

To reflect the internal free-trade market in the European Union, Norway and Iceland (by November 2024), an adapted trade structure was designed for GCAM-Europe. By default, commodity trade in GCAM (covering energy, food and some industrial commodities like steel and ammonia) is reflected through Armington coefficients (Armington, 1969), defining the level of substitution at the international market, and also within each region between domestically produced and imported commodities. In the update for GCAM-Europe, trade of EEA countries is represented as one block with the rest of GCAM regions (including the newly isolated one in GCAM-Europe, e.g. United Kingdom) in the international market (see Figure 6). Within the EEA countries, there is another level of trade, again modelled through Armington coefficients, representing within-EEA trade. Costs of international trade (between regions inside and outside EEA) is identical as for non-EEA regions for each commodity, but within-EEA trade has lower cost in this updated representation, aiming to reflect lower trade barriers within the EEA. Apart from this improved trade representation, this function allows to represent common trade policies between the EU or EEA (e.g. CBAM) more easily in future modelling exercises.

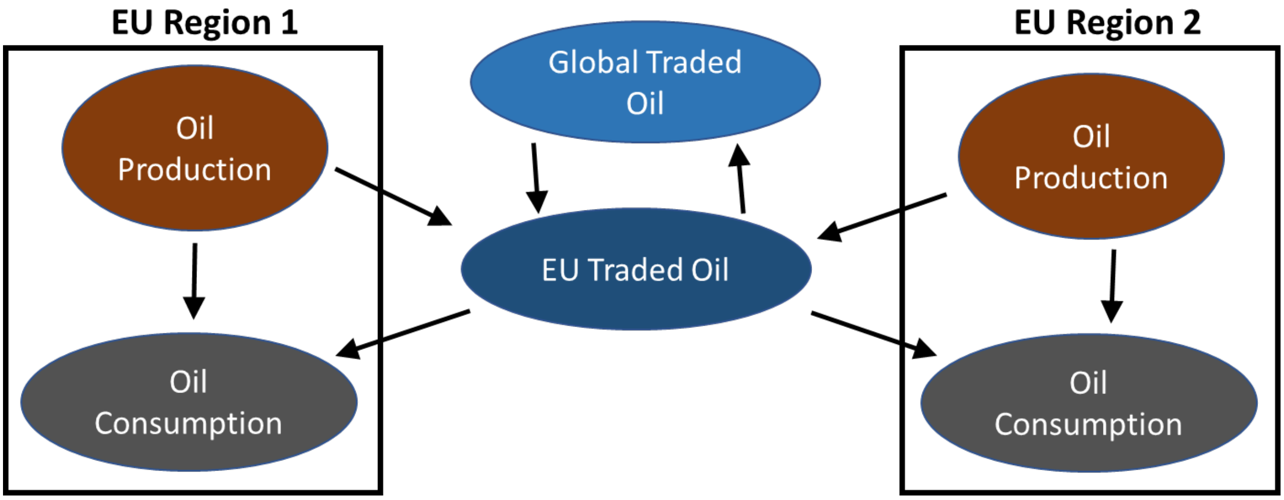

Figure 6. Updated trade structure in GCAM-Europe

3.1.5 Subsequent development steps

3.1.5.1 Household groups

Exploring the use of multiple consumers, rather than a single representative average consumer, has become an active area of research within the IAM community, with various models adopting this approach in recent years. A recent version of core GCAM (GCAM-v7.1) includes consumer heterogeneity in the residential energy sector in the form of income deciles. An example of the produced results when multiple consumers are incorporated (in the global version) can be found in the following figure:

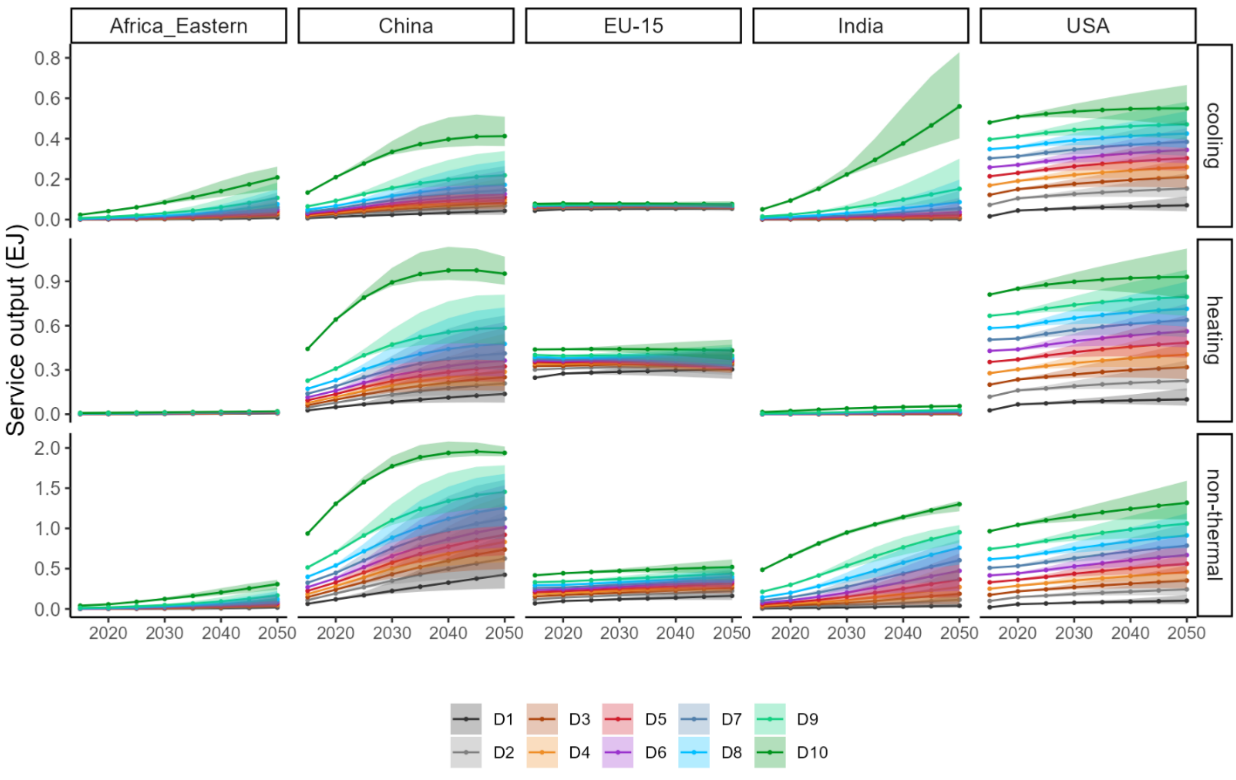

Figure 7. Residential energy service output per period, region, service, and decile for the GCAM baseline scenario (EJ). (Sampedro et al, 2022).

Due to the lack of available harmonised data at a global level, in the core GCAM model the allocation of different residential energy services across subregional consumer groups is made using exogenous assumptions based on the form of the demand function within each of the sectors. In GCAM-Europe, we will improve this representation by using empirical data from the country-level Household Budget Surveys (HBS), which are available for all member states. In those European (non-EU) countries, where these data are not accessible, we will follow the process developed for core GCAM, based on the used functional forms.

Beyond the residential sector, the implementation of consumer heterogeneity in further end-use sectors, namely food, transportation and municipal water, is expected to be integrated into the core in the near-term[4]. GCAM-Europe will coordinate with the GCAM development team to implement multiple consumers in these end-use sectors following a similar structure that will be consistent will the core model. However, unlike the core model, GCAM-Europe will have a better representation of consumer heterogeneity by incorporating empirical country level household data (HBS).

3.1.5.2 Further WP4 links

The links with additional sectoral and bottom-up models are in the preliminary phase, considering that the main focus has been the development of a beta version of GCAM-Europe. However, some initial conversations have been carried out with different modelling teams, in order to discuss potential integration activities:

[4] Some initial implementation of consumer heterogeneity in multiple endues demand sectors has been developed during the GRAPHICS project: https://github.com/jonsampedro/gcam-core/tree/GCAM_GRAPHICS_v7

- Link between GCAM and ENGAGE (UCL): The planned expansion of the industrial sector in GCAM-Europe will include inputs and insights of the ENGAGE module to develop additional capacities, including for example the endogenizing the availability and use of secondary metals relative to primary metals.
- Adding household heterogeneity into GCAM (CESAR): The implementation of multiple consumers in GCAM-Europe, based on country-level HBS will be developed in coordination with the CESAR team. In addition, having the household structures for the different countries will allow to connect the model outcomes with "Medusa"[5], an R package aimed at estimating the distributional impacts of alternative policies. While this package has originally been developed for Spain, the expansion to different EU member states and its connection with GCAM-Europe will be developed between BC3 and CESAR.
- Labour and financial module (UM): GCAM will use inputs from UM to modify its default capital costs, (Weighted Average Cost of Capital, WACC), and other financial variables (e.g., discount rates), in order to have values which are differentiated by region and technology. Furthermore, the energy demand module developed at UM, focusing on differentiated household preferences with respect to large investments, is planned to be emulated in GCAM to reflect more realistic household investment behaviour.
- Behavioural change (UNIBAS): Use of findings from studies on consumer behaviour to improve the parameters included in the different end-use demand functions, which will be particularly relevant when multiple consumers are implemented. For example, the adjustment of the income and price elasticities, or preference ("shareweight") parameters for different countries and within-region consumer groups will be a direct and timely connection of the models.
- openTEPES electricity model (IIT): After developing the initial GCAM-Europe version based on electricity grid regions as outlined above, the results of this version will be compared with comparable results from openTEPES to identify structural differences that may be better represented in openTEPES due to simplified assumptions in GCAM-Europe. Subsequently, the electricity module in GCAM-Europe may be adapted where necessary, with the aim to emulate openTEPES as detailed as possible.

3.1.5.3 Further sectoral coverage expansions to be explored

Detailed, well-structured and updated data for European countries allows for potential sectoral expansions, of which the following ones have already been identified:

- Energy supply sectors:
  - Improved district heat representation (crucial in Scandinavian and former Soviet-Union countries)
  - Hydrogen trade between European regions including e.g. blending in natural gas grids
  - Explicit representation of biogas potential (potentially linked to agricultural sector)
- Industry energy demand:
  - More disaggregated industrial sectors to cover
  - Explicit representation of investments in efficiency improvements
- Building energy demand:

[5] https://github.com/bc3LC/medusa

    - More disaggregated energy services in residential and commercial buildings, i.e. through detail in JRC-IDEES (Rozsai et al, 2024)
    - Representation of renewable heat pumps (aerothermal, geothermal, hydrothermal, solar thermal; link with cooling)
    - Endogenous representation of building efficiency improvements
- Transport energy demand:
    - Separation of gasoline, diesel, LPG vehicles (improved representation of emission standards and air pollution)
    - Improved representation of transportation demand by country based on JRC-IDEES (Rozsai et al, 2024)
    - Separation of intra-EU and extra-EU international passenger transport

Whether and when these expansions will be included depends on modelling feasibility and time/capacity constraints.

3.1.6 GCAM-Europe references

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3.2 From TIMES-GEO to OMNIA

3.2.1 Overview

TIMES is a modelling platform for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating how energy system operations will evolve over a long-term, multiple-period time horizon (Loulou and Labriet, 2007). These energy system operations include the extraction of primary energy such as fossil fuels, the conversion of this primary energy into useful forms (such as electricity, hydrogen, solid heating fuels and liquid transport fuels), and the use of these fuels in a range of energy service applications (vehicular transport, building heating and cooling, and the powering of industrial manufacturing plants). In multi-region versions of the model, fuel trading between regions is also estimated. The TIMES framework is usually applied to the analysis of the entire energy sector but may also be applied to the detailed study of single sectors (e.g., the electricity and district heat sector). The framework can also be used to simulate the mitigation of non-CO_2 greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O). The TIMES-GEO Model Integrated Assessment Model, TIAM, is the multi-region, global version of TIMES, which combines an energy system representation of different regions with options to mitigate non-CO_2 greenhouse gases as well as non-energy CO_2 mitigation options. It can be used to explore a variety of questions on how to mitigate climate change through energy system transformations, as well as reductions in non-energy CO_2 emissions and non-CO_2 emissions.

The Open-source MuNdus Integrated Assessment model (OMNIA) is a customised, open-access global IAM based on the TIMES framework. It provides a technology-rich basis for estimating how energy system investments and operations evolve over a long-term, multiple-period time horizon. It is a partial equilibrium, 'perfect foresight', welfare cost optimisation model. The OMNIA model integrates and expands the TIMES-GEO. Regional representation is configured on 29 regions (see Table 10 and Figure 8). Key technologies to decarbonise hard-to-abate sectors are comprehensively represented and industry representation is enhanced based on ongoing research. The upstream sector, including fossil fuel extraction, is able to fully explore the implications of the transition. OMNIA also incorporates a spatially explicit representation of key energy carrier trades, including bioenergy, hydrogen, as well as commodities including captured CO_2. Temporal representation of energy demand and supply is increased to properly model the increased penetration of weather-dependent renewables, storage, and new demand technologies, expanding the time slices to 20. OMNIA also integrates a climate module to estimate global average temperature changes of scenarios and includes abatement supply-cost curves for all major non-CO2 options, based on up-to-date assessments. In addition, with a newly calibrated and improved water module, the model is able to evaluate the interdependence between energy production and water consumption.

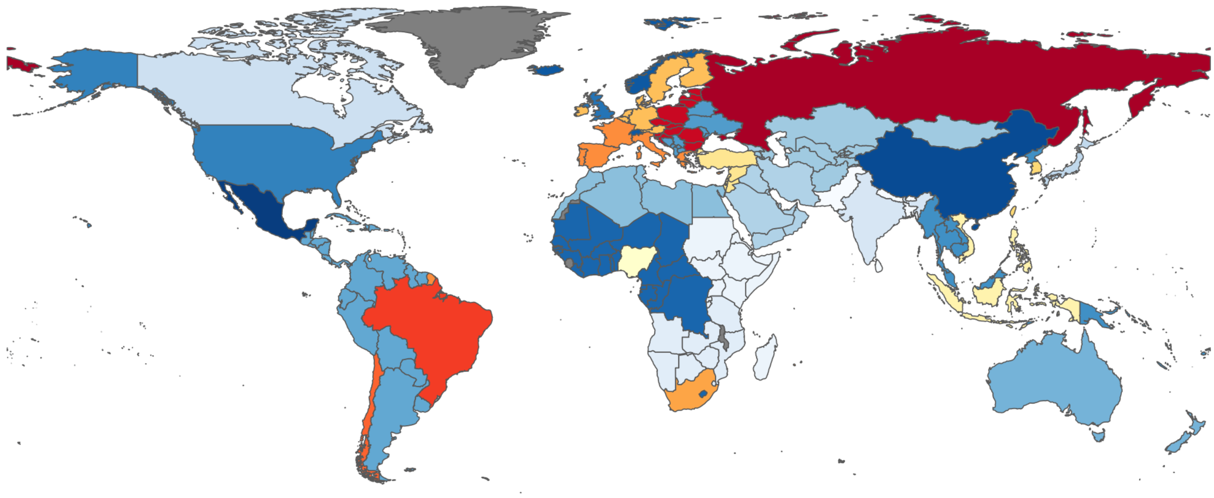

Figure 8. Regional disaggregation in OMNIA.

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.

Table 10. List of model regions in OMNIA

Model regions	*Description*	*List of countries*
AFE	*Eastern Africa*	*Ethiopia, Kenya, Sudan, Mauritius, Eritrea, South Sudan, Burundi, Comoros, Djibouti, Madagascar, Réunion, Rwanda, Somalia, Uganda*
AFN	*Northern Africa*	*Egypt, Algeria, Morocco, Libya, Tunisia*
AFW	*Western Africa*	*Democratic Republic of the Congo, Cote d Ivoire, Ghana, Cameroon, Gabon, Benin, Senegal, Togo, Niger, The Republic of Congo, Burkina Faso, Cape Verde, Central African Republic, Chad, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Malawi, Mali, Mauritania, Sao Tome and Principe, Seychelles, Sierra Leone, Swaziland*
AFZ	*Southern Africa*	*Tanzania, Angola, Mozambique, Zimbabwe, Zambia, Botswana, Namibia, South Africa*
NIG	*Nigeria*	*Nigeria*
RUS	*Russian Federation*	*Russian Federation*
ASC	*Central Asia*	*Kazakhstan, Uzbekistan, Turkmenistan, Azerbaijan, Mongolia, Georgia, Kyrgyzstan, Armenia, Tajikistan, Afghanistan*
ASE	*Southeast Asia*	*Thailand, Malaysia, Singapore, Myanmar, Cambodia, Brunei Darussalam, Lao People's Democratic Republic, Democratic People's Republic of Korea, Cook Islands, East Timor, Fiji, French Polynesia, Kiribati, Macau, Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu*
CHN	*China Mainland*	*People's Republic of China, Hong Kong*
IDN	*Indonesia, Philippines, Vietnam*	*Indonesia, Philippines, Vietnam*
IND	*India*	*India*

ASO	*South Asia*	*Bangladesh, Nepal, Sri Lanka, Pakistan, Bhutan*
JPN	*Japan*	*Japan*
SKT	*South Korea, Taiwan*	*Taiwan, South Korea*
ANZ	*Australia and New Zealand*	*Australia, New Zealand*
USA	*United States*	*United States*
CAN	*Canada*	*Canada*
LAM	*Latin America*	*Argentina, Venezuela, Colombia, Peru, Trinidad and Tobago, Ecuador, Guatemala, Cuba, Bolivia, Dominican Republic, Honduras, Paraguay, Uruguay, Costa Rica, El Salvador, Haiti, Panama, Nicaragua, Jamaica, Curacao, Suriname, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Cooperative Republic of Guyana, Martinique, Montserrat, Puerto Rico, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Sint Maarten, the Turks and Caicos Islands*
BRA	*Brazil*	*Brazil*
MEX	*Mexico*	*Mexico*
CHL	*Chile*	*Chile*
ENE	*Non-EU Eastern Europe*	*Ukraine, Belarus, Serbia, Bosnia and Herzegovina, Moldova, Republic of North Macedonia, Kosovo, Albania, Montenegro*
ENW	*Non-EU Western Europe*	*Norway, Switzerland, Iceland, United Kingdom, Gibraltar*
EUE	*Eastern Europe Union*	*Poland, Czech Republic, Romania, Hungary, Bulgaria, Slovak Republic, Croatia, Lithuania, Slovenia, Estonia, Latvia*
EUW	*Western Europe Union*	*Germany, Netherlands, Belgium, Sweden, Austria, Finland, Denmark, Ireland, Luxembourg*
EUM	*Mediterranean-Europe Union*	*France, Italy, Spain, Greece, Portugal, Cyprus, Malta*
MEA	*Middle East (Gulf States)*	*Iran, Saudi Arabia, United Arab Emirates, Iraq, Qatar, Kuwait, Oman, Bahrain, Yemen*
MDA	*Mediterranean Asia*	*Turkey, Israel, Syrian Arab Republic, Jordan, Lebanon*

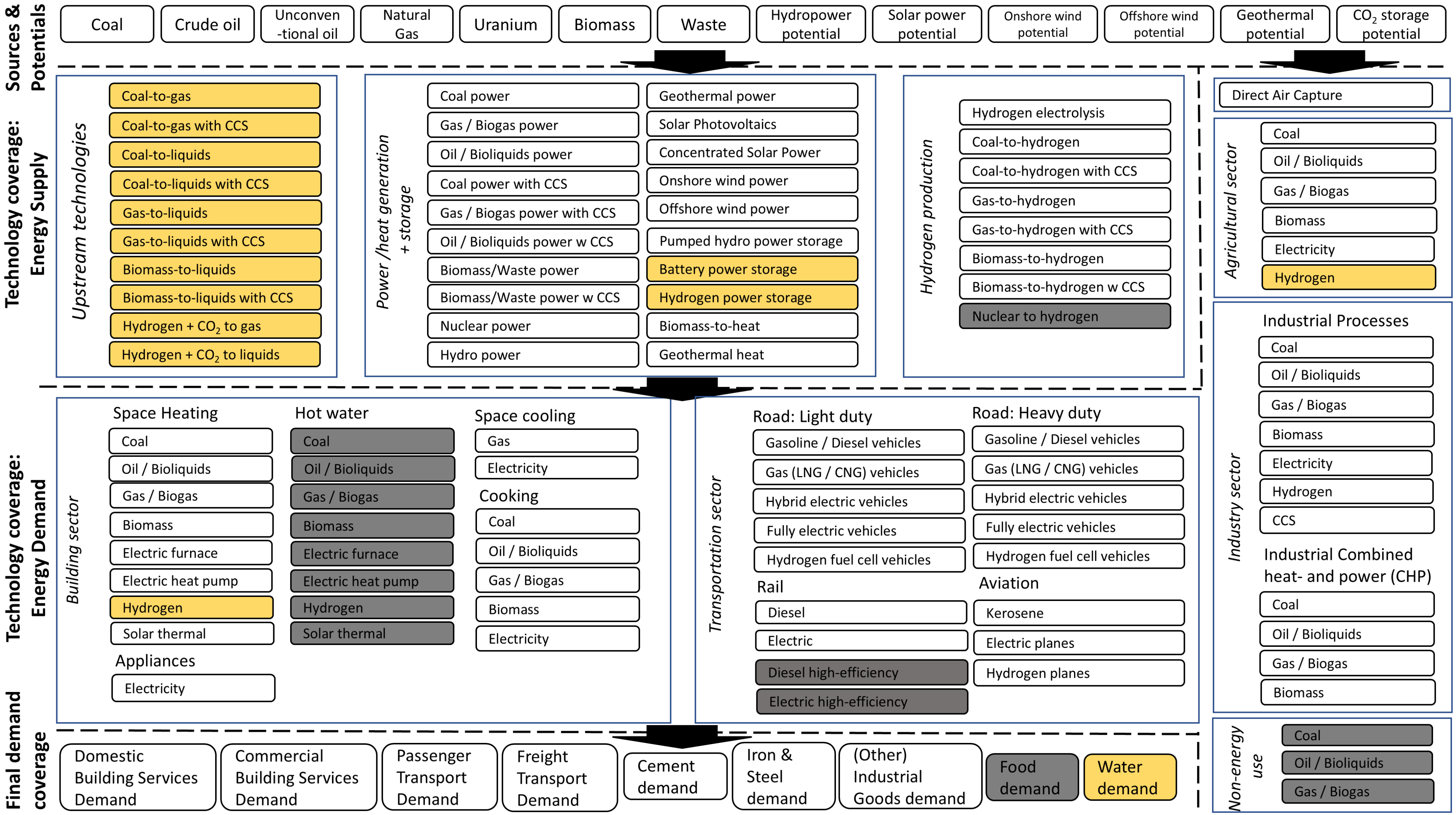

Figure 9. Summary of the resource, technology, and end-use demand representation in OMNIA.

White boxes indicate features already part of the original model. Grey boxes indicate features not part of the core nor the updated model. Dark yellow boxes indicate the features that will be explicitly developed for OMNIA in the DIAMOND project, and which are not in the core version of the model.

3.2.2 Development timeline

By the end of the year (December 2024), work on OMNIA focuses on delivering:

- The final design for the demand projection module (working and usable version of the module, including reporting)
- the new model for industrial sub-sectors
- improved power and residential sectors
- the calibrated transport sector for OMNIA regions based on 2019 UN energy balance and the preliminary report
- the new updated upstream sector including the new supply chain for fossil fuels, and the new module for hydrogen supply chain
- the key inputs file for transport and the bioenergy supply chain

A first version of the new improved sectors is planned to be ready by December 2024. During the first quarter of 2025 the team will start to integrate and test all the developed main sectors (upstream, power, industry and residential, calibrated version of transport) and will complete the development of the remaining sectors (transport) and the additional modules (climate, water). Testing of the modules is scheduled to be continued until July 2025. The first official release of the model will be released as part of MS8) and feature all new and updated sectors and modules. In the second half of 2025, the team will carry out full model testing, including scenario analysis and will integrate all the necessary revisions and improvements to sectors and modules.
The OMNIA timeline is presented in Figure 10.

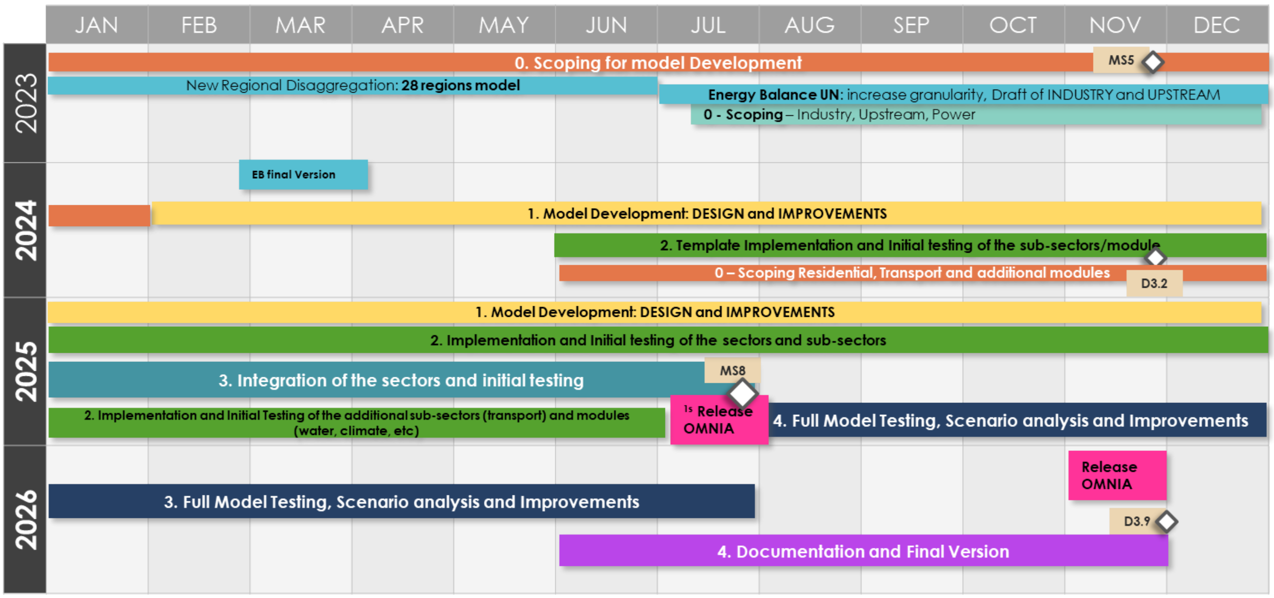

Figure 10. OMNIA timeline: development phases and steps

3.2.3 Meetings (internal modelling team and external)

Several meetings were held in the two first years of the project for Omnia development including recurring meetings within the Omnia team, bilateral/multilateral meetings for the harmonisation process.

Table 11. OMNIA meetings key discussion points

Type of meeting, description and dates		**Date**
Physical (Turin)	**Kick off Meeting** First Design Meeting. Detailed planning of the improvements at sectoral level	3rd March 2023
Online	Decision about priorities of model development and update of the GANTT	29th March 2023
Physical (Turin)	**NEMESIS-World, OMNIA** Bilateral workshop in Torino: Discussions on how to share information between models and ensure possible soft linkage (E4SMA & SEURECO)	24th of August 2023
Hybrid (Maastricht)	**All Models** Maastricht Workshop: How to improve finance, labour and distributional modelling	21st and 22nd of September 2023
Online	**Soft-Link** Discussion about upstream design and ENGAGE soft-link with industry sector	25th September 2023
Online	**OMNIA** Discussion about the energy balance update, and soft links with openTEPES (COMILLAS) and behavioural change (UNIBAS)	23rd October 2023
Online	**OMNIA** Discussion about the implementation of the new design of industry sector, proposal for the first release of OMNIA, planning of workshops and soft-linking activities	5th February 2024
Online	**Soft Link.** Preliminary meeting for Climate and Water module integration (E4SMA and CICERO)	5th March 2024
Online	**Workshop** on demand projections organised by UCL and with the participation of CICERO for WP5 integration	28th March 2024
Online	**Workshop** Discussion on data source and preliminary design options for the OMNIA and ENGAGE soft link (OMNIA and UCL)	9th April 2024
Online	Regional disaggregation proposals, Internal model sharing and workflow	23rd April 2024
Online	Discussion on the possible links and data needed for the implementation of behavioural model (E4SMA, CICERO and UNIBAS)	23rd April 2024
Online	Discussion on required disaggregation for the bioenergy sector in Omnia according to the MAgPIE granularity (E4SMA, UCL and CICERO)	14th May 2024
Online	Update of the activities and implementation of improvements for the power sector, management of activities for the May GA in Lausanne	15th May 2024
Online	Regional disaggregation finetuning, feedback on industry and upstream current model files to start the scoping phase	23rd May 2024
Physical (Lausanne)	Discussion on the parameters exchanged between model and information needed for the surveys.	24th May 2024
Online	Discussion about the energy balance for industry sector UCL-E4SMA	8th July 2024
Online	Discussion about the preliminary design of the residential and transport sector Imperial College-E4SMA	9th July 2024
Online	Presentation of the advancements for the upstream, industry, residential and power sector.	12th September 2024

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the European Union

Online	Discussion about the definitive structure of the residential sector between Imperial College and E4SMA	19th September 2024
Online	**Bilateral Meeting Omnia-Nemesis World** Discussion about data harmonisation between the two models	27th September 2024

3.2.4 Completed development steps

The following sections cover key advancements and methodologies applied across various OMNIA model components, including updates to energy balances, sector-specific developments, and model linkages. Each subsection begins with the latest progress in updating energy data, restructuring supply chains, and advancing sectoral representations. This includes model enhancements for residential, power, industry, and water sectors, alongside detailed integration methods between OMNIA and other models. Data collection processes, methodology improvements, and specific structural adjustments are introduced for each module, providing a comprehensive overview of the ongoing work and the data sources underpinning these advancements.

3.2.4.1 Energy balance update

***Progress**: The energy balance was successfully delivered at the beginning of the second year of the project and applied for the development of all sectors:*

The base year has been updated to 2019. The sources that have been used are:

- UNSD Energy balances (https://data.un.org/SdmxBrowser/start)
- UNSD Energy statistics (https://data.un.org/SdmxBrowser/start)

The UNSD Energy statistics have been used to disaggregate the Energy Balances, which in the UNSD database are represented only with aggregated commodities:

1. Primary coal and peat
2. Coal and peat products
3. Primary Oil
4. Oil products
5. Biofuels and waste
6. Nuclear
7. Electricity
8. Heat
9. Renewables

The procedure to disaggregate the energy balance is shown in the following Figure.

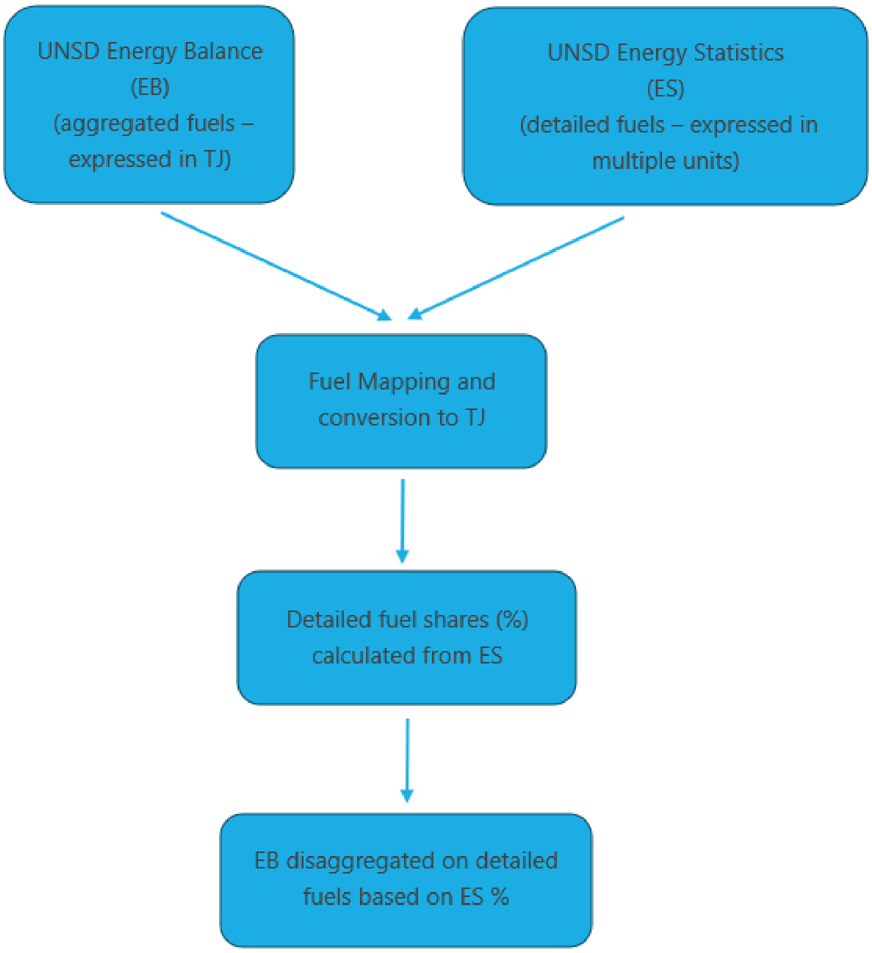

Figure 11. Disaggregation procedure of UNSD Energy Balance

3.2.4.2 New modelling approach for upstream sector

Progress: *Alternative representation of coal, natural gas, oil and biofuels supply chains scoping phase completed during the first year of the project. Data collection and final design of the fossil fuel supply chain have been finalised in August 2024. Data collection and final design for import/export, hydrogen, biofuels and synthetic fuel supply chains are expected to be finalised in December 2024.*

The Upstream sector regroups all processes related to primary fuel production and transformation. It comprises several groups:

- fossil fuel extraction and transformation,
- imports and exports of fuels and products,
- biofuel production, hydrogen production and synthetic fuel production.

Within fossil fuel extraction and transformation group, the supply chains in OMNIA are structured as follows:

a) Cumulative reserves and resources
b) Extraction processes
c) Processing processes (there can be one or several)
d) Delivery processes to consumption end points

The supply chains for the other groups are modelled with a simpler approach and includes two steps:

1. Production process

2. Delivery process

The added fossil fuels included:

- Coal: two types of coal are modelled lignite and other coal types.
- Crude: we modelled crude oils from conventional extraction process and crude oil from enhanced oil recovery.
- Natural gas: addition of natural gas liquids
- Uranium

- Biomass feedstock: five feedstocks including forest residues, crops grown for energy, agricultural residues, oil crops (1st generation crops biodiesel) and cereals (1st generation crops ethanol).

An initial stage in the extraction chain that correspond to the reserve of fossil fuel has been added. The team is integrating a supply curve for each commodity, with at least three levels, to depict the cumulative reserve of the commodity with increasing cost. For each reserve commodity, an extraction process that consumes energy and produces the corresponding commodity will be included, as well as any additional commodity and emissions. For specific commodities additional processing steps have been already integrated, such as upgrading processes for certain crude commodities (heavy crude and oil sands), and a liquefaction process for natural gas.

By December 2024 the refining process will be improved to include additional decarbonisation options. Firstly, hydrogen production for the refining process will be handled separately from the refining process itself, allowing for the decarboniation of hydrogen production. Secondly, if computational complexity permits, energy service processes such as boilers and HVAC systems to manage energy consumption will be leveraged and the replacement of conventional ones by low emission alternatives using electricity or biomass enabled.

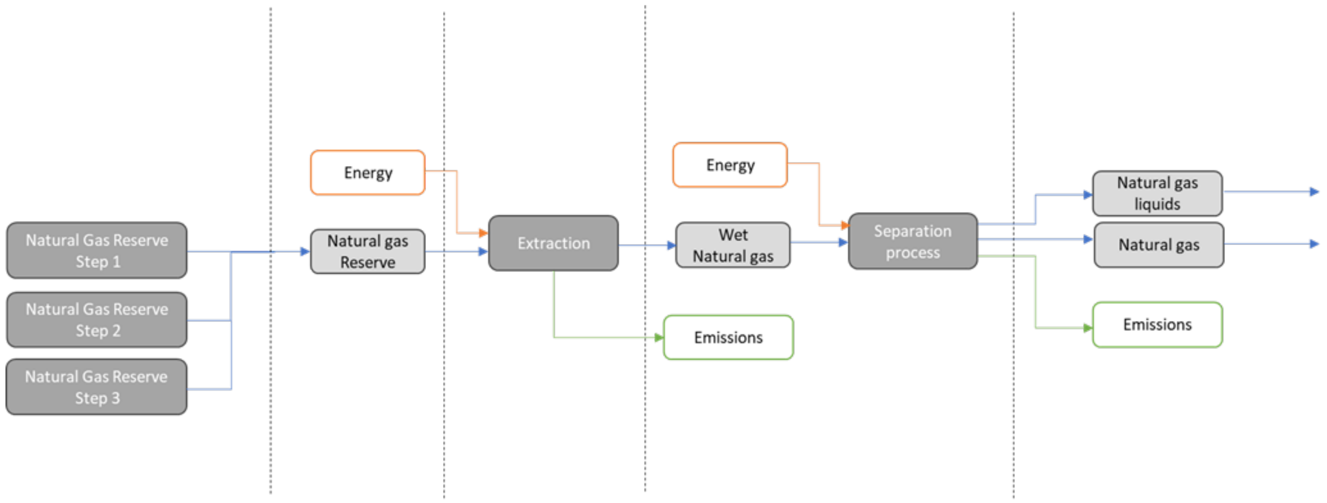

Figure 12. Natural gas extraction chain in OMNIA

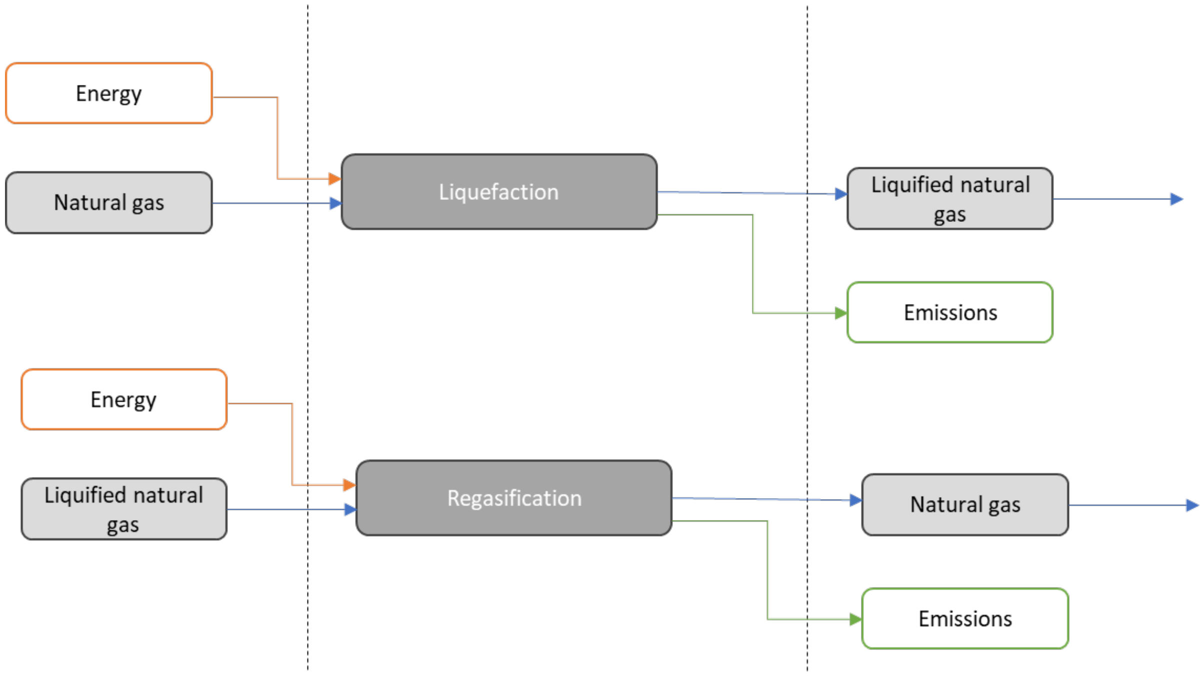

Figure 13. Liquefaction and regasification process for Natural gas in OMNIA

For each modelled chain, data required, and possible sources are indicated and will be included in the model documentation. Table 12 shows the example of data used for the fossil fuel extraction and processing for the base year, Table 13 provides the data needed for future years.

Table 12. Fossil fuel extraction and processing data needs – For calibration years

Description	Source
Energy balance	OMNIA Energy balance
Fossil fuel reserves and historic production data by country	Statistical Review of World Energy 2023 and 2024 https://www.energyinst.org/statistical-review
Uranium production and demand	Uranium 2020 Ressource https://www.oecd-nea.org/jcms/pl_52718/uranium-2020-resources-production-and-demand?details=true
Liquefaction capacity, Regasification terminal capacity, trade between regions	2020 World LNG Report. https://www.igu.org/resources/2020-world-lng-report/
Hydrogen consumption in refineries by types and world regions	Global Hydrogen Review 2023. https://www.iea.org/reports/global-hydrogen-review-2023
Fossil fuel trade movements	Statistical Review of World Energy 2020 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-

	economics/statistical-review/bp-stats-review-2020-full-report.pdf

Table 13. Fossil fuel extraction and processing data needs – For future years

Description	Source
Extraction, production costs for Crude oil and natural gas	Aguilera, R. F. (2014) https://www.sciencedirect.com/science/article/pii/S0301421513007763 Barrel Breakdown https://graphics.wsj.com/oil-barrel-breakdown/
Extraction, production cost for coal	Coal 2020 https://www.iea.org/reports/coal-2020/prices-and-costs
Coke ovens techno-economic parameters	Qin, S., & Chang, S. (2017) https://www.sciencedirect.com/science/article/pii/S0360544217316250
Natural gas processing plants techno-economic parameters	Khwanpruk, S., Sriudom, W., & U-tapao, C. (2015) https://www.researchgate.net/publication/380001788_Identification_Optimal_Strategies_for_Natural_Gas_Pipeline_Network_Management_in_Thailand
Liquefaction and regasification of natural gas techno-economic parameters	(Zhang, Meerman, Benders, & Faaij, 2020) https://www.sciencedirect.com/science/article/pii/S1359431119358399 (Pospíšil, et al., 2019) https://www.sciencedirect.com/science/article/pii/S1364032118306828 (Agarwal, et al., 2020) https://www.sciencedirect.com/science/article/pii/S1875510020301451
Refineries techno-economic parameters	(Favennec, 2022) https://link.springer.com/chapter/10.1007/978-3-030-86884-0_3
Industrial boilers techno-economic parameters	(Panos & Kannan, 2016) https://www.sciencedirect.com/science/article/pii/S0360

	544216308817?via%3Dihub
Enhanced oil recovery techno-economic parameters	(Abuov, Serik, & Lee, 2022) https://pubs.acs.org/doi/10.1021/acs.est.1c06834 (Kwak & Kim, 2017) https://www.sciencedirect.com/science/article/pii/S1750583617300099
Oil and natural gas liquids pipelines techno-economic parameters	Global Oil Infrastructure Tracker - Oil/NGL Pipelines https://globalenergymonitor.org/projects/global-oil-infrastructure-tracker/
Natural gas pipelines techno-economic parameters	Global Gas Infrastructure Tracker https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

3.2.4.3 New modelling approach for the Residential Sector

Here, we present the adaptations and improvements made to move from the residential sector's representation of the TIMES-GEO model to the OMNIA model. The TIMES-GEO model input excel spreadsheet was adopted for OMNIA's input requirements. This report presents the improvements and adaptations made and explains how these actions will be improving the model's functionality and use.

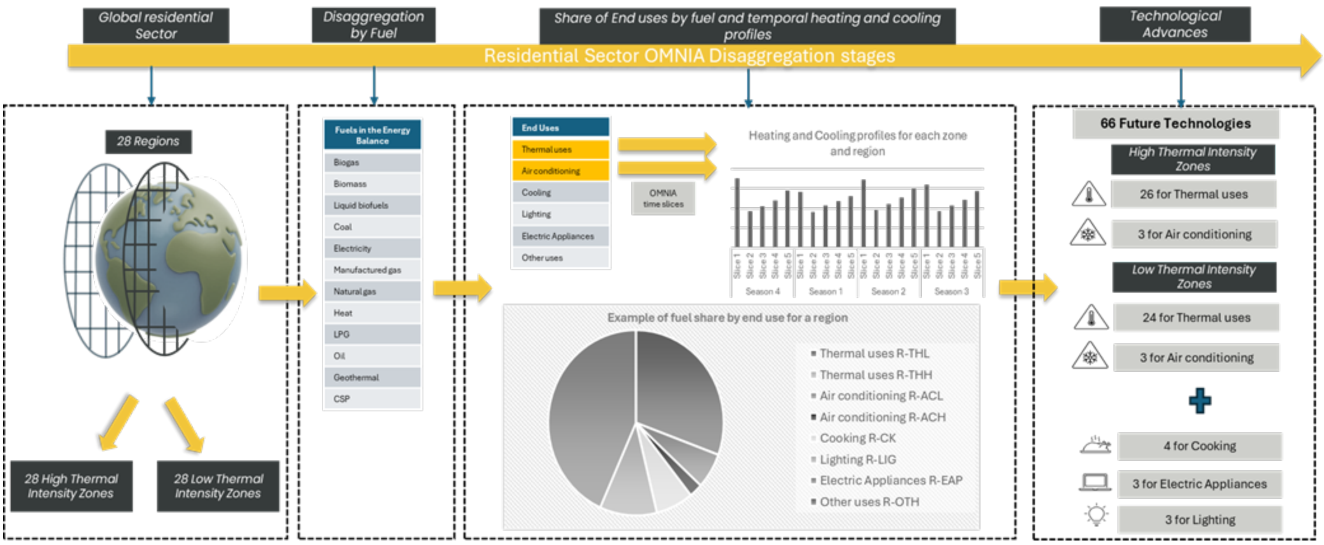

Figure 14. OMNIA Model Residential Sector Disaggregation: A detailed framework capturing global energy demand by breaking down fuel types, end uses, heating and cooling profiles, and future technological needs across regions and intensity zones, enabling precise modelling of residential energy consumption patterns and efficiency opportunities.

Specifically, Figure 14 outlines the disaggregation and modelling process for the OMNIA model's residential sector, illustrating the approach to analysing fuel use, end uses, and future technology needs across different global regions. The process starts with the global residential sector divided into 28 world regions. Each region is further divided into high and low thermal intensity zones, resulting in 28 high and 28 low thermal zones. The model considers the share between various fuel types within the energy balance for each region and zone. These fuel types include biogas, biomass, liquid biofuels, coal, electricity, manufactured gas, natural gas, heat, LPG, oil, geothermal, and concentrated solar power (CSP).

The 6 end uses were adjusted according to OMNIA's time slices, accounting for seasonal and temporal variations in heating and cooling needs across zones and region. Each region and zone have distinct heating and cooling profiles, which vary across seasons and affect fuel consumption for end uses. These profiles consider demand changes within each season. In Figure 1, an example pie chart illustrates how fuel is allocated to different end uses for a single region. End uses are further divided to specify usage types, such as:

- Thermal uses for high (R-THH) and low (R-THL) thermal intensity zones
- Air conditioning for high (R-ACH) and low (R-ACL) thermal intensity zones
- Cooking (R-CK), lighting (R-LIG), electric appliances (R-EAP), and other uses (R-OTH)

The model considers 66 future technologies needed for the residential sector. These technologies are specified by use and intensity zone:

- For high thermal intensity zones: 26 technologies for thermal uses and 3 for air conditioning.
- For low thermal intensity zones: 24 technologies for thermal uses and 3 for air conditioning
- Additional technologies are dedicated to cooking, electric appliances, and lighting.

The two extra thermal technologies for the high Intensity Zones are because the model considers only for the high intensity zones the use of district heating.

3.2.4.4 New modelling approach for the Power Sector

New modeling approach for power sector

This section provides an overview of the key developments and updates made to the OMNIA power sector with respect to TIMES-GEO. As summarized in Table 14, the focus is on the improvement the decommissioning profiles, introducing new commodities and technologies, and enhancing the renewable energy models.

Table 14. Sources used for the improvement of the power sector in Omnia

Description	Source
New power plants decommissioning profiles	Global Energy Monitor (GEM) Global Energy Monitor
Introduction of manufactured gas commodity and related technologies	Technologies characterised using data from existing and analogous natural gas-based technologies
New storage technology: Pumped hydro	National Renewable Energy Laboratory (NREL) NREL ATB
New structure for Renewable Technologies: Solar and Wind	(Cheng-Ta Chu,Adam D. Hawkes, 2020) A geographic information system-based global variable renewable potential assessment using spatially resolved simulation - ScienceDirect

New Power Plant Decommissioning Profiles

Previously, the decommissioning profiles in the power sector module used a simplified approach, with a single average life value assigned to each plant family (e.g., coal, gas plants). The residual life of each plant type was calculated based on the technical life assumption, and a linear retirement profile was applied from the model's start year to the year when the plant was expected to be decommissioned.

To improve this approach, a new set of decommissioning profiles was developed. These profiles now utilise a more detailed, data-driven method, incorporating information from the **Global Energy Monitor (GEM)** database. This GEM-based database covers more than 90% of global power plant capacity and includes detailed commissioning year data for each plant (source: Global Energy Monitor).

By applying the technical life values from the previous model, we can now estimate the expected decommissioning year for each plant more accurately, resulting in a more realistic capacity retirement schedule. This improvement allows for the decommissioning of specific capacity percentages each year, based on actual plant lifespans rather than the generic average.

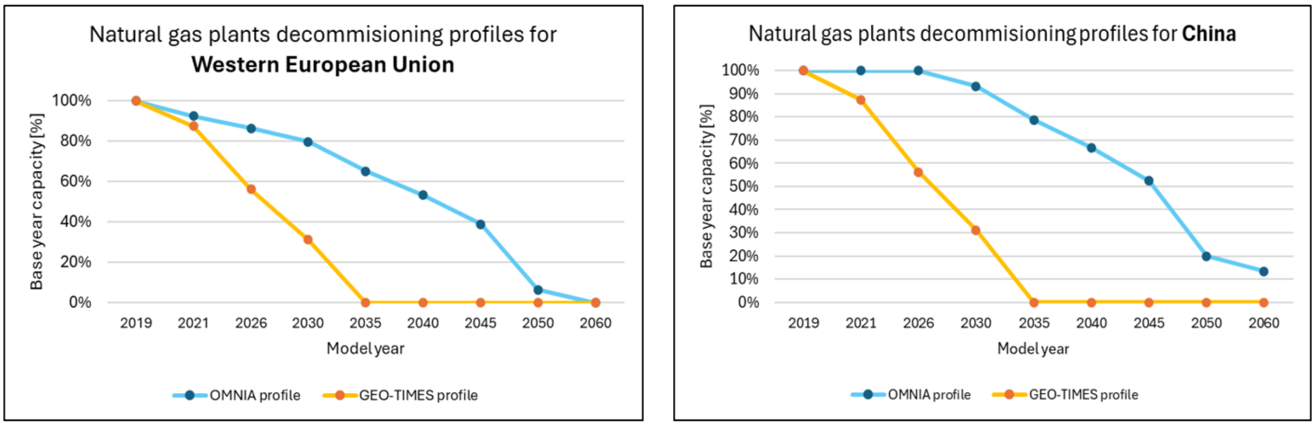

Figure 15. Examples of different decomissioning profiles between GEO-TIMES and OMNIA

Introduction of Manufactured Gas Commodity

A new commodity, **Manufactured Gas**, has been introduced into the power sector model. This commodity aggregates three types of gases that were previously classified under **Natural Gas**:

- **Blast Furnace Gas**
- **Coke Oven Gas**
- **Gasworks Gas**

This disaggregation allows for a more accurate assessment of emissions, as the individual properties of these gases differ significantly from natural gas. By considering these gases separately, the model can evaluate plant emissions with higher precision.

Additionally, a new set of technologies has been developed to handle the consumption of Manufactured Gas, adopting the same techno-economic characteristics as the natural gas technologies.

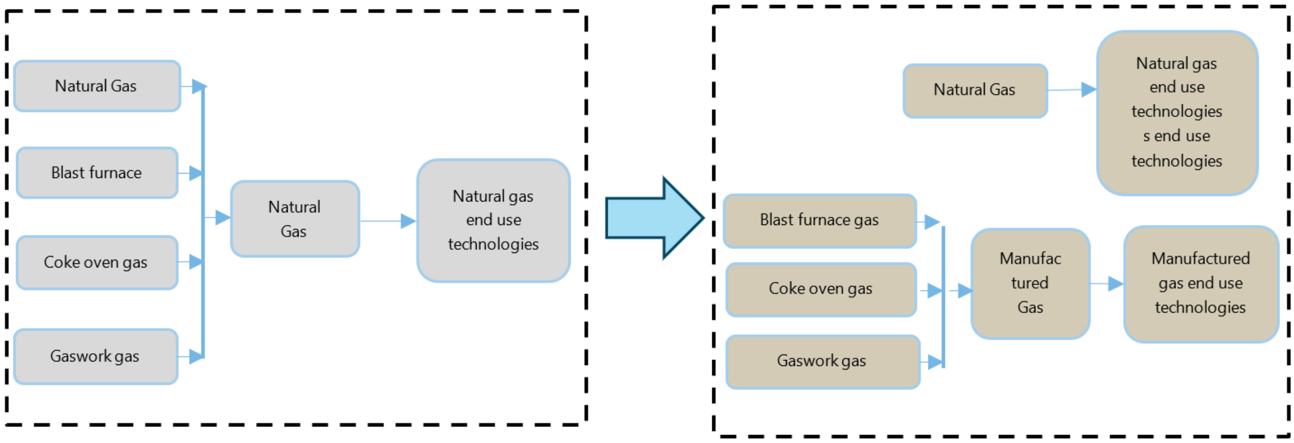

Figure 16. Evolution of the manufactured gas representation within the model

New Storage Technology: Pumped Hydro

Pumped Hydro has been added as a new storage technology in the model. This technology has been characterised using a detailed study by the **National Renewable Energy Laboratory (NREL)**.

Pumped Hydro offers significant potential for large-scale energy storage by using water to store energy in the form of potential energy, which can be converted back to electricity as needed. The techno-economic characterisation provided by NREL includes cost data, efficiency rates, and performance parameters, which have been integrated into the model.

New Structure for Renewable Technologies: Solar and Wind

Significant structural modifications have been made to the solar and wind technologies with respect to TIMES-GEO model. In the original model, these technologies maintained the same availability factor regardless of the installed capacity. With these adjustments, however, the total potential of each technology has been divided into four tiers for wind technologies and three tiers for solar technologies, with each tier assigned a different availability factor. This allows the model to prioritize the installation of tiers with the highest availability factors first, moving to lower tiers only as capacity expands.

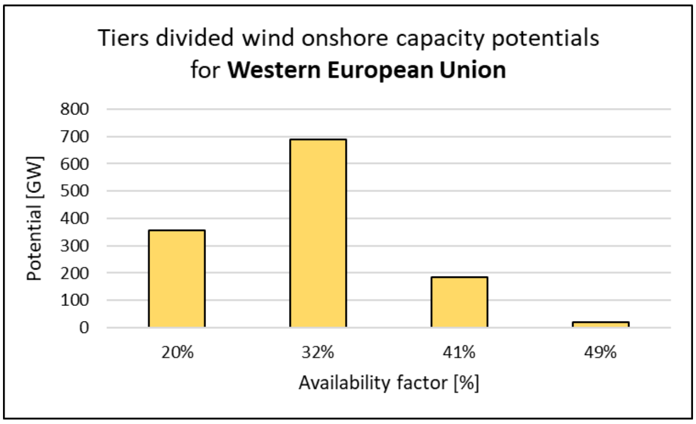

Figure 17. Example of availability factor subdivided by potential tier

3.2.4.5 New modelling approach for Industry

Recent progress: New improved more technology explicit representation for iron and steel, aluminium and cement design scoping completed. Data collection, energy balance disaggregation and first draft of design implementation *completed for aluminium in Oct 2024. For iron and steel and cement this is due to be completed in Dec 2024.*

As set out in MS5, our initial plans were to develop more technology rich representations of iron and steel, ammonia, aluminium and cement. Due to limitations with the UN energy balances that underpin the model we were unable to break out ammonia, i.e. because petrochemical feedstocks are not included in the balances. Nevertheless, this was not a sector that we intended to link with ENGAGE and so this does not impact our wider modelling plans.

Therefore, within OMNIA the following sectors will be represented in a detailed, technology explicit manner (including primary and secondary production):

- Iron and steel
- Aluminium
- Cement

The structure of the aluminium sector which has been implemented in its current iteration is shown in Figure 18. The Base Year (BY) data (see Table 15) is used to model primary and secondary production in the base year. Process emissions from anode degradation are represented. For future years, new primary production options include a replacement fossil route using natural gas, an electricity only route and a route using hydrogen to provide the necessary thermal energy for refining and anode production. For the electricity and hydrogen routes, options are available to capture process emissions using CCS or use inert anodes that do not product process CO2. Future secondary production has a new fossil option and two low carbon routes, electricity only and hydrogen for thermal energy.

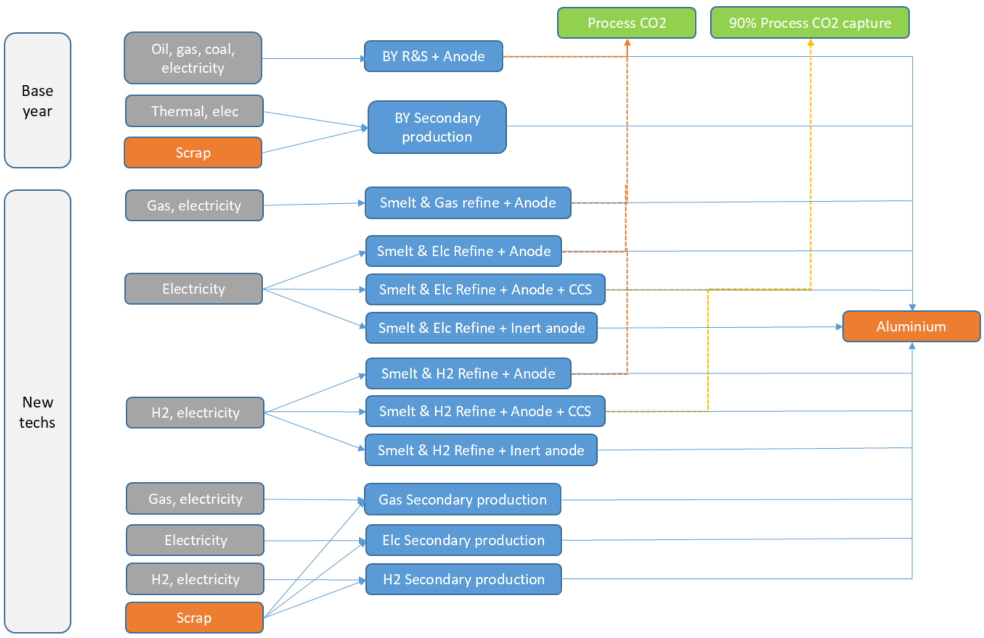

Figure 18. Aluminium sector production pathways in OMNIA. R&S = Refining and smelting, BY = Base year, H2 = Hydrogen.

The rest of the non-ferrous metals sector is then modelled using a generic energy service approach. The references for the data used in both aluminium and other non-ferrous metals will be made available in the model documentation. A sample of which are included in Table 15.

Table 15. Data used in OMNIA aluminium sector

Dataset	Description	Source

Energy balance	Non-ferrous sector energy balances	UN statistics
Production statistics	Primary aluminium production available from the US Geological Survey. Secondary aluminium production at regional level. Given the lower granularity of the secondary data, assumptions are made to disaggregate it.	Primary: https://www.usgs.gov/centers/national-minerals-information-center/aluminum-statistics-and-information Secondary: https://alucycle.international-aluminium.org/public-access/public-global-cycle/ https://www.statista.com/markets/407/topic/434/metals/#overview
Historic input energy mix	Energy mix into primary and secondary aluminium production in base year. For secondary production, the required energy mix (electricity and thermal) is taken from the cited paper and assumptions made about what provides the thermal energy in each region in the base year.	Primary production (2019): https://international-aluminium.org/resource/2019-life-cycle-inventory-lci-data-and-environmental-metrics/ Secondary production: https://www.mdpi.com/2673-4141/4/1/7
Technology parameterisation	Data aggregated as necessary, i.e. we aggregate refining and smelting.	https://missionpossiblepartnership.org/wp-content/uploads/2023/03/MPP-Aluminium-Technical-Appendix.pdf https://european-aluminium.eu/wp-content/uploads/2023/11/23-11-14-Net-Zero-by-2050-Science-based-Decarbonisation-Pathways-for-the-European-Aluminium-Industry_FULL-REPORT.pdf

For iron and steel, we are close to finalising the implementation of the new sector structure shown in Figure 19. The sector design is based on recently published work (see Pye et al, 2022) and models primary and secondary production, to enable modelling of the circular economy and the planned link with ENGAGE.

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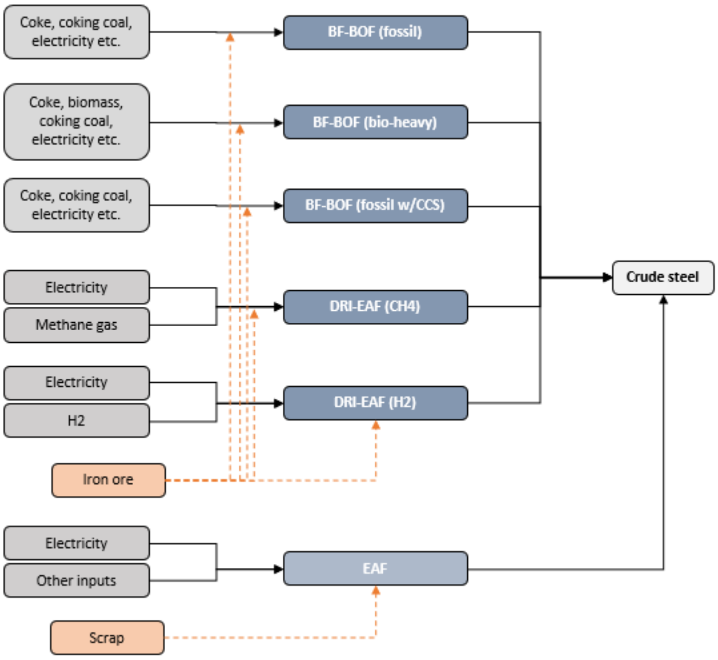

Figure 19. Improved representation of the steel sector in OMNIA

The design of the sector was discussed with industry IPCC AR6 industry author Chris Bataille. Whilst we are not proposing to explicitly represent all material flows in OMNIA, the costs associated with raw iron ore inputs (e.g. through sinter or pellets) into steel production pathways will be included.

3.2.4.6 New approach for demand projections

Recent progress: New general approach for energy services demand projections identified. Data collection and first draft implementation for residential and transport sectors to be completed by December 2024.

The guiding principles in defining the new approach are, first, to introduce the dependency from multiple drivers, second, to have the possibility of modelling demand trajectories that are decoupled from historical trends (and hence from what can be obtained through regression analyses), and third, to keep the projections at a country level, provided that enough data is available.

The expression for the annual variation – year *t* over year *t-1* – for a generic energy service demand (ESD) can be expressed as follows:

$$\frac{ESD_t}{ESD_{t-1}} = k_t \times \frac{X_{1,t}}{X_{1,t-1}} \times \frac{X_{2,t}}{X_{2,t-1}} \times \frac{X_{3,t}}{X_{3,t-1}} \times \cdots \times \frac{I_t}{I_{t-1}}$$

Where k_t is a decoupling factor to maintain the freedom to introduce trends not directly related to the drivers considered, $X_1, \ldots, X_N$ are the drivers of interest for the specific ESD and I is the intensity term, given by:

$$I_t = \frac{ESD_t}{X_{1,t} \times X_{2,t} \times X_{3,t} \times \cdots}$$

Drivers are grouped into primary drivers and intermediate levers. A description of the three elements composing the Equation is given in the following, while a visual representation summarising the approach is shown in Figure 20.

- **Primary drivers** represent the impacts of socio-economic development on end-use demand and include population, GDP, GDP per capita, etc. Primary drivers are defined per country – or region – and represent the basis for building demand projections for different scenarios, that can be based on SSP framing as well as other scenario frameworks.

- **Intermediate levers** are used to provide additional flexibility and adjust the demand to reflect the impacts of sector-specific, service-oriented drivers (e.g., heating or cooling degree days, floor space per capita) while maintaining consistency with primary drivers. Future projections of intermediate levers vary depending on factors such as geographic location, economic development, population density. For example, air conditioner ownership has already reached saturation in some developed countries, while it is still increasing in most developing countries and will reach varying degrees of saturation at different rates in the future. Most of the intermediate levers are cross-cutting indicators which are influenced by factors such as income level, climate change, building conditions, transport mode. Therefore, data of intermediate levers can be estimated based on historical development trends, calculated using socio-economic indicators with econometric approaches, or acquired from other sectoral-specific studies.
- **Intensity term** denotes the final energy required to deliver a unit of service, and the definition depends on the drivers considered for each specific ESD. In general, the service-specific intensity term is assumed to remain constant. However, in practical applications, scenario modellers can adjust this parameter according to their scenario narratives, considering factors such as digitalisation and technological advancements using the decoupling factor k_t.

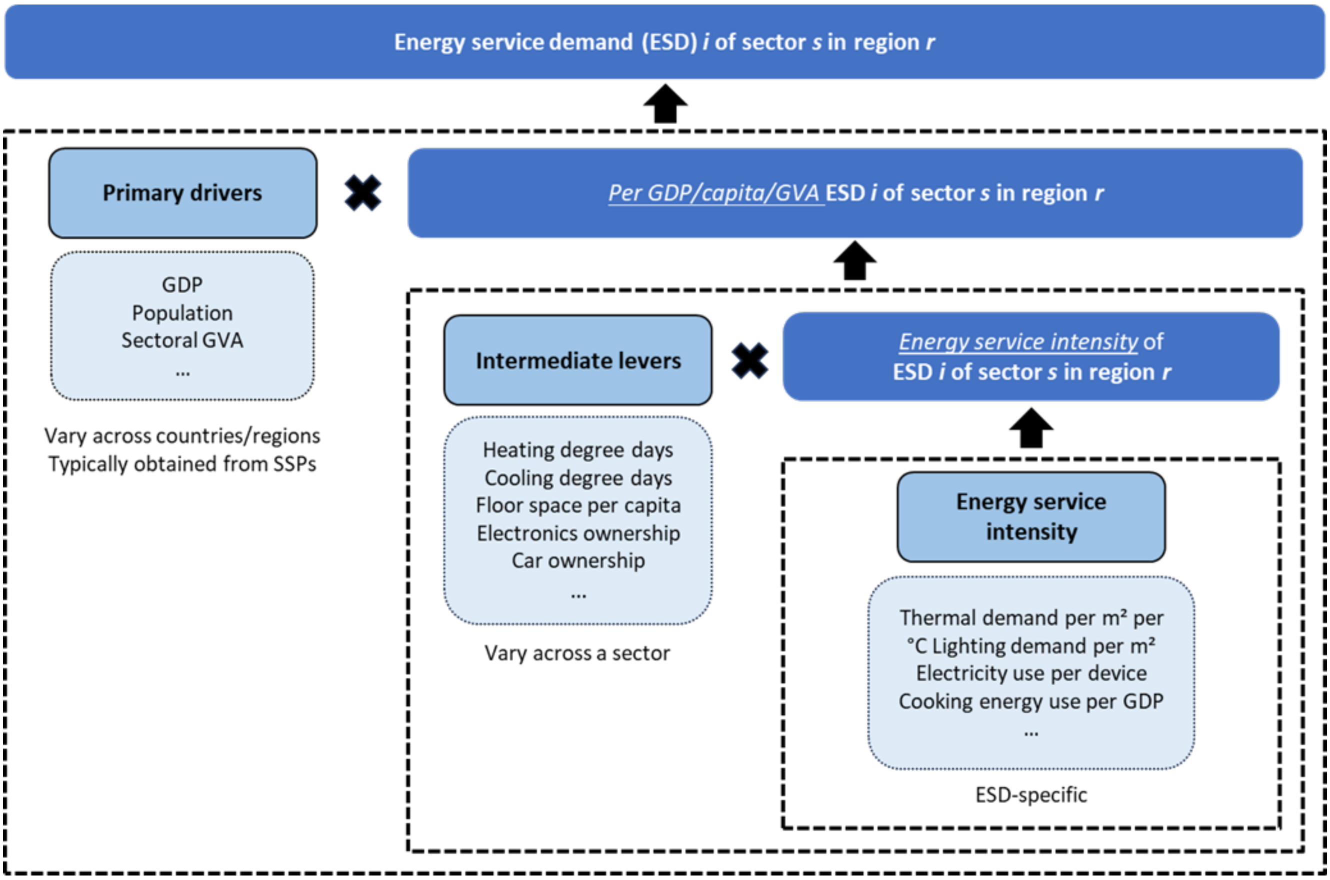

Figure 20. Visual representation of the approach to energy service demands projections.

3.2.4.7 Water module

***Progress**: First design proposal of the water module shared by M6. Final design expected to be finalised by M26. Expected to be part of the first version of OMNIA (MS8)*

A first meeting among OMNIA developers on the possible design of the water module has been organised. A first design proposal sees the representation of the following water contributions:

- Water supply

  1. Groundwater and surface water availability, through a link with scenarios from CICERO: The surface water availability in different basins is linked with different climate scenarios.

  2. Cross water interactions among OMNIA regions

- Water demand

  1. Agricultural water demand and water demand for livestock will be taken from the Magpie model.

  2. Water use in cooling of thermal power plants and resource extraction (endogenous representation): The water consumption for cooling in the power sector will be calculated using water use coefficients that vary across different technologies and regions. These coefficients are taken from Jin et al. (2019). The water consumption factors for fuel production are taken from Sprang et al (2014).

  3. Desalination at regional level: Desalination technologies are incorporated in the model to convert seawater into fresh water for coastal areas. The mapping of coastal basins to regions is harmonised with the regional mapping of the GCAM model.

3.2.4.8 Interlinkages with WP4 models

The linkages between OMNIA and WP4 models have been discussed in more detail. The information required by OMNIA and the characteristics of each model have been considered to determine modifications and adjustments required to implement the linkages.

Soft-link OMNIA-EnGAGE (T.4.1)

The link between OMNIA and ENGAGE has been discussed in more detail and the outputs from each model that will be used as inputs in the other have been identified. The common assumptions that need to be set to ensure the coherency between both models have also been defined, while the particular scenarios and policies that will be tested with this integrated modelling framework are still under discussion. The next figure presents an example of scenarios and policies that can be considered using such an integrated framework.

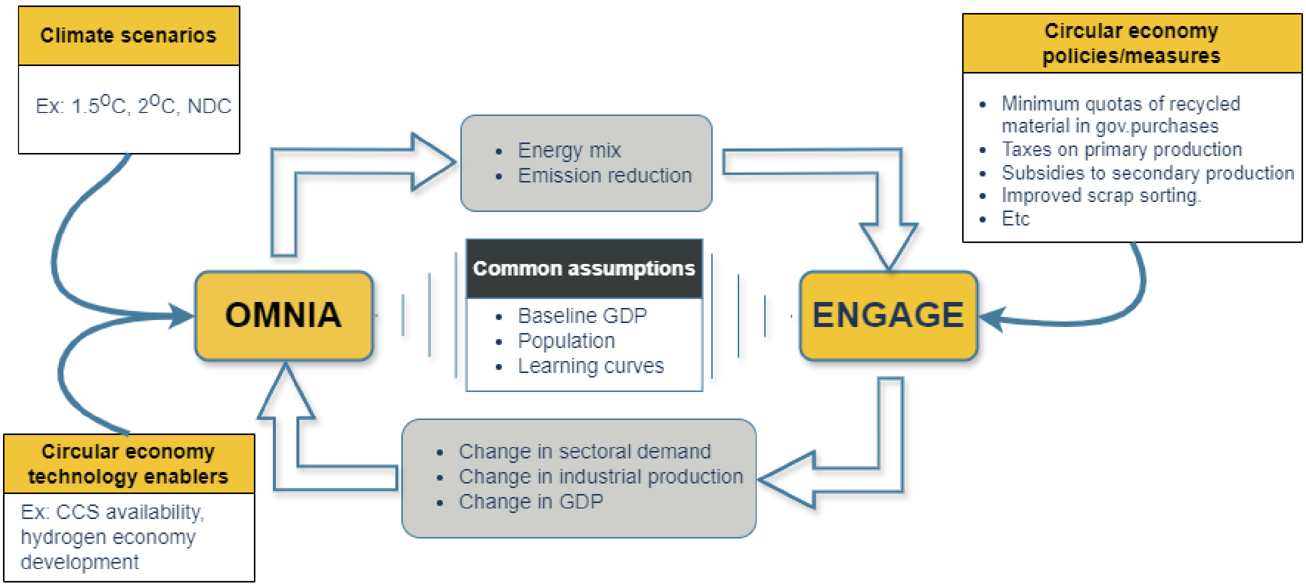

Figure 21. Soft-link OMNIA-ENGAGE

Key insights from ENGAGE will include changing demand for metals and construction materials, primarily cement, given how decarbonisation and circular economy policies and pathways impact demand. and how changes to steel, cement, aluminium stocks impact secondary production potential. Hence, the need for OMNIA to represent these sectors in detail.

These links will allow to assess economic implications of different decarbonisation pathways/ net-zero targets in an integrated manner with circular economy policies, helping to highlight synergies, trade-offs, and rebound effects, as well as energy, emissions, and investment impacts of decarbonisation scenarios in the steel, aluminium and cement industries. This will lead to new IAM capabilities, as key economic activities related to circularity will be incorporated, eventually enabling to quantify how relevant interventions can contribute to energy, resource and emissions cuts, while increasing the process resolution for key circular economy sectors.

The latest modifications in ENGAGE have focused on detailing the representation of the relevant sectors with the objective to allow for a full representation of circular economy measures and provide OMNIA with detailed information.

For steel modelling, the three different pathways to produce steel and various intermediate inputs have been explicitly added. In addition, high and standard steel scrap qualities have been included and final steel products that are currently limited to the use of primary steel and high-quality scrap-based secondary production have been identified. This allows us a representation of the technical constrains to replacing primary steel by secondary steel from end-of-life scrap. For aluminium modelling, bauxite and aluminium production have been disaggregated into their distinct sub processes, intermediate and final products.

Soft-link OMNIA – MAgPIE (T.4.2)

The MAgPIE and OMNIA soft-link will cover different systems:

- AFOLU emissions: MAgPIE can inherit GHG prices from OMNIA and generate corresponding land use and land use change GHG emissions, or provide a complementary analysis on land use emissions. CO2, CH4 and NO2 emissions from AFOLU sector for each scenario will be extracted from MAgpie model and in the OMINA

- Bioenergy: Based on different socio-economic specifications, MAgPIE can generate biomass feedstock availability and related costs and GHG emissions. These are incorporated into OMNIA, which will estimate carbon prices and new demand levels for biomass feedstock. This is an iterative process which is run until there are minimal differences between MAgPIE and OMNIA. Note that this is only possible when OMNIA is complete, early 2025. Meanwhile, unilateral connection MAgPIE to OMNIA is being established, with MAgPIE providing cost supply curves for biomass feedstocks and AFOLU emissions.

- Water: the two models can provide complementary analysis (water consumption from electricity and agriculture). As OMNIA will include the water sector assessing the water demand for energy production, MAgPIE will provide the water consumption for fertilizers and irrigation.

The modelling approach for the OMNIA – MAgPIE soft-link is shown in Figure 22.

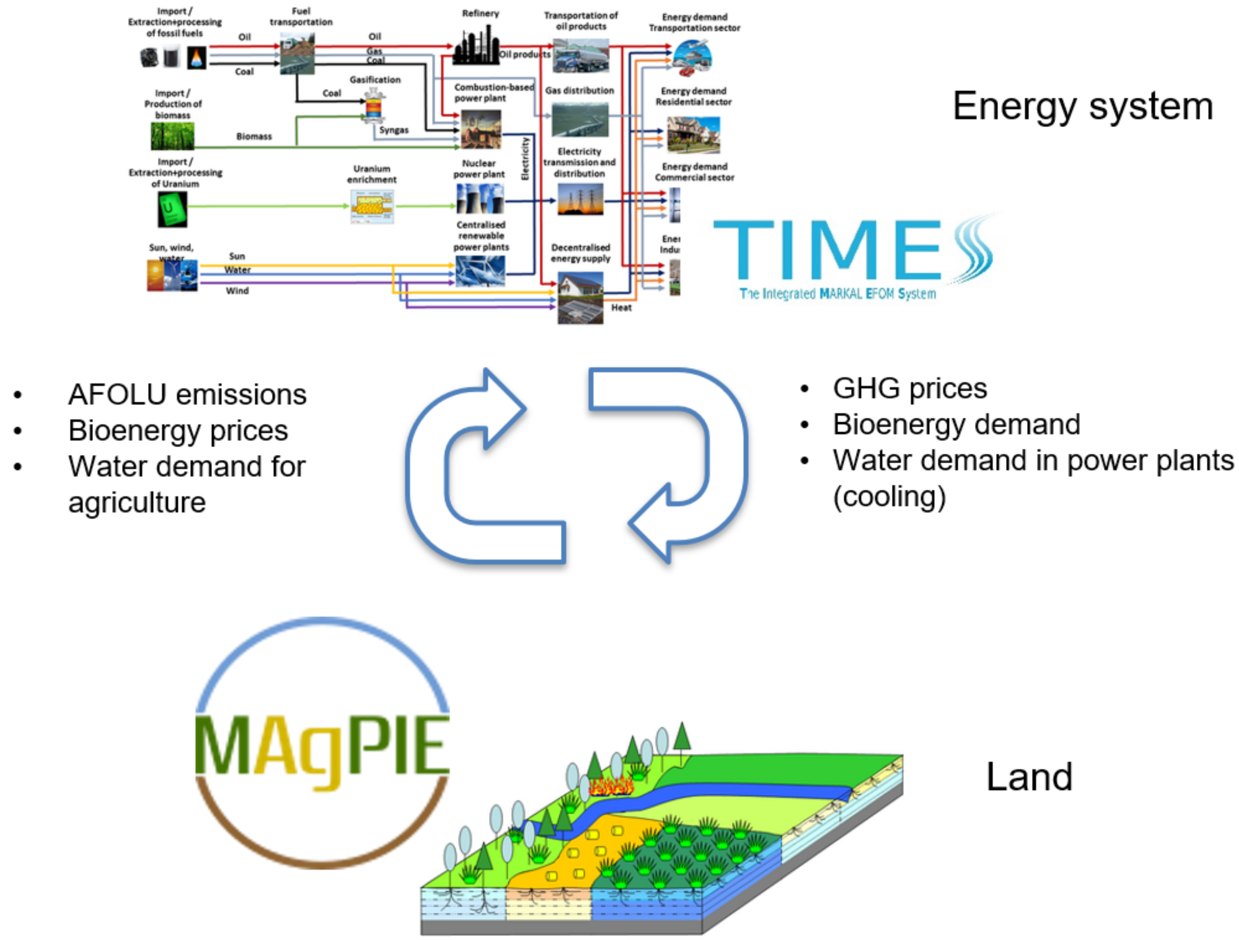

Figure 22. Modelling approach of OMNIA - MAgPIE soft-link

Currently, MAgPIE has been reconfigured to run on OMNIA regions and on the same socio-economic settings, i.e. population and GDP trajectories. Also, the bioenergy sector design in OMNIA has been updated to match outputs from MAgPIE on five biomass feedstocks, i.e. forestall residues, agricultural residues, crops cultivated purposely for energy, first generation bioethanol and first-generation biodiesel. As of November 2024, first biomass feedstock cost-supply curves and related biomass and AFOLU GHG emissions are being prepared for OMNIA.

Soft-link OMNIA – climate/physical impacts models (T.4.4)

The soft-link between OMNIA and the climate physical impacts models of CICERO is going to be defined during the first semester of year 3.

A first meeting was organised with CICERO team in November 2023 to start discussing the design of the link. A first proposal includes the possibility of OMNIA delivering emissions as output and CICERO models (openSCM) providing climate variables, e.g., global temperature. The subset of GHG emissions (CO2, CH4 and SO2, No2) from OMNIA model will be inputted to the infilling tool named Silicone to estimate the remaining gases. Once all the emissions trajectories for the given scenario are estimated, then these emissions will be inputted into a simple climate model to estimate the physical climate variables (like temperature and precipitation). These variables are downloaded using the pattern scaling model named METEOR model. In scenarios where we consider climate impacts, these regional climate variables will be used to assess changes in heating and cooling demand, crop yields, and other climate change related impacts.

Soft-link OMNIA – UNIBAS module on behavioural changes (T.4.6)
After three meetings with the UNIBAS team, that is going to develop a specific module on behavioural changes to be linked to several IAMs, it was decided to primarily focus on 2 societal behaviours:

- Adoption of insulation in households
- EV adoption

The UNIBAS module will provide as outputs the societal groups more prone to these two behaviours. These outputs will be converted into the share of population that is going to adopts house insulation and EVs and will be integrated into OMNIA demand drivers and constraints. UNIBAS team during the second year has developed an approach similar to be applied both OMNIA and CLEWs models.

Soft-link OMNIA – openTEPES (T.4.7)
The soft-link between OMNIA and openTEPES is going to be defined and developed during the first semester of year 3.
Two meeting with the openTEPES team members has been already organised and the first proposal of soft-link sees openTEPES providing for the European regions:

- Infrastructure costs per country
- Energy corridors between OMNIA regions

Concerning the approach to be applied to all the global regions, this will be defined during the first semester of year 3.

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3.3 From CLEWs to CLEWs-EU

3.3.1 Overview

The Climate, Land, Energy and Water Systems (CLEWs) is a Nexus modelling framework for integrated assessment of resource systems and of interlinkages among energy, water, and agricultural systems as well as their impacts on—and vulnerability to—climate change (e.g., food, energy, and water security). It builds on the OSeMOSYS energy modelling framework (Gardumi et al., 2018; Howells et al., 2011) and has been further advanced for global-level, user-friendly, exploratory analysis in GLUCOSE (Global CLEWs model) (Beltramo et al., 2021). This Global CLEWs model is used as a conceptual base for the development of a CLEWs-EU model. Hence, the CLEWs-EU model is essentially being populated with relevant data from scratch. DIAMOND will build on the already open nature of CLEWs, as well as on the large community of practice in both the modelling research community and the policy world, to develop CLEWs-EU. An additional, low-complexity implementation has been built and will be provided for capacity development.

Structure of CLEWs-EU

The CLEWs-EU model will have a similar structure to the Global CLEWs model (Beltramo et al., 2021), but several enhancements are foreseen. Two separate modules – energy and land with water – will be developed with several interlinkages between them. Greenhouse gas emissions are tracked across the three modules, while these are in turn affected by climate assumptions; for instance, temperature affects water demand in agriculture and heating and cooling demand in buildings, while precipitation affects hydropower output and crop yield. In the energy module, a large set of technologies will be used to represent primary energy supply, electricity generation, transport, buildings and industry (Figure 24). In addition, the suite of technologies will be expanded to include a broader range of decarbonisation options. For instance, use of hydrogen – either imported or locally produced – is an option that was not available in the Global CLEWs but will be included in the CLEWs-EU model. In the land module, the available land resources for crop production, livestock grazing and other uses are being defined at the EU level and for each country individually, assessing the impact of policies and climate on water and energy. Furthermore, whereas the Global CLEWs model employs a simple accounting approach to calculate water requirements throughout the system, the CLEWs-EU model will have a more explicit representation of water demand and supply. More information on each of the module's structure is provided in section 3.3.4.2.

Two levels of geographical resolution are adopted:

a. **Aggregated regional model**, in which the EU is represented as a single node, serving as an engagement model, upon which capacity development activities on EU climate policy can be developed due to its simplified structure and low computational effort. Coupled with the adoption of a user-friendly interface, enabling direct changes in model parameters and visualisation of the system dynamics, it will allow the exploration of climate change mitigation pathways by a broad range of stakeholders. This will ensure consistency with the philosophy behind the initial development of the Global CLEWs model.

b. **Disaggregated model**, in which the level of spatial resolution will extend to the national level (see Figure 23), to be used for the more extensive analyses foreseen within DIAMOND (e.g., through soft-links in WP4). Unlike the high-level focus of the aggregated model, the disaggregated model will be able to provide more focused insights and can be used to support development of national policies within the context of mutual EU obligations/targets. As expected, the disaggregated model will require a larger volume of input data compared to the aggregated model.

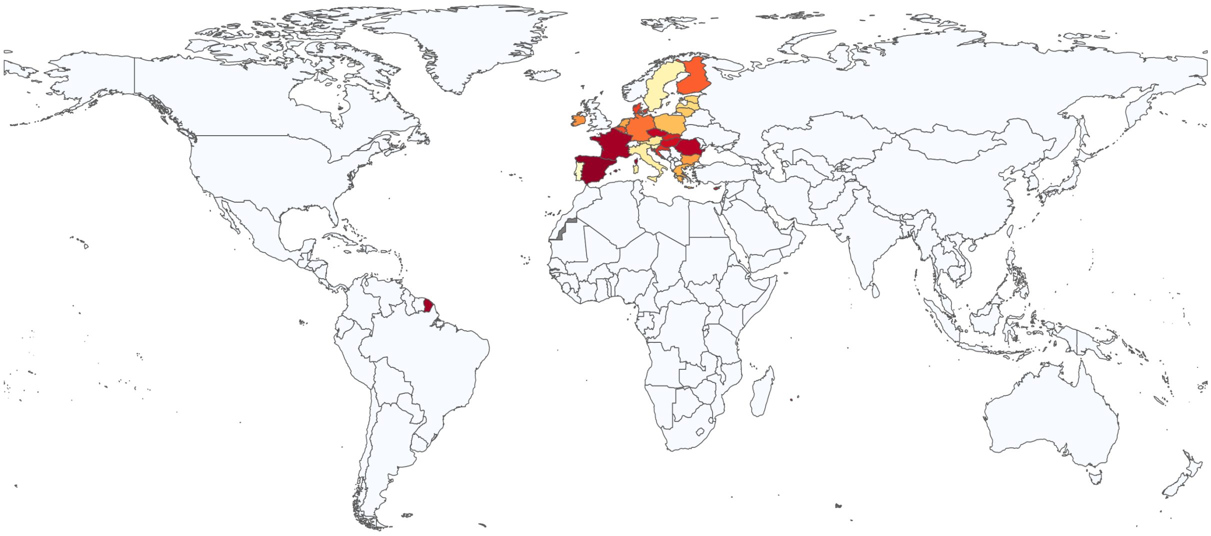

Figure 23. Regional disaggregation in CLEWS-EU, disaggregating all 27 EU member states.

Yellow-to-red colours represent the regional groups that are explicitly disaggregated for this model.

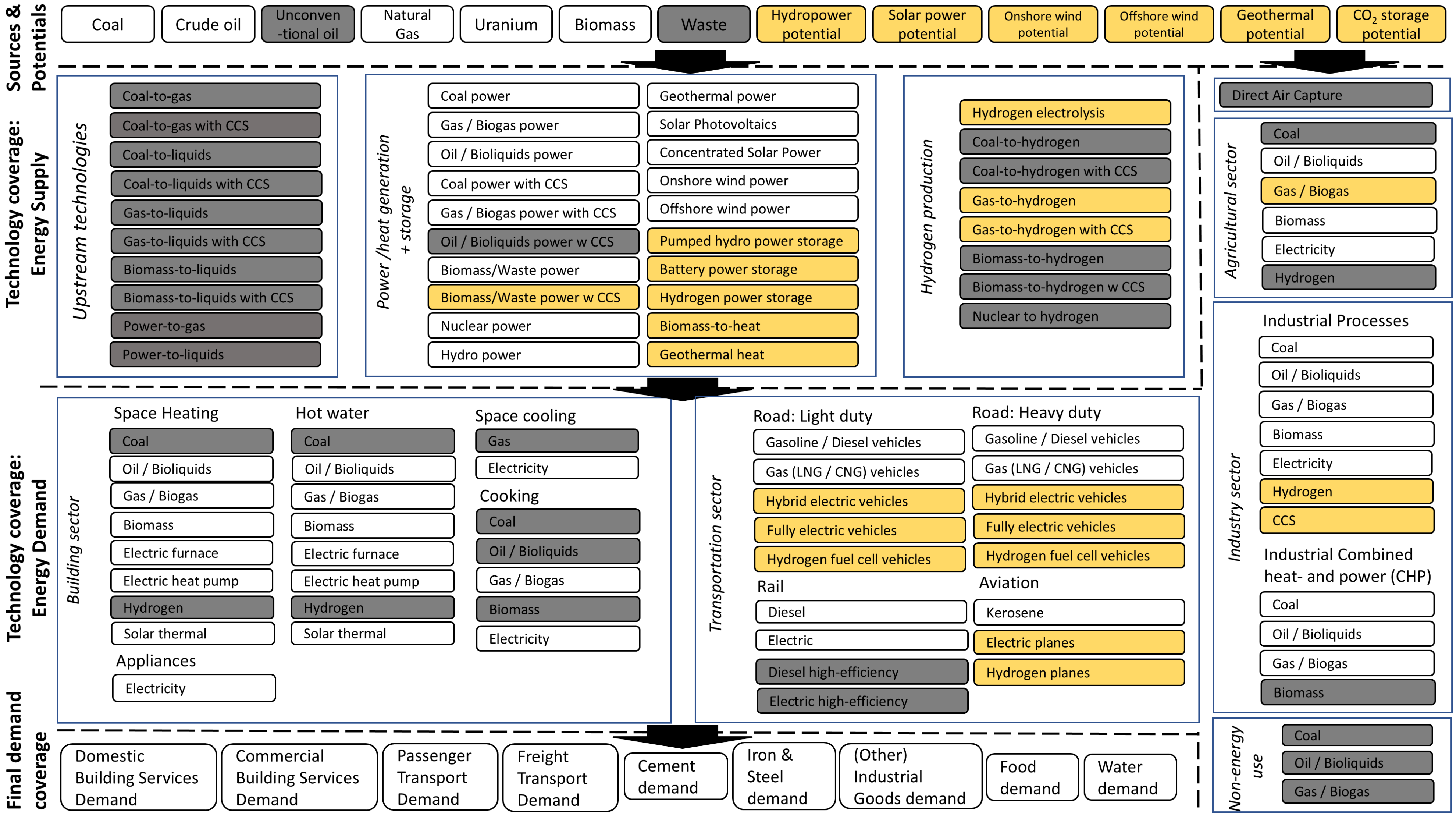

Figure 24. Summary of the resource, technology, and end-use demand representation in CLEWS-EU.

White boxes indicate features already part of the original model. Grey boxes indicate features not part of the core nor the updated model. Dark yellow boxes indicate the features that will be, and light-yellow boxes features that might be (still to be decided), explicitly developed for CLEWs-EU in the DIAMOND project, and which are not in the core version of the model.

3.3.2 Development timeline

As the CLEWs-EU model is developed with two distinct levels of geographical detail, the efforts have been split chronologically in the same manner. The initial focus (M4-M18) was on developing the aggregated version of the model, as this will act as a template upon which the disaggregated national version will be developed.

Since the aggregated version of the model is finalised and a draft version has been made available[6] in May 2024 (M18), efforts have been diverted towards the disaggregated version of CLEWs-EU. Instead of setting up each country's system separately, since data collection occurs uniformly across countries, development of each sector will be conducted simultaneously for all countries. Similarly, module development will occur in parallel. However, the aggregated regional CLEWs-EU model may be updated/revisited during the development of the disaggregated national CLEWs-EU model as needed.

As the disaggregated CLEWs-EU model is being developed from scratch, a large number of tasks have already been identified regarding data collection in each sector/module. However, the list is not exhaustive and is constantly enhanced; thus, we choose not to include it in this report. Nonetheless, Table 16 provides a summarised overview of the foreseen overarching timeline for the development of the disaggregated version of the model.

Table 16. Timeline for the finalisation of the disaggregated national CLEWs-EU model.

Project phase / Duration of the project (in months)	**17-19**	**20-22**	**23-25**	**26-28**	**29-31**	**32-34**	**35-36**
	2024			**2025**			
	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Disaggregated national model development					Draft Version		Final Version
Construction of national model shell based on aggregated version							
Population of model with energy technology data - primary supply, electricity & heat							
Population of model with energy technology data - transport							
Population of model with energy technology data - buildings							
Population of model with energy technology data - industry							
Population of model with land technology data							
Population of model with water technology data							
Initial model runs and model calibration							
Preliminary scenario analysis							
GitHub repository and model documentation							

3.3.3 Meetings (internal modelling team and external)

The CLEWs-EU model is developed as a cross-institutional effort. Specifically, CYI, Imperial and ICCS are contributing to the model development. In order to more efficiently coordinate efforts, regular progress meetings are held between the team members, approximately on a monthly basis (Table 17). These meetings provide a forum for discussion where consensus is reached on key aspects (e.g., technological representation, naming convention), before decisions are taken and implemented in the development process.

[6] The draft aggregated version of CLEWs-EU can be accessed through DIAMOND's GitHub repository at: https://github.com/CLIMATE-DIAMOND/EU-CLEWS/tree/main/Aggregated%20EU%20Model

Table 17. CLEWs-EU team meetings up to November 2024.

Date	Type	Aim of meeting
06 March 2023	Virtual	Short kick-off meeting and team acquaintance
24-25 April 2023	Physical (Athens, Greece)	Official kick-off meeting and detailed discussions on model development strategy
13 June 2023	Virtual	Data collection updates
21 July 2023	Virtual	Discussion on temporal resolution, technological detail and technoeconomic assumptions
11 September 2023	Virtual	Discussion on consolidation of technological detail
25 September 2023	Virtual	Discussion on model naming convention
16 October 2023	Virtual	Discussion on development interface, reference system diagram, data collection on water and land
06 November 2023	Virtual	Discussion on technological detail, scenario narratives, data collection for buildings sector
01 December 2023	Virtual	Discussion on model structure setup and choice of interface, data collection on buildings, water and land
15 January 2024	Virtual	Data collection updates, interface troubleshooting, integration with behavioural aspects
19 January 2024	Virtual bilateral meeting for WP4 soft-links	Call with UNIBAS to discuss integration with behavioural aspects (Task 4.6)
05 February 2024	Virtual	Data collection updates, discussion on model structure finalisation, update on discussion regarding integration of behavioural aspects
13 February 2024	Virtual bilateral meeting	Discussion with HOLISTIC on options for results visualisation
26 February 2024	Virtual	Update on discussion with HOLISTIC on results visualisation, discussion on ongoing development of aggregated model version for the energy, land and water modules.
20 March 2024	Virtual	Update on status of energy, land and water modules development for aggregated EU version. Setting a plan for integration of modules and the need for subsequent calibration
08 April 2024	Virtual	Update on calibration efforts of individual modules. Discussion on the need for transparent and detailed datasets regarding assumptions. Discussion on the need for internal model review.
22 April 2024	Virtual	Integration of energy, land and water modules. First run of aggregated CLEWs-EU version.
14 May 2024	Virtual	Coordination on CLEWs-EU presentations ahead of the General Assembly in Lausanne
23 May 2024	Bilateral meeting for WP4 soft-links (Lausanne)	Discussion with UNIBAS on the methodological approach and the parameters needed for the integration of behavioural aspects
17 June 2024	Virtual	Discussion on incorporation of shipping sector in energy module and

Date	Type	Aim of meeting
		required updates for land and water module. Allocation of tasks between partners for disaggregated model version
02 July 2024	Virtual	Discussion on participation of CLEWs-EU team in stakeholder engagement workshop, availability of aggregated model version on GitHub repository and updates on model development
22 July 2024	Virtual	Discussion on ongoing model development across modules
02 September 2024	Virtual	Updates on model development efforts across modules. Coordination regarding input to stakeholder requirements workshop
23 September 2024	Virtual	Updates on model development for electricity and heat generation, transport, buildings, land and water module
04 October 2024	Virtual bilateral meeting with UCL	Discussion on demand projections work conducted by UCL for the buildings and transport sectors, and how these can be incorporated into CLEWs-EU.
14 October 2024	Virtual	Updates on ongoing model development and data updates
08 November 2024	Virtual	Updates on model development for electricity and heat generation, transport, buildings, land and water module

3.3.4 Completed development steps

The following subsections provide information on key overarching model development aspects, development approach, as well as module-specific features. The structure of each of the modules and the data collection process for each of these are presented separately.

3.3.4.1 General considerations

Development overview

As mentioned above, two versions of the CLEWs-EU model will be developed: an aggregated and a disaggregated. In terms of model development, the following actions have been taken, which have resulted in a draft aggregated EU model version:

Energy module

- Baseline information has been collected and implemented for the key sectors of the energy system: primary energy supply, electricity and heat generation, transport (road, rail, aviation), industry and buildings. Following feedback received from the broader consortium during the General Assembly in Lausanne (in M18), the shipping sector, both international and domestic, has also been added to the transport sector.
- Data to set up the base representation of the energy system have been extracted primarily from Eurostat, ENTSO-E, IRENA, JRC-IDEES.
- Technoeconomic assumptions have been derived mainly from EU Reference Scenario 2020.

Land and Water module

- The land and water system (balance) are modelled as one entity with demands for crops and water in different sectors (public, industries and other services).
- Data has been extracted mainly from Eurostat, Aquastat, GAEZ (Global Agro-Ecological Zoning) and relevant academic literature.
- Technoeconomic assumptions have been derived mainly from JRC publications, Clim-ADAPT

database, European Environment Agency (EEA) and relevant academic literature.
- Calibration for land cover and crop production has been completed,
- For the water system, all the sector specific withdrawal and consumption data is not reported by every European country. Therefore, assumptions are being made to fill in the gaps wherever needed. This activity might only be finalised when all the missing data at the national level is collected for the disaggregated model version.

Time horizon and temporal resolution

Even though the climate neutrality of the European Union is aimed to be achieved already by 2050, the modelling horizon of the project will be extended to **2070** with an annual resolution. The extension of the modelling horizon implies great uncertainty as to the technological advances and relevant cost assumptions, climatic conditions and energy demand projections to be expected so far into the future, but since impacts of a changing climate are projected to be more adverse in the latter half of the century, it is deemed crucial to be able to capture part of this timeframe. The base year will be 2018, but statistics up to 2021 will be accounted for and these years will be calibrated accordingly wherever possible.

It was agreed during the project conception that the temporal resolution of the model would be enhanced from the 3 intra-annual parts adopted in the GLUCOSE (i.e., Global CLEWs) model. These will increase to **16 annual timesteps**, which will consist of **4 seasons** (i.e., winter, spring, summer, autumn) represented by a typical day; each consisting of **4 intra-day parts**. Initially, the model will be developed with this temporal resolution, but in case the computational effort during the model optimisation permits further enhancement, this will be explored in future stages of the model development. Such an enhancement would strengthen the model's capability to provide valuable insights regarding variable renewable energy integration. In this sense, the data collection process for time-variable statistics (e.g., electricity demand variability, renewable energy generation profiles, heating and cooling demand profiles etc.) will have to consider this plausibility.

Naming Convention

As the CLEWs-EU model is essentially being built from scratch, the way in which technologies and commodities would be represented within the model had to be agreed upon. Specifically, the short codes abbreviating these had to be formulated. This would facilitate the standardisation and automation of data entry and results extraction and visualisation. A 12-character naming convention was agreed for technologies, while a 6-character naming convention was adopted for commodities. Table 18 shows an extract of the naming convention adopted for the energy module, while Table 19 and Table 20 highlight the naming convention implemented for the land and water modules. The full explanation of the naming convention will be made available as part of the model documentation in the model's GitHub repository, which is still under development.

Table 18. Naming convention sample for technologies and commodities in the energy module (CLEWs-EU).

Technology	Country/Region (2 Characters)	Module (1 Character)	Sector (2 Characters)	Fuel (3 Characters)	Technology/ Destination (2 Characters)	Type (2 Characters)
EUEPTVPGSLPH Gasoline-fired plug-in hybrid passenger car in the EU	**EU** (European Union)	**E** (Energy)	**PT** (Passenger Transport)	**GSL** (Gasoline)	**VP** (Passenger vehicle)	**PH** (Plug-in hybrid)
ATEGNELCDEIC	**AT** (Austria)	**E** (Energy)	**GN**	**ELC** (Electricity)	**DE** (Germany)	**IC**

Technology	Country/Region (2 Characters)	Module (1 Character)	Sector (2 Characters)	Fuel (3 Characters)	Technology/ Destination (2 Characters)	Type (2 Characters)
Electricity interconnector between Austria and Germany			(Grid Networks)			(Inter-connector)
PLEEGCOAPPCS Coal power plant with CCS in Poland	**PL** (Poland)	**E** (Energy)	**EG** (Electricity Generation)	**COA** (Electricity)	**PP** (Power Plant)	**CS** (Carbon Capture and Storage)

Commodity	Country/Region (2 Characters)	Module (1 Character)	Fuel (3 Characters)
ITEHY2 Hydrogen fuel in Italy	**IT** Italy	**E** (Energy)	**HY2** (Hydrogen)
PTESEL Secondary electricity generated by power plants in Portugal	**PT** Portugal	**E** (Energy)	**SEL** (Secondary electricity)

Table 19. Naming convention sample for technologies in the land module (CLEWs-EU).

Technology	Country/ Region (2 Characters)	Module (1 Character)	Identifier 1 (3 Characters)	Identifier 2 (3 Characters)	Input Level (1 Character)	Water supply (1 Character)	Dummy (1 Character)
EULIMPWHE000 Wheat imports in the EU	**EU (Europe)**	**L (Land)**	**IMP (Imports)**	**WHE (Wheat)**	**0 (Dummy)**	**0 (Dummy)**	**0 (Dummy)**
EUL000WAT000 Land cover under water bodies	**EU (Europe)**	**L (Land)**	**000 (Dummy)**	**WAT (Water)**	**0 (Dummy)**	**0 (Dummy)**	**0 (Dummy)**
EUL000MAIHR0 Potential for rainfed maize cultivation under high input level	**EU (Europe)**	**L (Land)**	**000 (Dummy)**	**MAI (Maize)**	**H (High Input Level)**	**R (Rainfed type)**	**0 (Dummy)**

Table 20. Naming convention sample for technologies in the water module (CLEWs-EU).

Technology	Country/ Region (2 Characters)	Module (1 Character)	Identifier 1 (3 Characters)	Identifier 2 (3 Characters)	Identifier 3 (3 Characters)
EUWDEMPUBGWT Ground water supply technology for public use	**EU (Europe)**	**W (Water)**	**DEM (Demand)**	**PUB (Public supply)**	**GWT (Ground water)**
EUWDEMAGRSUR Surface water supply technology for agricultural use	**EU (Europe)**	**W (Water)**	**DEM (Demand)**	**AGR (Agricultural Use)**	**SUR (Surface water)**
EUWMIN000PRC	**EU (Europe)**	**W (Water)**	**MIN**	**000 (Dummy)**	**PRC (Precipitation)**

Technology to produce water from Precipitation			**(Resource Technology)**		

3.3.4.2 Energy module

The CLEWs-EU energy module is broken down into several subsectors. The sectoral and technological detail was discussed amongst the team and agreed upon during the kick-off and regular progress meetings. Enhancements in technological representation will be conducted to increase the number of options that can render net-zero emission pathways technically feasible. As an essential feature, hydrogen energy chains, currently missing from the Global CLEWs model, will be added to the energy sector module. More information on the module structure and the associated data requirements is provided in the next subsections.

Module structure and technological representation

Five overarching sectors are developed to represent the broader energy system. Each of these will include a large set of technologies to capture the current status of energy mix, as well as future technology options for decarbonisation. Specifically, the following sectors will be modelled:

a) **Primary energy supply** – this relates to fossil fuel supply, nuclear fuel supply, renewable energy potential and hydrogen imports. Primary energy supply and transformation infrastructure (e.g., gas pipelines, LNG regasification terminals, oil refineries, etc.) will not be modelled explicitly, with the only exception of electricity interconnectors between countries in the disaggregated version of the CLEWs-EU model. Supply of biomass into the energy system will occur via an interlinkage with the land module of the model.

b) **Electricity and heat generation** – fossil fuel, nuclear and renewable energy technologies will be represented, along with a simplified representation of grid networks to capture associated losses. Additional technology options to be represented include electricity storage, use of Carbon Capture and Storage (CCS) technologies, electrolysers for the production of green hydrogen; hydrogen production will also be possible through steam methane reforming (i.e., using natural gas as feedstock) with or without CCS.

c) **Transport** – the transport sector will include road transport, which will be further broken down to passenger (passenger cars and buses) and freight (light commercial vans and heavy trucks), rail transport (passenger and freight), aviation and shipping.

d) **Buildings** – this sector basically comprises of the households and service sectors. It will be broken down into end-use services (i.e., space heating, space cooling, cooking, sanitary hot water, lighting and appliances).

e) **Industry** – the five most energy intensive industries – a considerable variation exists according to the latest energy balances (Eurostat, 2023) – will be represented separately for each country, while the rest of the industries will be lumped together in a sixth category[7]. The output of each of the industries will be represented in generic terms (i.e., PJ of energy services), similar to the approach previously employed by

[7] The breakdown of the industrial sector will be based on the categories available in Eurostat's energy balance: Iron & steel, Chemical & petrochemical, Non-ferrous metals, Non-metallic minerals, Transport equipment, Machinery, Mining & quarrying, Food, beverages & tobacco, Paper, pulp & printing, Wood & wood products, Construction, Textile & leather.

GCAM for some of the industries (JGCRI, n.d.).

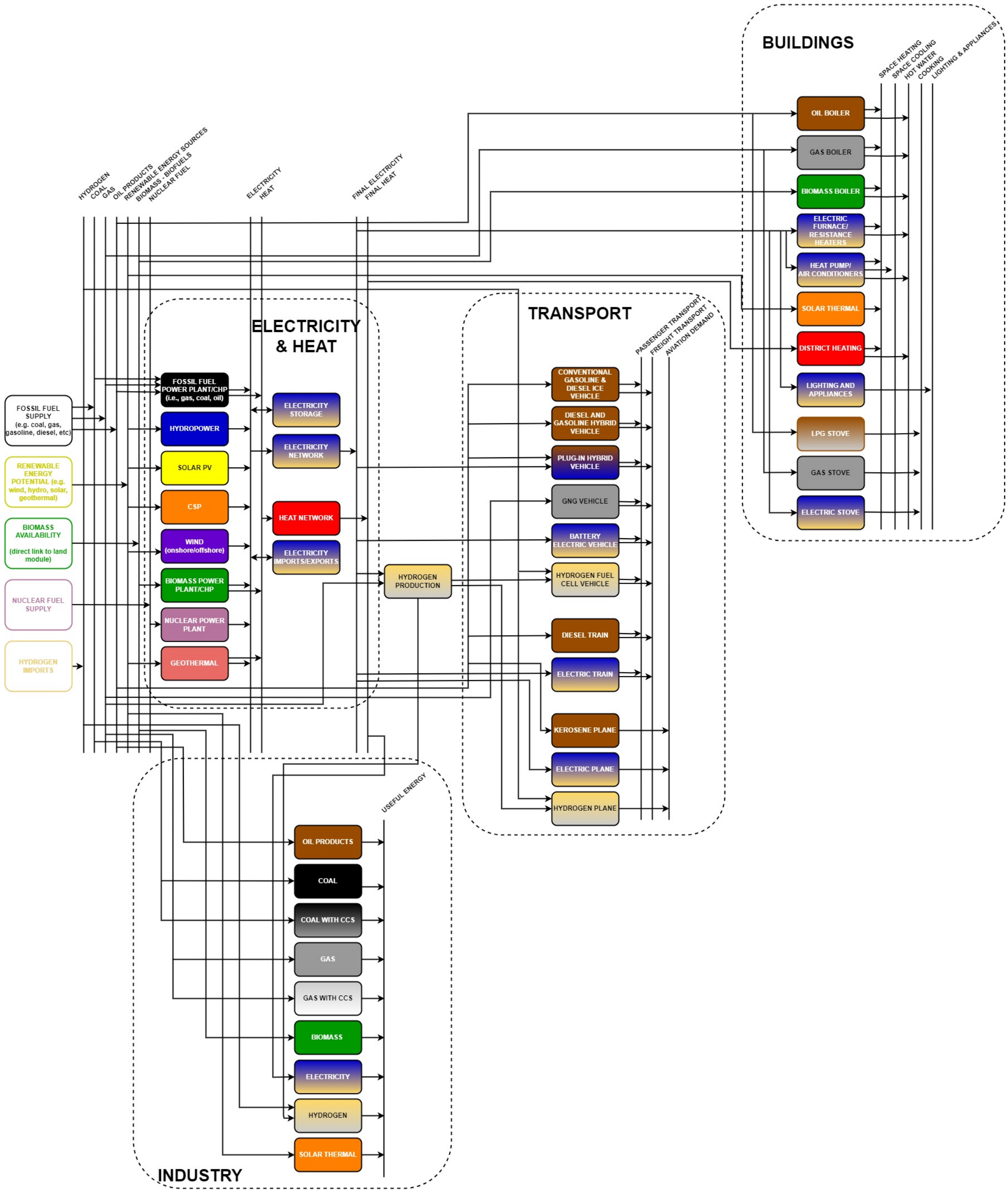

Figure 25. Simplified representation of CLEWs-EU energy module.

It should be noted that the energy demands in all sectors are inputs to the model[8]. A simplified representation of the structure of the energy module is provided in Figure 25; further disaggregation of technologies will be available in the model than is depicted. For instance, the various vehicle technologies will be further broken down into

[8] Estimation of energy demand projections need to account for official targets on efficiency and electrification; these need to be derived exogenously through the use of appropriate top-down and/or bottom-up models.

passenger cars, buses, light commercial vans and heavy trucks. Similarly, the structure of the industrial sector will be constructed for each of the five key industries (and other industries) to be represented in each country or the EU as a whole. Additionally, interlinkages with the land and water modules are presented in section 3.3.4.3.

Data collection for energy module

Since the CLEWs-EU model is developed from scratch, a large volume of data has to be collected and transformed for input. Table 21 provides a brief overview of some of the main data requirements relating to the energy module. Even though the aggregated regional EU version of CLEWs-EU will be developed first, information on all of the data items is collected at a national level to expedite the development of the disaggregated national version of the model. The only exception relates to technoeconomic assumptions (e.g., cost and efficiencies of technologies), for which generic data will be used.

Table 21. Key data requirements of the CLEWs-EU energy module.

Sector	Data item	Status	Primary Source
General	National energy balances	Complete	(Eurostat, 2023)
	Technoeconomic assumptions across sectors	Complete	EU Reference Scenario 2020 (European Commission. Directorate General for Energy. et al., 2021)
Electricity and heat	Installed capacity by technology	Complete	Eurostat & ENTSO-E
	Electricity generation by technology	Ongoing	Eurostat, ENTSO-E
	Electricity demand load profile	Complete	ENTSO-E
	Renewable energy generation profile	Complete	ENTSO-E
	Transmission and distribution losses	Complete	Eurostat
	Grid interconnector capacity	Complete	ENTSO-E
Transport	Vehicle fleet statistics	Complete	Eurostat, JRC-IDEES 2021
	Annual mileage per vehicle category	Ongoing	National statistics, JRC-IDEES 2021
	Mobility demand projections	Pending	EU Reference Scenario 2020 (European Commission. Directorate General for Energy. et al., 2021), Soft-link with UCL demand projections
Buildings	Heating and Cooling Degree Days statistics	Complete	Eurostat
	Heating and Cooling Degree Days projections	Pending	(Climate-ADAPT, n.d., n.d.)– can also be linked with WP4
	Statistics on demand by useful energy service in households and activity be each technology	Complete	Eurostat, JRC-IDEES 2021
	Statistics on demand by useful energy service in commercial sector and activity be each technology	Complete	Eurostat, JRC-IDEES 2021
Industry	Final energy demand by fuel by industry	Ongoing	Eurostat, JRC-IDEES 2021
	Industrial activity projections	Pending	To be determined; Potential for own projections

3.3.4.3 Land and Water modules

The water and land use modules are effectively interlinked in nature. Though we have different naming conventions and technologies to represent the two modules inside CLEWs-EU, their inputs and outputs are interdependent. The water module will represent the different primary sources, namely water from precipitation and snow melt, water from existing surface and ground water sources, water from neighbouring geographies by transboundary river exchanges, as well as secondary sources like water from treatment plants in some countries. In the land module, the total land available in the continent (in the engagement model) and in each country (in the disaggregated model) is divided into nine major land categories based on the European Space Agency's land cover classifications. They are namely: grassland, cropland, snow cover, water bodies, shrubland, forest cover, built up land, barren land, other land (includes mangroves, lichens and wetlands). Representing land and water systems in a generic systems optimisation setup involves using relevant assumptions to simplify their characterisation and at the same time ensuring not a lot of the essential detail is lost. Effectively the land and water modules represent the balance of the two resources (i.e., land and water) in the respective systems. Despite accounting for the balance of these resources, some components like groundwater storage are not considered in these modules as it involves detailed sub surface flow modelling, which is outside the scope of the project. In the following section, a sample of the technology representation in the land and water modules is presented, along with some common data sources.

Module structure and technological representation

Figure 26 represents a diagrammatic illustration of the land component within a general CLEWs systems framework. The diagram breaks down "Total land" into various land uses and their subsequent products or services.

<u>Land Uses:</u>

This includes various classifications of land such as Cropland, Barren land, Forests, Pastures/Grasslands, Built-up land, and Water bodies. Each category of land use is dedicated to a specific type of production or ecosystem service.

<u>Production:</u>

From each type of land use, there is also a corresponding output:

- Cropland is associated with the production of agricultural commodities like Maize, Rice, Coffee, Sugarcane, Bananas, and other crops.
- Forests contribute to the production of wood and other forest products.
- Pastures and Grasslands are tied to the production of meat and dairy, implying livestock farming.
- Built-up land is related to residential, industrial, commercial, and transport services, indicating areas of human development and infrastructure.

The arrows indicate the flow from land use to the type of production. The diagram encapsulates the interconnectedness of land use with various economic and environmental outputs, emphasising the integrated approach of the CLEWs framework where changes or policies affecting land use have cascading effects on food, energy, water, and ecosystem services.

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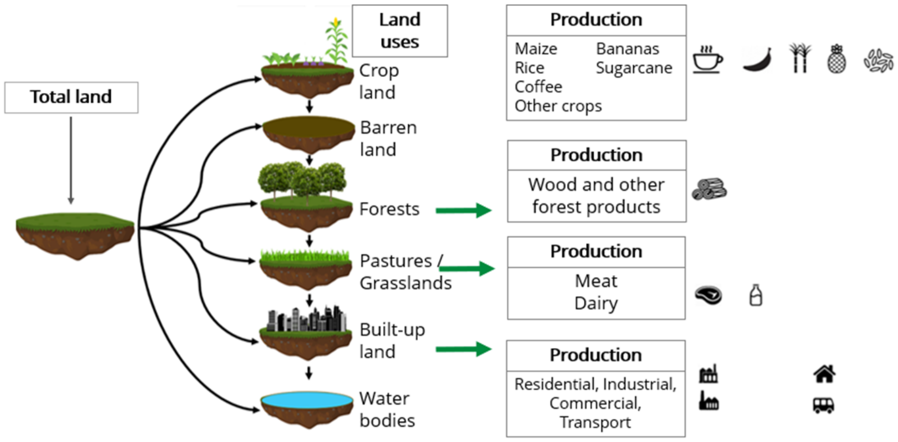

Figure 26. Primary level of land categories breakdown in the land module (CLEWs-EU).

A more complex system diagram is illustrated in Figure 27 and portrays how the CLEWs-EU land and water modules will be represented, along with key interactions with the energy module.

The diagram is organised into several columns, each representing different components of the CLEWs systems:

- *Land Use (left-most column):* This column lists various types of land uses such as agricultural land (which will be divided into up to 10 different crop types), barren land, forests, built-up land, and water bodies. Each land type is linked to specific outputs, i.e., specific crops and the different aspects of the water system.
- *Precipitation and Sea Water (bottom rows and centre columns):* This section details the sources (precipitation and sea water) and uses of water, distinguishing between surface water and groundwater, and their respective uses in agriculture, power generation (PWR), and other needs.
- *Energy Supply and Use (top right box):* The diagram includes simplified forms of electricity generation, to show how these energy sources contribute to meeting the demands of different sectors, including transport, meat processing, and the transport and distribution (T&D) of water resources.
- *Interlinkages (arrows and lines):* The arrows and lines represent the flow of resources and interconnections between the land, water, and energy components. For example, water from different sources is used for land irrigation, electricity generation requires water for cooling, and agriculture produces biofuels.

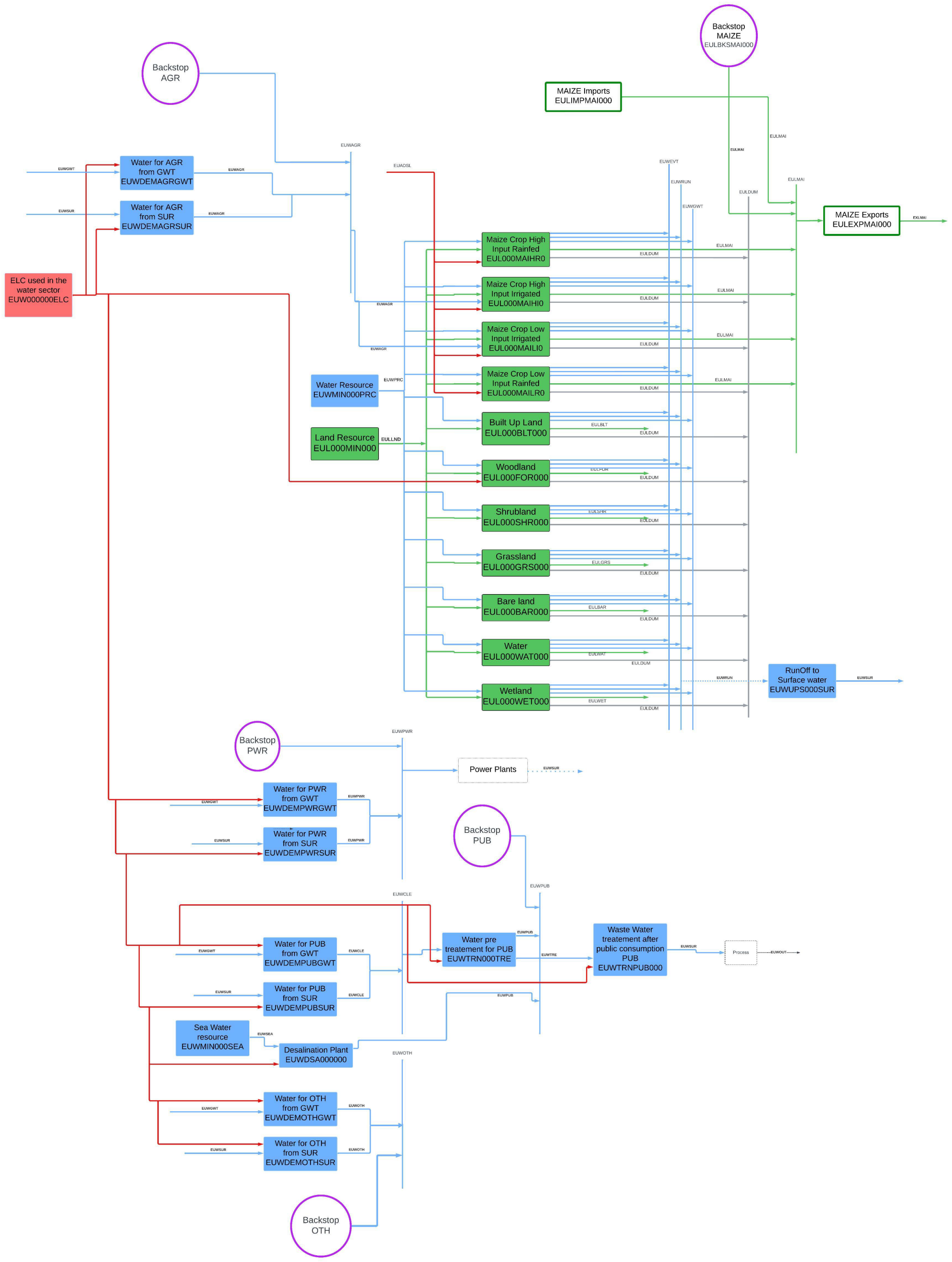

Figure 27. Simplified representation of CLEWs-EU land and water modules and illustration of key interactions with the energy module.

Data collection for land and water modules

The construction of the Land and Water modules within the CLEWs-EU framework necessitates an extensive acquisition and processing of data. Table 22 delineates a summary of the primary data requisites pertinent to the land and water components of the model. In alignment with the approach adopted for the energy module, we are amassing data at the individual country level, despite the initial development focus on a regional EU aggregate. This strategy is to facilitate a seamless transition to the more granular national models in subsequent phases. For land, this includes data on land use patterns, agricultural productivity, and potential changes due to climate or policy shifts. For water, we gather information on water availability, usage statistics across sectors, withdrawal limits, and quality standards. Exceptions are made for general hydrological parameters and land management practices, where universally applicable figures are employed in the preliminary stages. Nevertheless, country-specific calibration will be essential to enhance accuracy and relevance, particularly in reflecting the unique hydrological and agricultural conditions of each member state.

Table 22. Key data requirements of the CLEWs-EU land and water modules.

Sector	Data item	Status	Primary Source
Land Cover	Area under different land cover classes	Completed	FAO, Eurostat, European Space Agency (WorldCover2021)
	Area under crop cultivation	Completed	Aquastat & Eurostat
Agriculture	Crop yields and production statistics	Pending	Global Agro-Ecological Ecological Zoning-GAEZ (FAO/IIASA) & Eurostat
	Crop yield variation under future climates	Pending	Global Agro-Ecological Ecological Zoning-GAEZ (FAO/IIASA)
	Fertilizer usage in Crop production	Pending	Eurostat
	Crop import statistics	Partially completed	Eurostat
	Costs involved in crop production	Pending	National Statistics, Eurostat & Derived entity in some cases
	Fuel usage in the agriculture and forestry sector	Completed	Energy Balances
Water availability and Use	Precipitation statistics	Completed	Eurostat and GAEZ
	Groundwater potential	Pending	National Statistics and Academic Journals
	Water use factors in different sectors	Pending	Eurostat
	Evapotranspiration under different land categories	Pending	GAEZ
	Water losses during transportation	Pending	Eurostat, National Statistics
	Demand projections for water in different sectors	Pending	Derived entity based on economic projections

3.3.5 Planned development steps

3.3.5.1 Module development efforts

Current efforts of the CLEWs-EU team are focused on developing the disaggregated model version. The various sectors will be developed in parallel. Specifically, the following activities are planned:

- **Energy Module** – Even though information for the aggregated version of the model was gathered from a variety of sources, the disaggregated version will utilise more detailed information. As such, the entire energy module will be updated with the most recent release of the JRC-IDEES database (Rózsai et al., 2024).
    - *Electricity and heat generation* – Relevant data is being gathered and transformed for input to OSeMOSYS, using complementary sources, such as Eurostat and ENTSO-E. An expanded list of technology options is being considered (e.g. to allow differentiation between dam and run-of-river hydropower), which can provide more detailed insights. The model shell will be developed before the end of the year, so that it can be directly populated with information.

   - *Buildings* – Historical data has already been extracted from the JRC-IDEES 2021 database. Demand projections will be adopted once the relevant methodology being developed by UCL is finalised. Development of the model shell for each EU member state has started and should be finalised by the end of January 2025 (M26).
   - *Transport* – Relevant scripts are under development for the extraction of historical data at a national level from the JRC-IDEES 2021 database. The model shell for each EU member state is under development and should be populated with respective information by the end of January 2025 (M26).
   - *Industry* – Extraction of historical data and model development for this sector at a national level will commence by February 2025 (M27).

- **Land and Water Module**
   - The representation of the desalination system is being finalised. This is applicable only to some European countries where a share of the water demand is met through desalination technologies. It should be completed by Dec 2024.
   - Sector specific water withdrawal and consumption numbers are being extracted from relevant literature (Fridman et al. 2024). The demands will be finalised by January 2025 (M26).
   - A simplified emissions accounting methodology is being implemented for the different Land Use categories. Will be tested by December 2024 and implemented across the EU27 countries in the model by February 2025 (M27).
   - A step-by-step method is being developed to apply the land and water module structure to all the EU27 countries in a streamlined manner. Structure will be developed by January 2025 (M26) and applied by March 2025 (M28).

3.3.5.2 Linkages with WP4

In an effort to go beyond the structural limitations of IAMs, the CLEWs-EU team is engaging with the modelling teams of WP4 – Integrate & Expand. Specifically, the envisioned integration will be conducted in collaboration with CICERO (Task 4.4), UM (Task 4.5) and UNIBAS (Task 4.6).

Soft-links with the DIAMOND climate modelling and pattern scaling suite will be established within **Task 4.4** to examine the effect of various climate scenarios on critical aspects of the food-energy-water nexus, such as water availability, land productivity and renewable energy output. During the physical meeting in Athens, it was agreed between the team members that a guiding document will be needed that identifies each parameter that needs to be adjusted across the various modules of the CLEWs-EU model, whenever a specific climate scenario will be represented[9]. This will facilitate the identification of soft-linking possibilities, while it will help avoid potential inconsistencies across the assumptions to be adopted for each scenario. The aforementioned document should be available when key sectors of the disaggregated version of the model will be ready (i.e., by M26 of the project). The CLEWs-EU model itself will be able to provide projections on greenhouse gas emissions with an annual resolution.

[9] This includes but is not limited to parameters relevant with: annual precipitation, irrigation requirements, crop yield, water demand for domestic uses, hydropower output, thermal plants cooling requirements and efficiency, space heating and cooling demands in buildings.

Furthermore, representation of financial markets can be enriched within **Task 4.5**. The CLEWs-EU team participated in September 2023 in the workshop held at the University of Maastricht on integration of aspects related to consumption, finance and labour dynamics in IAMs. Possibilities for incorporation of these aspects were discussed and a possible entry point that was identified is the variability in discount rates across technologies, sectors and countries. An additional possibility relates to the incorporation of labour intensity factors to estimate labour requirements for the various investments projected in each scenario.

Finally, representation of behavioural aspects will be pursued in **Task 4.6**. The CLEWs-EU model will be developed within OSeMOSYS, which is a cost-optimisation modelling framework. Cost-optimisation models assume economically rational consumer behaviour and thus investments in technologies are primarily determined by the cheapest life-cycle costs. In reality, such choices are not merely based on economic decision criteria. Deviation of consumer behaviour from economic norms will be explored via incorporation of behavioural aspects in decision-making, from psychology insights. A set of case countries representative of the diverse socioeconomic conditions in the EU will be determined to explore aspects that are crucial for the decarbonisation of national economies. Discussions were held with UNIBAS regarding the operationalisation of the envisioned integration and relevant technoeconomic assumptions were shared with an initial focus on the transport sector. UNIBAS will prepare a draft module for integration which will be tested after March 2025.

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3.4 From GEMINI-E3 to GEMINI-E3 EU

3.4.1 Overview

GEMINI-E3 is a multi-country, multi-sector, recursive computable general equilibrium (CGE) model. It simulates all relevant markets, domestic and international, considered as perfectly competitive, which implies that the corresponding prices are flexible in markets for commodities (through relative prices), for labour (through wages), and for domestic and international savings (through rates of interest and exchange rates). Time periods are linked in the model through endogenous real rates of interest determined through the balancing of savings and investment. Countries and regions in GEMINI-E3 are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses. There is one notable—and usual—exception to this general assumption of perfect competition, which concerns foreign trade. Goods of the same sector produced by different countries are not supposed to be perfectly competitive; they are considered as economically different goods, more or less substitute according to an elasticity of substitution known as the Armington assumption. The main outputs of the GEMINI-E3 model are on a country and annual basis and include: carbon taxes, marginal abatement costs and prices of tradable permits (when relevant), effective abatement of CO_2 emissions, net sales of tradable permits (when relevant), total net welfare loss and components (net loss from terms of trade, pure deadweight loss of taxation, and net purchases of tradable permits when relevant), macro-economic aggregates (e.g. production, imports and final demand), real exchange rates and real interest rates, and data at the industrial level (e.g. change in production and in factors of production, and prices of goods).

The development of the new version of GEMINI-E3 aims to improve the granularity and empirical consistency of the model. First, the databases will be updated, mainly from the upgraded GTAP and GTAP Power versions. Updating other economic sources such as transfer, taxes, and other macro indicators is based on various sources such as IMF, IEA, and OECD. Second, GHG emissions coverage will be expanded to include local air pollutants. This expansion contributes to a more comprehensive assessment of the ancillary benefits of mitigation policies in standard CGE modelling. Integration of air pollutants in the new version of the model is based on the development of the air pollution database for GTAP that covers emissions for nine substances.

The former EU 27+UK regions will be divided into nine individual countries (including the UK) and six aggregated regions (see **Error! Reference source not found.** and **Error! Reference source not found.**). This reclassification is based on historical data evaluation and statistical analysis. There will be 24 countries/regions represented in the new version of the model. We will use the same approach for sectoral reclassification by focusing on essential sectors in climate economics while keeping concordance with IPCC classification and its reporting standard. This includes the Emissions Trading Scheme (ETS) that covers electricity generation, energy-intensive industries (EII), petroleum production, and the newly added aviation sector. In the original version, fossil fuels are represented by coal, oil (petroleum as its product), and natural gas sectors following the IPCC. Natural gas distribution is defined as a separate sector to distinguish between gas-producing and importing countries. Hydrogen will be introduced as part of energy sectors, along with the better representation of bioenergy (biomass and biofuel) (see Figure 26). Manufacture group will also be reclassified based on the IPCC classification of manufacturing industries in line with the International Standard Industrial Classification of All Economic Activities (ISIC) Vol. 4 (United Nations, 2008).

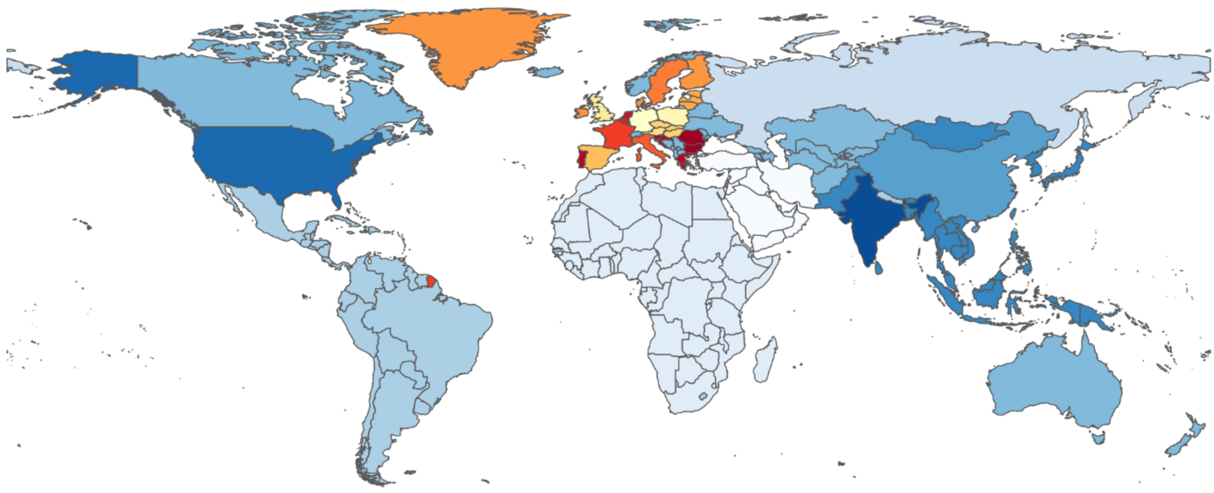

Figure 28. Regional disaggregation in GEMINI-E3 EU.

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.

Table 23. GEMINI-E3 EU Regional description

European Union countries/ regions	Non-EU countries/ regions
Germany (**DEU**)	United Kingdom (**GBR**)
France (**FRA**)	United States of America (**USA**)
Italy (**ITA**)	China (**CHI**)
Spain (**SPN**)	India (**IND**)
Netherlands (**NLD**)	Russia (**RUS**)
Sweden (**SWE**)	Central South and America **(CSA)**
Poland (**POL**)	Middle East (**MID**)
Belgium (**BEL**)	Africa (**AFR**)
Croatia, Cyprus, Greece, Portugal, Malta (**EU1**)	Rest of Asia (**ASI**)
Austria, Luxembourg (**EU2**)	Rest of the Word (**ROW**)
Czech Rep., Hungary, Slovak Republic (**EU3**)	
Bulgaria, Romania, Slovenia (**EU4**)	
Estonia, Latvia, Lithuania (**EU5**)	
Denmark, Finland, Ireland (**EU6**)	

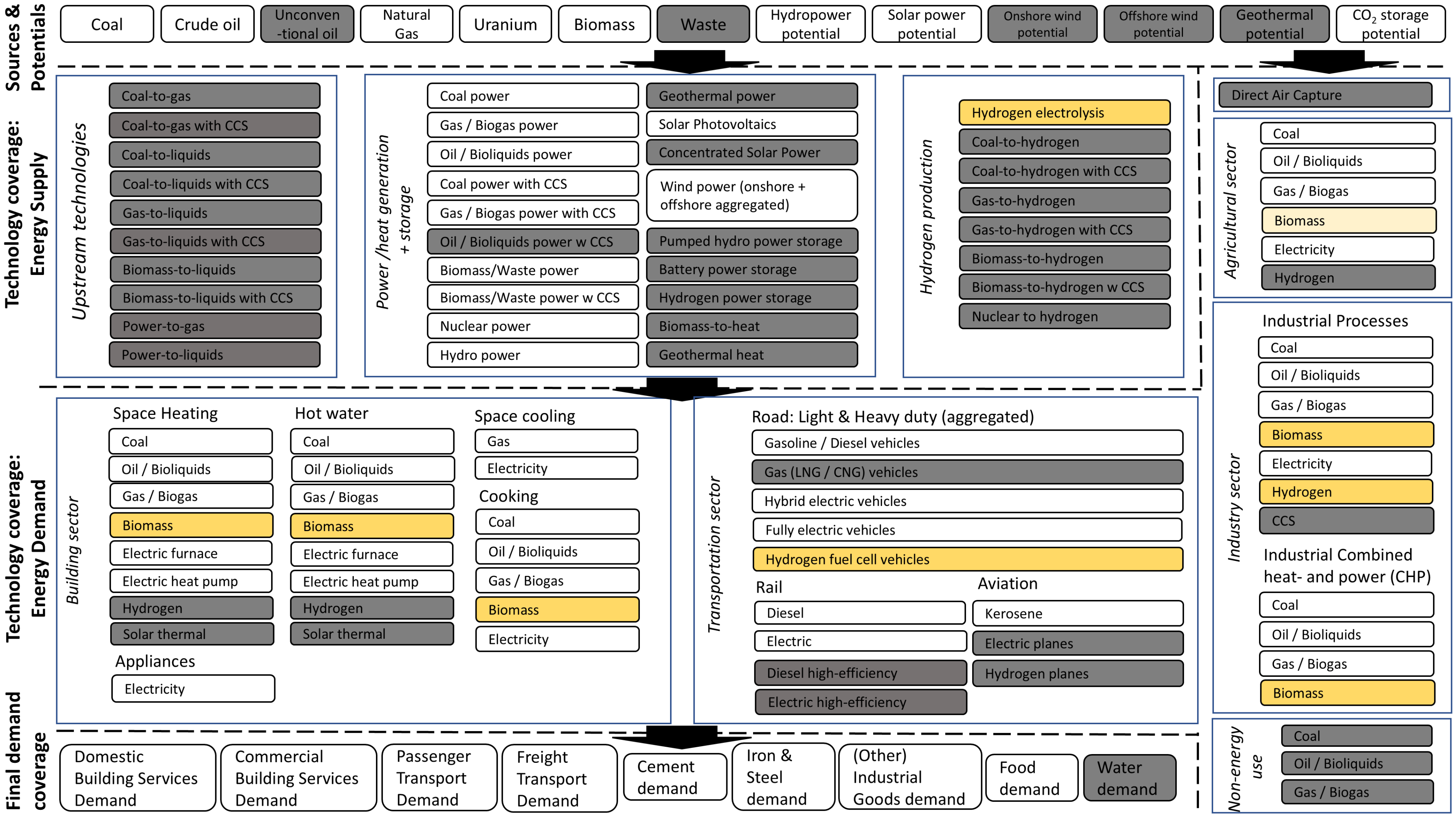

Figure 29. Summary of the resource, technology, and end-use demand representation in GEMINI-E3-EU.

White boxes indicate features already part of the original model. Grey boxes indicate features not part of the core nor the updated model. Dark yellow boxes indicate the features that will be, and light-yellow boxes features that might be (still to be decided), explicitly developed for GEMINI-E3-EU in the DIAMOND project, and which are not in the core version of the model. Note that detailed market coverage in GEMINI-E3 is not included in the figure.

3.4.2 Model development timeline

Planned model updates and expansions aim to enhance GEMINI-E3's level of climate policy insights and improve empirical consistency with other IAMs. In addition to updating the main database, this includes developments on three critical elements. First, from a regional disaggregation perspective, the EU region in this updated version will be further broken down into the EU Member State level, improving the model's granularity and accuracy by linking to national results and allowing analysis of implementation challenges at the Member State level. Second, emissions coverage will be expanded in the new GEMINI-E3 EU model. The current version represents all GHG emissions; but upgrading local air pollutants remains critical to improving empirical consistency in the model's projections. These upgrades will enable integration of the health impact of these air pollutants, contributing to a more comprehensive assessment of ancillary benefits of mitigation policies in standard CGE modelling. The last element lies in innovative decarbonisation: technology options will be enriched, to improve empirical tractability by particularising to technological options in hard-to-abate sectors (MS8). Modules will then be developed to enhance capacity for household heterogeneity, climate feedback, and labour dynamics, in Tasks 4.3-4.5 to accompany the core model development in Task 3.4 (D3.6). A detailed timeline of the current progress and future plans of GEMINI-E3 EU is summarised in Table 24.

Table 24. Timeline of the GEMINI-E3 EU progress and finalisation

Tasks	2023				2024				2025				2026			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Definition of regional and sectoral classification																
Economic database update																
Biofuel specifications design and data collection																
Hydrogen specifications design and data collection																
New nesting structure design and implementation																
Beta GEMINI-E3 version coding																
GHG modeling																
Air Pollutant modeling																
Final GEMINI-E3 version without interlinkage defined in WP4																
Testing and validation of the final version																
Reference scenario and scenarios development																
Model documentation																
Interlikages with other modules (WP4)																
Open Sourcing																

3.4.3 Meetings (internal modelling team and external)

In addition to the General Assembly Meeting held in Lausanne from May 23 to 24, 2024, the GEMINI-EU team organised six bilateral meetings between January 2024 and November 2024. Two meetings were conducted in the context of Work Package 2 (WP2), one meeting focused on Model Development under Work Package 3 (WP3), and three meetings were initiated to support linkages for Work Package 4 (WP4). Details of the meetings are as follows:

29 January 2024, **(EPFL & ETH Zurich – WP2)**: The meeting centered on inclusive stakeholder engagement, emphasizing experiences and expectations concerning DIAMOND's participatory and transdisciplinary approach. The objective is to support and facilitate the mapping of stakeholder actions to tasks as the next step in the engagement process, including on the expectation of the new version of the model.

1 February 2024, **(EPFL & MU – WP4):** Discussions addressed potential strategies and action points for advancing collaboration in 2024, specifically concerning the development of labour coupling compatible with the GEMINI-EU model. Both groups agreed to initiate work on an empirically validated model to quantify labour transition costs within GEMINI-E3's labour taxonomy, focusing on skill levels and occupational classifications (at a minimum, high/low skilled, green/brown, and white/blue collar distinctions).

***6 February 2024,* (EPFL & SEURECO – WP3):** This meeting emphasised the importance of representing diverse hydrogen production technologies, including traditional steam reforming (dirty hydrogen), "blue" hydrogen (steam reforming with CCS), and electrolysis, with differentiation of electricity sources (grid, nuclear, or renewable) in the production processes. Deliberations underscored the need to assess the feasibility of integrating these technologies, considering the granularity of each modelling approach. Collaborative efforts will explore potential partnerships with the OMNIA team, either by sharing technical parameters (CAPEX, OPEX, load factor, etc.) used in energy-system models or by coupling the models to gain regional cost insights for these technologies.

***21 February 2024,* (EPFL & NTUA/Project Coordinator – WP2):** The discussion considered the inclusion of an initial beta version of GEMINI in the stakeholder engagement process, alongside a preliminary version of CLEWs-EU.

***11 April 2024,* (EPFL, SEURECO & CESAR – WP4):** This initial meeting explored the integration of household heterogeneity and behavioural factors in climate-related models to enhance the assessment of policy and scenario impacts. To support preliminary work on household heterogeneity, CESAR shared matched EU-SILC/HBS data with EPFL and SEURECO. The modelling teams are currently reviewing documents from CESAR and defining their strategies, with EPFL focusing on applying household heterogeneity by income at the quintile level.

***21 September 2024,* (EPFL, SEURECO, BC3 & CESAR – WP4):** This online meeting aimed to clarify issues related to the database shared by CESAR, particularly addressing discrepancies identified in the files. A comprehensive review is underway to resolve these inconsistencies, with CESAR providing the necessary data support.

3.4.4 Completed development steps

3.4.4.1 Regional and Sectoral New Aggregation

Disaggregation of the former EU 27+UK region aims to improve the granularity and empirical consistency of the new version of GEMINI-E3. Though the representability of each Member State (MS) certainly matters, parsimony modelling principles—especially in a computationally intensive general equilibrium model—require limiting model classifications for a tractable and acceptable computable time. For this reason, all of the 27 EU MS could not be represented as individual countries, but some MSs will still be aggregated as one region (see Table 25). Reclassification of the EU27+UK was conducted through historical data evaluation and statistical analysis using hierarchical clustering. It is based on two main criteria of countries' socio-economic indicators (e.g., GDP per capita, GHG per capita, energy dependency, electricity mix, etc) and climate impact indexes (e.g., heating degree days, coastal area ratio, precipitation average, etc).

New sectoral/industrial aggregation of the upgraded GTAP database focuses on important sectors in climate economics, while keeping the concordance with IPCC classification and its reporting standard. Important sectors as mentioned, covers all under the Emissions Trading Scheme (ETS) which includes electricity generation, energy intensive industries (EII), petroleum production and newly added aviation sectors. Energy classification follows IPCC, where fossil fuels are represented by coal, oil (petroleum as its product) and natural gas sectors. In addition, we are also adding hydrogen as part of energy sectors represented in the model.

Besides energy, sectors included in the 'Manufacture' group are also reclassified based on IPCC classification of manufacturing industries. The IPCC classification follows the International Standard industrial Classification of All Economic Activities (ISIC) Vol. 4. Two sectors under the ETS, the EII and petroleum sectors, are part of this manufacturing group. Non-energy-intensive industries are aggregated as Other Manufacturing Industries in this model. This energy-intensity-based division in manufacturing sectors follows the Industrial Classification from International Energy Outlook. Defining new regional and sectoral aggregation has been accomplished by **March 2023.**

Table 25. GEMINI-E3 EU Sectors description

NO	Sectors	ABB.	GTAP Sectors
S07	Agriculture	AGRI	pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh
S01	Coal	COAL	coa
S02	Oil	OIL	oil
S03	Natural Gas	NGAS	gas, gdt
S06	Hydrogen	HYDR	-
S05	Electricity (Power Generation)	ELY	ely
S04	Petroleum	PETR	p_c
S08	Energy Intensive Industries	EII	oxt, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp
S09	Other Manufacturing Industries	OMNI	cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, fmp, ele, eeq, ome, mvh, otn, omf
S12	Air Transport	AIRT	atp
S10	Land Transport	LANT	otp
S11	Water Transport	WATT	wtp
S13	Services	SERV	wtr, cns, trd, afs, whs, cmn, ofi, ins, rsa, obs, ros, osg, edu, hht, dwe

3.4.4.2 Economic Database Update

The core element of the Global Trade Analysis Project is the GTAP Data Base, a comprehensively documented global database that contains extensive data on bilateral trade, as well as information on transport and trade protection measures (such as taxes and subsidies). The GTAP Database serves as a representation of the global economy and is employed by a vast number of institutions worldwide as a crucial resource for conducting applied general equilibrium (AGE) analysis on matters related to the global economy. The GEMINI-E3 database is mainly based on this new GTAP database, including for GHG emissions. The new reference year of the model is now **2017**. The model database has been updated by GTAP V.11A (Aguilar et al., 2022) in **August 2023**.

3.4.4.3 GEMINI-E3 coding and writing output interfaces

The new databases as well as some other economic sources coming from OECD, IMF and IEA databases have been harmonised and processed by different GAMS programs and Excel sheets to create a harmonised database that can be used by GEMINI-E3. The Beta version of the model that is based on the specifications used into the PARIS-REINFORCE project (see the description of this version in I^{2}AM PARIS platform[10]) has been created into the GAMS

[10] https://www.i2am-paris.eu/detailed_model_doc/gemini_e3

software environment and a reference scenario has been simulated. This step has several objectives:

1. To test the consistency of the database;
2. To check the solving property of the model;
3. To serve as a base for writing a new output interface that creates Excel templates;
4. To serve as a base for writing the new specifications of the model that are planned within the DIAMOND project.

This step was also advertised through a video in a LinkedIn post.

The GEMINI-E3 coding and writing output interfaces has been accomplished by end of **October 2023.**

3.4.4.4 Greenhouse Gases (GHG)

The latest version of the GTAP database provides estimated data of CO_2 by fuel and by user for each country/ region, for both combustion and non-energy combustion sources. The database also includes non-CO_2 greenhouse gas emissions - CH_4, N_2O, and F-gases. Following no emissions update from CEDS and PRIMAP that previously used as database for GEMINI-E3 (2014 baseline year), the new GEMINI-E3 EU adopt emissions GTAP database of year 2017.

To keep the consistency with previous classification of emission sources of CEDS (for CO_2 and CH_4), PRIMAP (for N_2O) and EPA (for F gases) which were designed in line with the IPCC classification of AR6, the updated GHG emissions of GTAP are mapped to this classification. For this purpose, we refer to GTAP Memorandum No.32, Development of the Non-CO_2 GHG Emissions Database for GTAP V.11A, Annex II: Definition, Units and Conventions of IPCC AR6 (IPCC, 2022). This mapping links emissions agents (GTAP sectors) and emission drivers (factors affecting the emissions level ex: output production, endowment used, or input used) to the previous related IPCC classification with previously estimated Marginal Abatement Cost. Defining the GHG definition and its implementation into GEMINI-E3 has been accomplished by end of **October 2023**.

3.4.4.5 Biofuel

Following the database update in the new version of GEMINI-E3, biofuel used in electricity generation is updated to year 2017, from the latest version of GTAP Power 11. As in previous version, GTAP Power 11 biofuel is still aggregated in Other-Sector. We disaggregate biofuels with the same methodology as in the previous version of GEMINI-E3. First, we get the percentage of biomass power plant from total power generation for each country. This share is obtained from BP Statistical Review 2022, and then aggregate it into the 24 regions of GEMINI-E3. Several adjustments are made to ensure that the principle of market clearing is applied, i.e., demand of biofuel power plants equal to its supply.

In addition to updating biomass, the new stage of model development is to consider the other uses of biomass/biofuel in the model. For this, we refer to IEA statistical data of 2017. The statistics represents 16 energy type for over 170 countries and regions and report aggregated number of biofuel and waste. To get the value biofuel energy balances, we deduct the waste components from the same source. The data is then aggregated. The aim is to obtain the data of total supply and total demand (intermediate goods and final consumption) of biofuel. Data collection on biofuel has been finalised in **October 2023**.

3.4.4.6 New CES Nesting Structure

The introduction of new energy inputs (biofuel and hydrogen) as well as a better representation of energy substitution within deep decarbonization scenarios require to reconsider the CES nesting structures for the production and consumption that we included in the former versions of GEMINI-E3. The design of this new nesting CES structure consider the work done within the DECARB project funded by the Swiss Federal Office of Energy where these two energy inputs are represented. This nesting CES structure details the energy that is used for transportation purpose, to the other uses (heat in industrial processes and space heating and cooling in buildings). Hydrogen can be used in industrial process and in transportation. Finally, the model assumes that biomass/biofuel can be used in industrial processes as well as in transport by blending biofuels with petroleum products. This new nesting structure is represented **Error! Reference source not found.**.

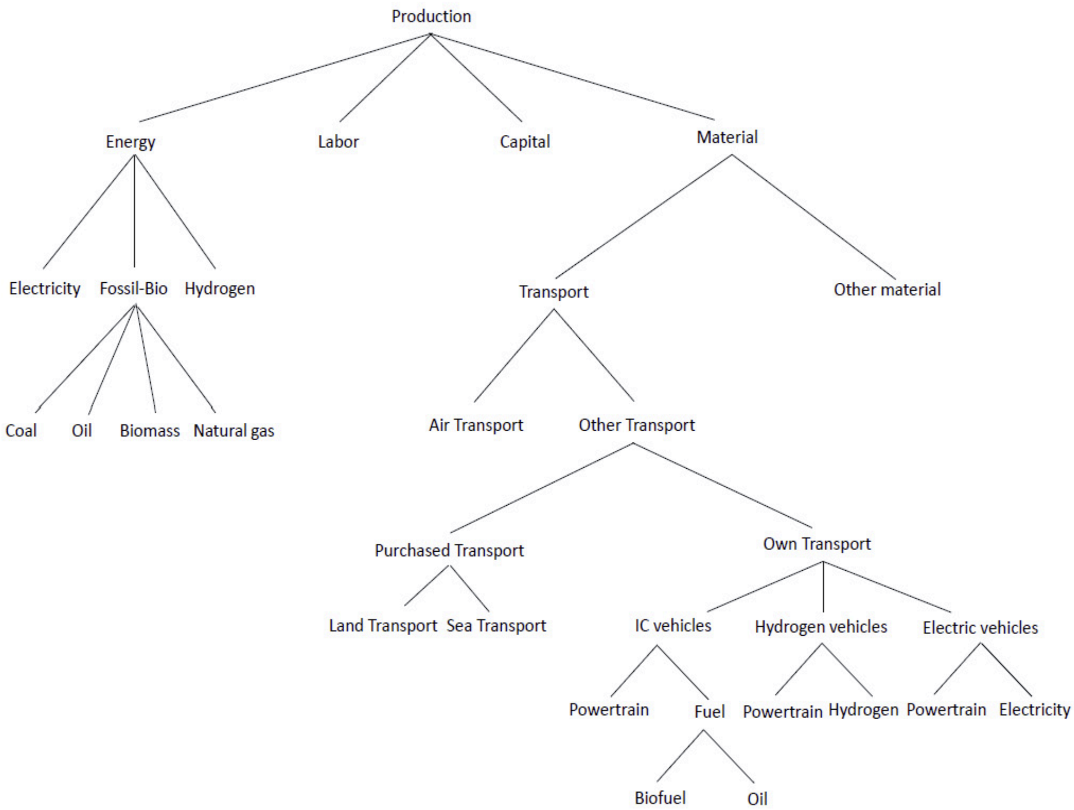

Figure 30. New nested CES production structure – Industrial sectors (GEMINI-E3)

This implementation of the new nesting CES structure has been finalised by **December 2023**.

3.4.5 Planned development steps

3.4.5.1 Air pollutants

With such a high magnitude of air pollution-related externalities, implementing more stringent environmental policies (e.g., emission taxation or energy subsidies elimination) may result in significant co-benefits. While CO_2 and non-CO_2 GHG emissions are usually well represented in most global economic databases, air pollution flows are not included in many cases. The new version of GEMINI integrates the pollution database for the GTAP Data Base Version 11A. Emissions for nine substances are reported in the database: black carbon (BC), carbon monoxide (CO), ammonia (NH_3), nonmethane volatile organic compounds (NMVOC), nitrogen oxides (NOx), organic carbon (OC), particulate matter 10 (PM_{10}), particulate matter 2.5 ($PM_{2.5}$) and sulphur dioxide (SO_2). The dataset covers five reference years – 2004, 2007, 2011, 2014 and 2017. EDGAR Version 5.0 database is used as the main data source. To assist with emissions redistribution across consumption-based sources, the IIASA GAINS-based model and IPCC-derived emission factors are applied. Each emission flow is associated with one of the four sets of emission drivers: output by industries, endowment by industries, input use by industries and household consumption. In addition, emissions from land use activities (biomass burning) are estimated by land cover types. These emissions are reported separately without association with emission drivers.

Current Progress and Ongoing Task:

By June 2024, air pollutant data had been aggregated in alignment with the model's new structure, and a basic integration of air pollutants using a simplified modelling technique was successfully completed **by August 2024**.

However, recognising that the drivers of air pollutants differ significantly across regions—due to factors such as industrialisation levels, economic activities, and policy frameworks—a comprehensive examination of emission control standards across various sectors and regions is essential to enhance the precision and reliability of the model's results.

Consequently, a dedicated research effort is underway to analyse heterogeneity in emission control measures, considering the specific characteristics of different pollutants, industrial sectors, and geographic regions. Due to the wide scope of pollutant types and limited existing literature on modelling approaches, the completion of this task has been revised, with finalisation anticipated by **Q1 of 2025.**

3.4.5.2 Hydrogen

Gronau et al. (2023) emphasise that few macroeconomic models incorporate hydrogen as an energy carrier to evaluate the macroeconomic impact of hydrogen-powered aviation, specifically through a Computable General Equilibrium (CGE) model. Similarly, Sylva et al. (2014) explore the potential of hydrogen-fueled vehicles by integrating a CGE model with an energy simulation model focused on road transportation. Gilmore et al. (2023) examine the energy mix and welfare implications of a deep decarbonization pathway that includes net-negative emission technologies. They employ Environment Canada's Multi-Sector, Multi-Regional CGE model in conjunction with the GCAM model, considering hydrogen technologies alongside negative emissions solutions such as Bioenergy with Carbon Capture and Storage (BECSS) and Direct Air Capture (DAC).

In the GEMINI-E3 model, we introduce a new "hydrogen sector," which produces hydrogen through water electrolysis, with production costs informed by the International Energy Agency's report, *The Future of Hydrogen* (IEA, 2019). These cost estimates are also utilised in both the GCAM and TIMES-based models (such as OMNIA). While we assume a uniform cost structure in USD across all regions, electricity prices are region-specific and are calculated within the model. Notably, electricity costs constitute the primary component of hydrogen production costs.

Current Progress and Ongoing Task:

1. Data collection on hydrogen and design of the integration of this new sector into GEMINI-E3 has been accomplished in **September 2023**.
2. Following bilateral discussions with SEURECO, we recognise the need for collaborative efforts to determine the most effective approach for representing hydrogen within the GEMINI-E3-EU model and the NEMESIS model. This endeavour may involve collaboration with the OMNIA team to facilitate parameter sharing or establish linkages.
3. Additionally, several areas require further examination, including methodologies for integrating hydrogen data into regional statistical frameworks, defining mechanisms for representing international hydrogen trade dynamics, and accurately modelling the hydrogen production supply chain. Given the relatively nascent state of hydrogen technology and the unique challenges associated with this topic, this project remains ongoing, with completion anticipated by **Q2 2025**.

3.4.5.3 Interlinkages within WP4

Following the objectives of WP4 to expand IAM representation of real-key world process our team has participated in a two-day workshop held on 21- 22 September 2023 in Maastricht, Netherlands, with the primary objective of exploring the feasibility of establishing a soft linkage of GEMINI-E3 with the modules developed by the participating WP4 team. This initiative aims to integrate key components of our economic landscape, including the financial sector, labour market, and heterogeneity in final demand. The workshop provided a valuable platform for collaborative discussions and knowledge exchange, allowing us to engage with experts in the field and gain insights into potential synergies and challenges. Through these deliberations, we have taken significant strides toward enhancing the integration of GEMINI across diverse economic domains, paving the way for more robust and comprehensive analyses in the future. Our focus was on seamlessly incorporating heterogeneity in consumer behaviour and representing diverse skill sets within the labour force through this integration.

Households Heterogeneity

The deliverable emphasises the critical role of incorporating household heterogeneity and behavioural factors in climate-related models to enhance the assessment of policy and scenario impacts. It underscores that household consumption expenditure is essential to achieving a climate-neutral economy, generally accounting for approximately 60% of GDP. While Integrated Assessment Models (IAMs) have historically lacked household heterogeneity, recent models such as EUROGREEN, E3ME, PET, IMAGE-TIMER, and MESSAGE-ACCESS have been developed to address this limitation. The new version of GEMINI model will introduce heterogeneity of Households, assisted by CESAR (Task 4.3) providing microdata of European Union Statistics on Income and Living Conditions (EU-SILC) and Households Budget Survey (HBS). Heterogeneity captured in GEMINI-EU will be based on quintile income level and potential different structures of households.

Current Progress and Ongoing Task:

Data exchange has been maintained between CESAR and EPFL; the completion of the data update, including the full dataset, will rely on the ongoing database management efforts for GCAM, anticipated to conclude by April to May 2025. Consequently, the finalisation of this task is projected for **Q2 2025**.

Modelling household heterogeneity in CGE models faces challenges, particularly with regard to significant negative savings observed in some countries, such as Greece and Poland. Addressing this issue requires careful calibration and consideration of household behaviours that impact savings rates. In response, the EPFL team has initiated discussions and brainstorming sessions with other modelling teams beyond DIAMOND, to conduct an extensive literature review, to refine approaches and enhance model accuracy in representing diverse household financial behaviours.

Labour Dynamic

The discussions and collaborative efforts during the workshop have resulted in a clear pathway for GEMINI to effectively capture the nuances of consumer diversity and skill differentiation within the labour market. UM and EPFL decided that work would begin on an empirically validated model that aids in quantifying labour transition costs within the scope of GEMINI-EU's labour taxonomy. The model will focus on skill levels and occupational types (distinguished at a minimum by high/low skilled, green/brown and white/blue collar designations)

Current Progress and Ongoing Task:

Regular correspondence and online meetings are conducted to share updates on the management of the new labour dataset. Full integration of labour heterogeneity is anticipated to be finalised by **Q2 2025**.

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Linking IAMS to climate/ physical impact models

The previous version of the GEMINI-E3 model has demonstrated its capacity to simulate climate impacts (Gonseth & Vielle, 2019; Vöhringer et al., 2019, Joshi et al., 2016, Labriet et al., 2015), though its focus was primarily on specific regions with deterministic projections of emissions outcomes. The updated model seeks to address greater complexity by incorporating relative confidence levels in climate outcomes, achieved through potential linkages to physically manifested climate change models. This interlinkage aims to strengthen the model's ability to represent the dynamic interconnections between emissions and climate impacts more robustly.

Current Progress and Ongoing Task:

Discussions regarding these enhancements are still in the early stages between EPFL and CICERO. EPFL is currently awaiting input from CICERO regarding the potential climate data and information that can be integrated into the GEMINI-EU framework.

3.4.6 GEMINI-E3 EU References

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3.5 From NEMESIS to NEMESIS-World

3.5.1 Overview

The NEMESIS model (New Econometric Model of Evaluation by Sectoral Interdependency and Supply) is a sectoral detailed macroeconomic model for the European Union (Boitier et al. 2018). It is a system of economic models for every European country (including the United Kingdom), devoted to study issues that link economic development, competitiveness, employment and public accounts to economic policies, and notably all structural policies involving long term effects. The essential purpose of the model is to provide a consolidated framework to realise "Business as Usual" (BAU) scenarios (or other alternative scenarios), up to 30 to 40 years, and to assess the socioeconomic impact of the implementation of all additional policies not already implemented in the BAU. The main mechanisms of the model are based on the behaviour of representative agents: firms, households, government and rest of the world. From the supply side, the model distinguishes 30 different economic activities that produce goods and services through production functions and, to do so, uses production factors: capital, energy, low and high-qualified labour and other intermediate consumption. All these economic activities are interrelated by inter-sectoral exchanges (conversion matrices) and external trades with other EU countries and the rest of the world. NEMESIS includes a detailed energy-environment module that allows the model to deal with climate mitigation policies, at an EU and Member State level. This module enhances the representation of the energy system of each Member State by detailing the energy used (ten different products) by each economic activity but also by households. It also details the power generation sector by allocating electricity production between different technologies through diffusion curves. CO_2 emissions from fossil fuel combustion (FFC) are then calculated from fossil fuel consumption whereas other GHGs (CO_2 from other sources, CH_4, N_2O, HFCs, PFCs and SF_6) are either calculated by other modelled sectors or calibrated on external studies. Furthermore, the model can be relatively easily linked to other tools. In case of a linkage with more detailed energy-system models, NEMESIS is then used to assess the socioeconomic impacts at EU and Member State level, with the energy system modelling being delegated to the detailed energy models.

The NEMESIS - World model is under development, and it will be a new multi-sector multi-region macroeconomic model, inspired by the NEMESIS model (EU version). It will be a system of economic models for 22 regions in the World (see Figure 31 and Table 26), devoted to study issues that link economic development, competitiveness, employment and notably structural policies involving long term effects, such as climate policy. The essential purpose of the model will be to assess the socioeconomic impact of some policies in a scenario comparative analysis framework. The main mechanisms of the model will be based on the behaviour of representative agents: firms, households and governments. From the supply side, the model distinguishes 58 different economic activities that produce goods and services through production functions and, to do so, use production factors: capital, energy, low and high-qualified labour and other intermediate consumption. All these economic activities are interrelated by inter-sectoral exchanges (conversion matrices) and external trades. NEMESIS-World will include a detailed energy-environment module that allows the model to deal with climate mitigation policies. This module enhances the representation of the energy-system of each region by detailing the energy used by each economic activity but also by households. It will also detail the power generation sector by allocating electricity production between different technologies through diffusion curves (see Figure 32).

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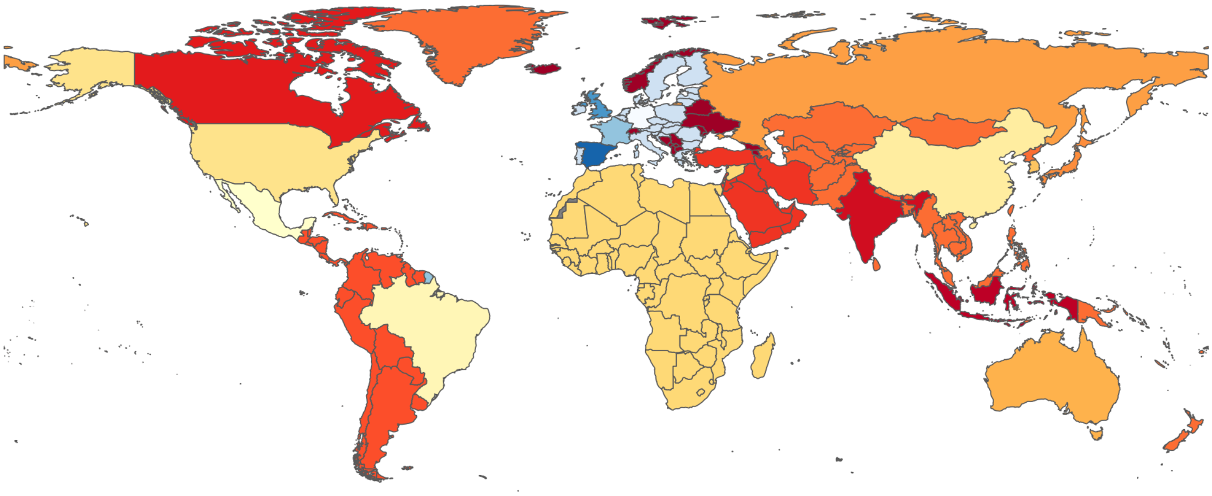

Figure 31. Regional disaggregation in NEMESIS-World

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.

Table 26. Regions in Nemesis-World

European Union countries/ regions	Non-EU countries/ regions
AU	Australia
BR	Brazil
CA	Canada
CN	China
DE	Germany
ES	Spain
FR	France
ID	Indonesia
IN	India
IT	Italia
JP	Japan
KR	South Korea
MX	Mexico
OE	Other EU
RU	Russia
UK	United-Kingdom
US	United States of America
WA	Rest of World - Asia & Pacific
WE	Rest of World - Europe
WF	Rest of World - Africa
WL	Rest of World - America
WM	Rest of World - Middle East

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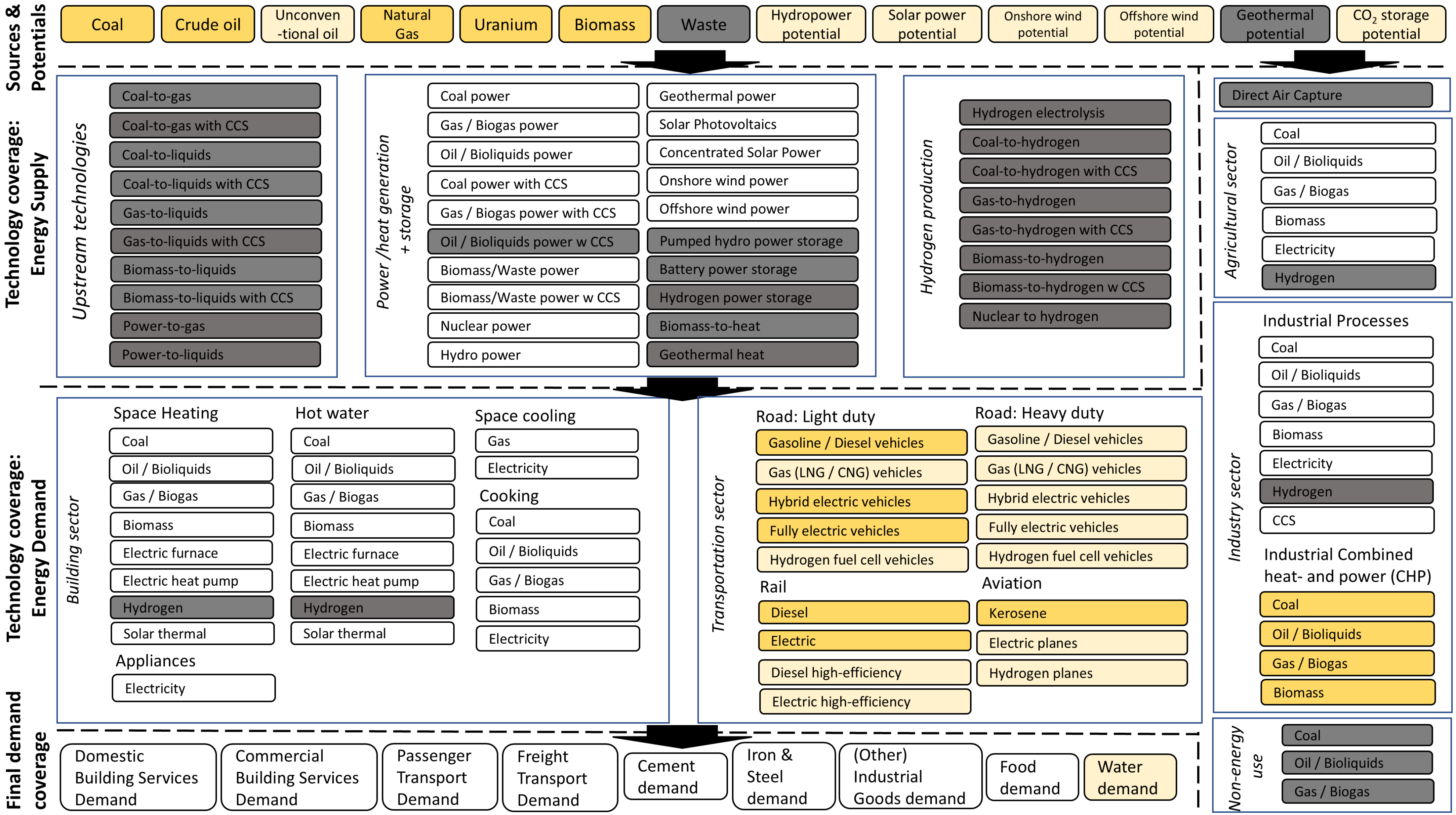

Figure 32. Summary of the resource, technology, and end-use demand representation in NEMESIS-World.

White boxes indicate features already part of the original model. Grey boxes indicate features not part of the core nor the updated model. Dark yellow boxes indicate the features that will be, and light-yellow boxes features that might be (still to be decided), explicitly developed for NEMESIS-World in the DIAMOND project, and which are not in the core version of the model.

3.5.2 Model development timeline

SEURECO has established a general working plan up to November 2025 (M36), with detailed process being presented in Figure 33 organised in four main activities:

1. The model construction *per se* with the following steps (from M2 to M36):
    a. the general modelling approach, started in M1 and finalised in M10
    b. the identification and selection of the software(s) for input data processing, model coding and solving and outputs data processing (M3 to M12).
    c. the general characterisation of the model coverage (geographical, sector, energy product, etc.) (M9-M17)
    d. the coding of the economic model (M16-M25)
    e. The coding of the energy/climate model (M24-M34)
    f. The testing and validation of the model (M24-M36)
    g. The realisation of a reference scenario (M32-36)
2. The data collection, analysis and processing with (M6 – M29):
    a. Taking stock of existing datasets (M6 – M13)
    b. A benchmarking of key databases (M6 – M15)
    c. The processing of the selected databases (M12 – M30)
3. The model's documentation (M13-M36) as well as the strategy to open the model (licensing, files organisation, coding documentation, code repository, etc. – M25-M36) and its implementation (M32-M36).
4. the link with other activities in the DIAMOND project to take advantage of potential synergies in the development and upgrade of other models (WP3) but also on the general modelling improvements (WP4).

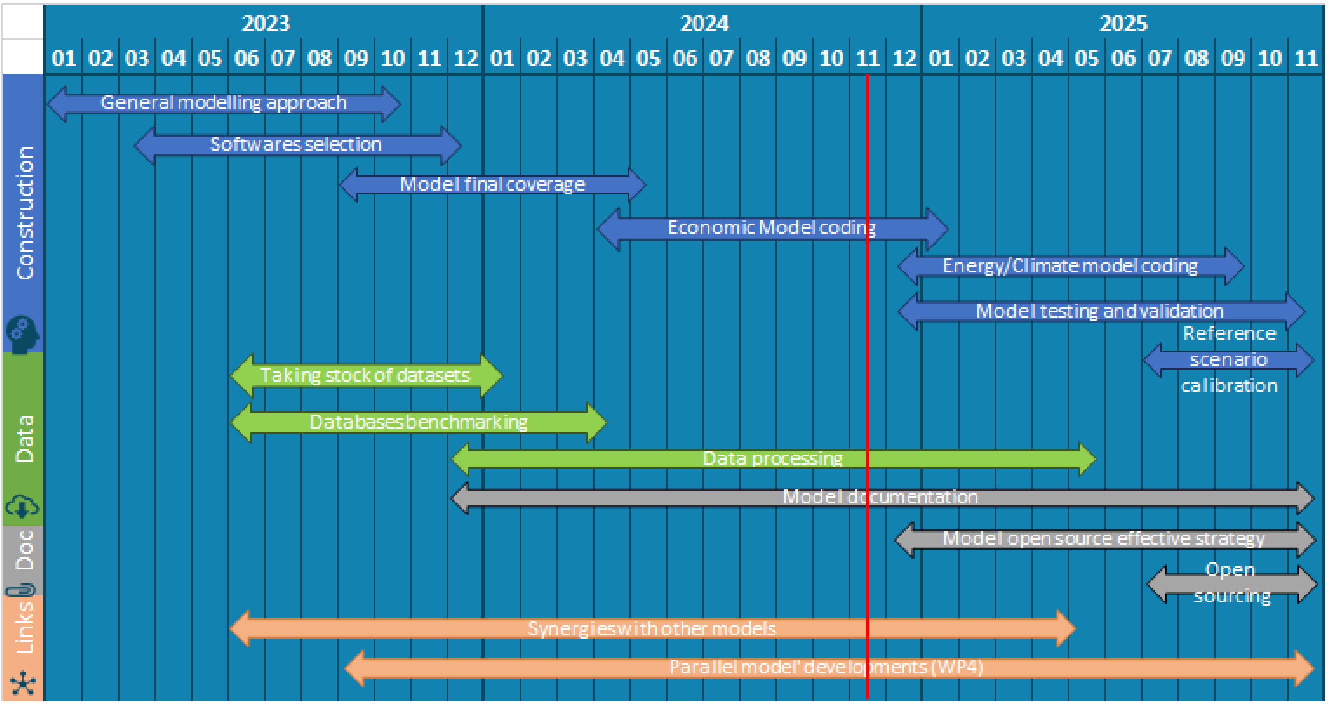

Figure 33. Gantt chart of the construction of the NEMESIS-World model

3.5.3 Meetings (internal modelling team and external)

NEMESIS-World – OMNIA Bilateral workshop - 24th August 2023

E4SMA has presented in detail the dataset under construction and consolidation for the OMNIA model, especially the energy balance sheets. Modellers have discussed in detail the content and the scope of the dataset. Thereafter, they have largely discussed about the dimensions of the OMNIA model (region, sector and energy products) and how the NEMESIS-World model could be designed with similar (or compatible) dimensions knowing the specificities of the economic dataset on which the NEMESIS-World model will be based (such as Multi-Regional Input-Output dataset). E4SMA has detailed all the sectors covered by the OMNIA model (up-stream energy sectors, Industry, Transport, Residential, etc.), going into the details of technologies covered (or to be included) in each sector. Finally, modellers have discussed on how the models, OMNIA and NEMESIS-World, could support each other. The first point will be that the OMNIA modelling group (E4SMA, UCL and Imperial) will share with SEURECO and the DIAMOND consortium the data used in the model as well as the technical parameters whereas, SEURECO proposed to share also its preparatory work, for the GHG emissions calibration, and envisage the implementation of a soft linkage later when both models will be operational. Both teams agreed to continue sharing knowledge and works on relevant issues.

Maastricht Modelling Workshop – 21st & 22nd September 2023

SEURECO has participated in the Modelling Workshop that took place at Maastricht, 21st and 22nd of September 2023. University of Maastricht has presented the work they will engage for the two next years and that will help to improve IAMs and other climate-energy models on the final demand side, the role of finance and of labour in energy transition. SEURECO has expressed its interest for the finance aspects (*e.g.,* endogenous transition channels of risk premium; link technology maturity with risk premium; differentiation of the cost of capital) and labour (e.g., interlinkage between NEMESIS labour demand and external supply module). Furthermore, discussions have taken place with UNIBAS on how to integrate heterogeneity in the modelling results, with SEURECO proposing to enhance the modelling of the consumption module by integrating households' consumption purposes by households' income decile (see thereafter) and then use micro analysis or agent-based modelling to discriminate behavioural parameters by decile of households (e.g., price and/or income elasticities). further linkage opportunities will be checked and pursued in the following period.

Heterogeneity – NEMESIS-World – UNIBAS – 10th of October 2023

UNIBAS and SEURECO had a bilateral call to discuss how the work done by UNIBAS could be integrated into the NEMESIS model. Firstly, UNIBAS has presented its work and discussions have followed. It has been established that the basic way to include works on heterogeneity into NEMESIS is through a differentiation of price and income elasticity by type of households, more complex link will be explored later when the model will be reading and when the work done by UNIBAS will be finalised or at a final step.

Modelling Hydrogen – EPFL & SEURECO – 6th of February 2024

This meeting aimed at discussing on how to model hydrogen production in macro-economic model. The discussions have emphasised the importance of representing diverse hydrogen production technologies, including traditional steam reforming (dirty hydrogen), "blue" hydrogen (steam reforming with CCS), and electrolysis, with differentiation of electricity sources (grid, nuclear, or renewable) in the production processes. Deliberations underscored the need to assess the feasibility of integrating these technologies, considering the granularity of each modelling approach. Collaborative efforts will explore potential partnerships with the OMNIA team, either by sharing technical parameters (CAPEX, OPEX, load factor, etc.) used in energy-system models or by coupling the models to gain regional cost insights for these technologies.

Households' heterogeneity - EPFL, SEURECO & CESAR – 11th of April 2024

This initial meeting explored the integration of household heterogeneity and behavioural factors in climate-related models to enhance the assessment of policy and scenario impacts. To support preliminary work on household heterogeneity, CESAR shared matched EU-SILC/HBS data with EPFL and SEURECO. The modelling teams are currently reviewing documents from CESAR and defining their strategies, with EPFL focusing on applying household heterogeneity by income at the quintile level.

Energy Data exchanges – SEURECO & E4SMA – 27th of September 2024

Short online bilateral meeting to find out how the energy data produced by OMNIA could be used in practice by the NEMESIS World model. It was agreed that SEURECO should send E4SMA the list of countries, economic activities and energy products covered by its model, so that E4SMA could see how the data could be linked with the OMNIA data. It has been planned to have a follow-up call some weeks after.

Households' heterogeneity data issues - EPFL, SEURECO, BC3 & CESAR – 21st of October 2024

This online meeting aimed to clarify issues related to the database shared by CESAR, particularly addressing discrepancies identified in the files. A comprehensive review is underway to resolve these inconsistencies, with CESAR providing the necessary data support.

3.5.4 Completed model development steps

By November 2024, we achieved several steps: the framing of the general modelling approach, the selection of the software, the coverage of the model and the taking stock of datasets and databases benchmarking, whereas important steps are still ongoing, but with major progress having already been achieved for data processing, and the coding of the economic model. We also started the documentation of the model.

Software selection

For data processing, we decided to use MS Excel and Python (Pandas package), with final data stored in csv files. For the model coding and solving, we decided to use in combination of the IODE software[11] and Python through the python package (pyiode)[12] developed to link IODE with Python.

Data selection and MRIO databases benchmarking

Global Multi Regional Input-Output (MRIO) tables are used as main economic data for the NEMESIS-World. This database has a worldwide coverage and describe the economic exchanges between economic activities and regions (inter-industries exchanges), the final demands by region, the value added and production and, for some, satellite accounts on economic inputs or environment (see general structure of MRIO database in Figure 34).

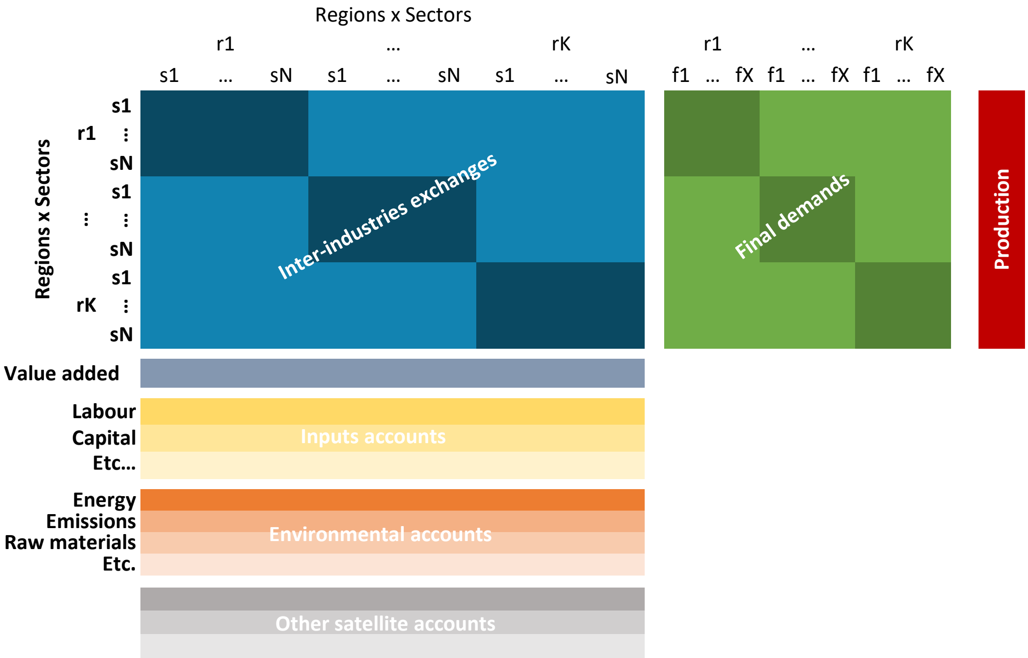

Figure 34. General structure of MRIO databases

We performed a review of existing data on the MRIO database trying to appraise the relevance of each dataset for the NEMESIS-World model, with the final choices being expected in the following period. Table 27 summarises some key characteristics of the reviewed MRIO database.

Following the characteristics of the different databases, we decided to use the EXIOBASE database as the main source of data for the economic part of the model, to be completed by OECD, Eurostat and National statistical officed for detailed inter-industrial investment matrices and for households and government non-financial accounts.

[11] https://github.com/plan-be/iode
[12] https://github.com/plan-be/iode/tree/master/pyiode

Table 27. Summary of global MRIO databases.

Name	Version	Coverage			Satellite accounts		Reference	Link	Note	Own appraisal on data accuracy
		Regions	Sector	Year	Economic inputs	Environment				
ADB	August 23	62 to 71 *(++)*	35 *(+)*	2000-2022 *(+++)*				link		*(+++)*
EMERGING	v2	245 *(+++)*	135 *(+++)*	2015-2019 *(++)*			Huo et al. (2022)	link	New dataset: not yet popular	*(+)*
EORA	full	190 *(+++)*	Differ according to regions: 15990 in total, 80 per region on average *(+++)*	1990-2022 *(+++)*	Employment (by sector, by gender) *(++)*	GHG emissions; Material usage; N and P emissions; Crop and Pasture Area; Crop Area, Production, and Average Yield; Water Use; Nitrogen; Energy (no more updated) *(+++)*	Lenzen et al. (2013)	link	Not open access (fee for business and free for academia)	*(+)*
	eora26	190 *(+++)*	26 *(+)*	1990-2022 *(+++)*	*Idem*	*Idem*	*Idem*	*Idem*		*(+)*
EXIOBASE	v3.8.2	49 *(++)*	163 *(+++)*	1995-2022 *(+++)*	Employment (by sector, skill and gender and in persons and hours) *(+++)*	Energy (up to 2015); GHG emissions (up to 2019); Air pollutants (up to 2011); Land use (2011); Materials (2013); Water use (2011) *(+++)*	Stadler et al. (2018)	link	Cover Rest of the World in 5 regions All EU Member States 17 non-EU individualised country	*(++)*
	v3rx	206 *(+++)*	163 *(+++)*	1995-2015 *(+)*	Employment (by sector, skill and gender and in persons and hours) *(+++)*	Land use (2015) *(+)*	Bjelle et al. (2020)	link		*(+)*
FIGARO	Edition 2022	46 *(++)*	64 *(++)*	2010-2020 *(++)*			Eurostat (2022)	link		*(+++)*
GLORIA	Release 057	164 *(+++)*	120 *(+++)*	1990-2027 *(+++)*	Employment, skill *(++)*	Material; Energy; Biodiversity; Water use; GHG emissions; Air pollutants *(+++)*	Lenzen et al. (2022)	link		*(+)*
OECD-ICIO	Nov. 2021	71 *(++)*	45 *(++)*	1995-2018 *(+++)*			OECD (2021)	link		*(+++)*

In brackets: appraisal of characteristics that are adequate for the NEMESIS-World model

Model geographical and sector coverage

We selected 22 different regions in the World divided as such (see also Table 26 above):

- Europe: France, Germany, Italy, Spain, United-Kingdom, Other EU, Rest of Europe (7)
- America: Brazil, Canada, Mexico, USA, Rest of America (5)
- Africa: Africa (1)
- Asia: Australia, China, India, Indonesia, Japan, Russia, South Korea, Middle East, Rest Asia and Pacific (9)

And we split each individual economy into 59 different economic activities (Table 29), such as:

- Agriculture, forestry and fisheries (4)
- Extraction (4)
- Energy supply (7)
- Manufacturing industry (25)
- Construction (1)
- Transport services (6)
- Other market services (8)
- Non-market services (4)

Additional information on the model detailed coverage is available in the "Model planned and updates and expansions" document.

Table 28. NEMESIS-World economic activities in each in region

01	Agriculture - vegetable	31	Manufacture of motor vehicles, trailers and semi-trailers
02	Agriculture - animals	32	Manufacture of other transport equipment
03	Forestry	33	Other manufacturing
04	Fishery	34	Wastes treatment and recycling
05	Mining of coal	35	Production of electricity
06	Extraction of oil	36	Transmission of electricity
07	Extraction of natural gas	37	Distribution and trade of electricity
08	Other mining	38	Manufacture of gas; distribution of gaseous fuels through mains
09	Manufacture of food, beverage and tobacco	39	Steam and hot water supply
10	Manufacture of textiles, wearing apparel and leather products	40	Water distribution
11	Manufacture of wood and wood products	41	Construction
12	Manufacture of pulp, paper and printing products	42	Trade
13	Manufacture of coke	43	Hotels and restaurants
14	Manufacture of petroleum and nuclear products	44	Transport via railways
15	Chemicals - platics	45	Other land transport
16	Chemicals - fertilisers	46	Sea and coastal water transport
17	Cheminals - others	47	Inland water transport
18	Manufacture of rubber and plactic products	48	Air transport
19	Manufacture of glass	49	Other transport
20	Manufacture of cement and lime	50	Finance
21	Manufacture of other non-metallic mineral products	51	Insurance
22	Manufacture of iron and steel	52	Real estate activities
24	Manufacture of other basic metals	53	Information and communication
25	Aluminium production	54	Research and development
25	Manufacture of fabricated metal products	55	Other business activities
26	Manufacture of machinery and equipment	56	Public administration and defence; compulsory social security
27	Manufacture of office machinery and computers	57	Education
28	Manufacture of electrical machinery and apparatus	58	Health and social work
29	Manufacture of radio, television and communication equipment	59	Other services activities
30	Manufacture of medical, precision and optical instruments		

Data processing

Data processing is still ongoing but, we already achieved important progress. We processed economic data from the EXIOBASE data (using the Python package pymrio)[13]. We calculated inter-industry supply and demand investments in coherence with EXIOBASE data and using information form OECD (2024a), Eurostat (2024a) and some national statistical offices. We also use non-financial accounts statistics from OECD (2024b; 2024c) to collect data on households and government incomes and expenditures.

Coding of the economic model

In Spring 2024, we developed a reduced version of the model for one country (France) and 13 economic activities to test software, data calculation and processing, code structuration, etc. We also did some econometric estimations the following key behavioural equations for this country: aggregated households' consumption and investment and production functions by sector, to be used as benchmark estimates.

[13] https://pymrio.readthedocs.io/en/latest/

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3.5.5 Planned model development steps

3.5.5.1 Interlinkages within WP4

Decile of households' income by income source and by consumption purposes

SEURECO has started a data collection process to enhance the representation of household heterogeneity. Eurostat databases, called "*Income, consumption and wealth*" (Eurostat, 2023a), "*Structure of consumption expenditure by income quintile and COICOP consumption purpose*" (Eurostat, 2023b) and "*Reconciling social surveys with household accounts*" Eurostat (2023c), have been combined to calculate households' consumption expenditures by consumption purposes, households' income decile and the source of income for each households' income decile. SEURECO also developed a module to parse the data into the NEMESIS model (EU version, so far). For now, the module splits the households by income decile with differentiated share of income by source and with aggregated income sources coming from the agent accounts of the model. Furthermore, the module splits the total as well as each individual expenditures by consumption purposes by households' income decile. The module is still in development, and further testing must be done on:

(i) the impacts of different modelling options (e.g., use the total aggregated consumption function as a driver and use shares for total consumption expenditures for each household decile or directly use households' decile total consumption functions, the total being the sum);

(ii) the link of the consumption purpose by households' income decile with the energy module;

(iii) some analytical tests to assess the impacts of some shocks and how these influence the model results;

(iv) the disaggregation of behavioural equations (i.e., parameters) by households' decile

Ultimately, the module will allow the distributional impact assessment of policies impacting income sources and/or relative cost of the different consumption purposes on households.

Economic climate damages by type of impacts

We completed a literature review on the expected economic impacts of 8 different climate impacts (sea level rise, river flooding, drought as well as induced economic impacts on labour productivity, agriculture yields and energy demand and supply, forestry and fishery economic activities) in EU and we estimate climate damage curves for all EU economies for 5 of these damages (SLR, river flooding, labour productivity, drought and, agriculture production). This work has been presented at the ECEMP 2024 Conference.

Labour market

In November 2024, we collected data for EU countries on the composition of national employment by sector, occupation and gender based on Labour Force Survey (Eurostat, 2024b). Due to confidentiality and statistical representativeness thresholds, data availability was weak for low-size countries and/or sectors. We then applied a methodology to fill in the dataset using available information or applying "closest" principle when no information was available. We will then use this information for an end-of-pipe split of the model's employment results by economic activity, occupation and gender. Thereafter, we will engage a collaborative work with UM to compare our labour demand projections with their labour supply projections.

Finance and capital markets

We have improved the modelling of interest rates. We have considered that the interest rates paid by end users are the result of various successive stages. Firstly, Central Banks define short term rate for refining according to their monetary policy that we assumed can be modelled using a Taylor rule. The long-term risk-free rate is then determined and on the top it, a national spread is applied depending on national key macro-financial indicators (government current balance, national public debt, external trade balance, etc.), defining as such the long-term national public bond rate (10 years). Thereafter, this rate is used to define the national interest rate applied to the private sectors that are also differentiated according to sectoral indicators on profitability and financial leverage.

3.5.5.2 Concrete next steps

We identify three-time horizons for the finalisation of the model, out of linkage with WP4.

Next steps – Winter 2024-2025

Up to the end of the 2024 and beginning of 2025, we will:

- Finalise the processing of economic data (December 2024 / January 2025)
- Complete the coding of the economic model (February 2025)
- Define the parameters of the economic model: estimates, calibrations, literature review, etc. (March 2025
- Start collecting and processing energy and GHG emissions data (December 2024 to March 2025)
- Adapting the coding of the economic model for the implementation of the energy module (March 2025)
- Document the model, from data collection to coding (from December 2024 to March 2025)

Following steps – Spring to Summer 2025

Thereafter, during spring and summer 2025, we plan to:

- Finalise the data collection and processing for the energy/climate module (April 2025)
- Code and calibrate the energy/climate module (June 2025)
- Collect and process input data for the model (May 2025)
- Testing and validation of the model (May-June 2025)
- Document the model, from data collection to coding (Milestone 8, May 2025)

Final steps – Autumn 2025

Finally in Autumn 2025, we will finalise the model publication completing outstanding work on previous steps, continue testing the model, run a reference scenario to be used in DIAMOND (with common set of assumptions), finalise the documentation of the model and ensure the implementation of the open-sourcing strategy for the model.

3.5.6 References for NEMESIS World

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3.6 From PROMETHEUS to OPEN-PROM

3.6.1 Overview

OPEN-PROM ("open PROMETHEUS") is the advanced and open-source version of the PROMETHEUS model. The two models are being developed by ICCS-E3M in Athens, Greece. PROMETHEUS is a global energy system model covering in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level. Its main objectives are: 1) Assess climate change mitigation pathways and low-emission development strategies for the medium and long-term 2) Analyse the energy system, economic and emission implications of a wide spectrum of energy and climate policy measures, differentiated by region and sector) 3) Explore the economics of fossil fuel production and quantify the impacts of climate policies on the evolution of global energy prices. The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices and investment to the future covering the global energy system. PROMETHEUS is a fully fledged energy demand and supply simulation model aiming at addressing energy system analysis, energy price projections, power generation planning and climate change mitigation policies. PROMETHEUS contains relations and/or exogenous variables for all the main quantities, which are of interest in the context of general energy systems analysis. These include demographic and economic activity indicators, primary and final energy consumption by main fuel, fuel resources and prices, CO2 emissions, greenhouse gases concentrations and technology dynamics (for power generation, road transport, hydrogen production and industrial and residential end-use technologies). PROMETHEUS quantifies CO2 emissions and incorporates environmentally oriented emission abatement technologies (like RES, electric vehicles, CCS, energy efficiency) and policy instruments. The latter includes both market-based instruments such as cap and trade systems with differential application per region and sector specific policies and measures focusing on specific carbon emitting activities. Key characteristics of the model, that are particularly pertinent for performing the analysis of the implications of alternative climate abatement scenarios, include world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements (increased uptake of a new technology in one part of the world leads to improvements through learning by experience which eventually benefits the energy systems in other parts of the World). PROMETHEUS is designed to provide medium- and long-term energy system projections and system restructuring up to 2050, both in the demand and the supply sides. The model produces analytical quantitative results in the form of detailed energy balances in the period 2015 to 2050 annually. The model can support impact assessment of specific energy and environment policies and measures, applied at regional and global level, including price signals, such as taxation, subsidies, technology, and energy efficiency promoting policies, RES supporting policies, environmental policies, and technology standards.

OPEN-PROM is in essence PROMETHEUS, but enhanced by expanding its regional resolution (from 10 to approximately 40 regions/countries, focusing on major emitters and EU countries, see Figure 35), time horizon (from 2050 to 2100 with annual time steps), sectoral coverage (various industrial subsectors, building types, transport modes including international shipping and aviation), and technology representation: it will include new mitigation options required for the transition to net zero, like hydrogen, synthetic e-fuels, bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), advanced biofuels, carbon capture, utilization and sequestration (CCUS), etc (see Figure 36). These enhancements will be underpinned by the development of a comprehensive and open database, input data framework, ensuring consistency between various datasets related to energy system, emissions, technology data, and policies. Current representation of fossil fuel production and trade will be expanded to simulate trade in new clean energy forms (e.g., hydrogen, synthetic fuels) to allow the analysis of geopolitical implications of the transition to net zero. The model will also be expanded to incorporate abatement cost-supply curves for all major non-CO2 gases by region. Several model features will be redesigned to allow soft linking with the models and methods developed in WP4 and in particular with MAGPIE (on land use), ENGAGE (for circular economy), finance and labour dynamics household heterogeneity (FIDELIO), and electricity (OpenTEPES). All model enhancements will be validated in a series of modelling benchmark scenarios, such as exogenous shocks (Harmsen et al 2021) and standard mitigation scenarios toward net-zero.

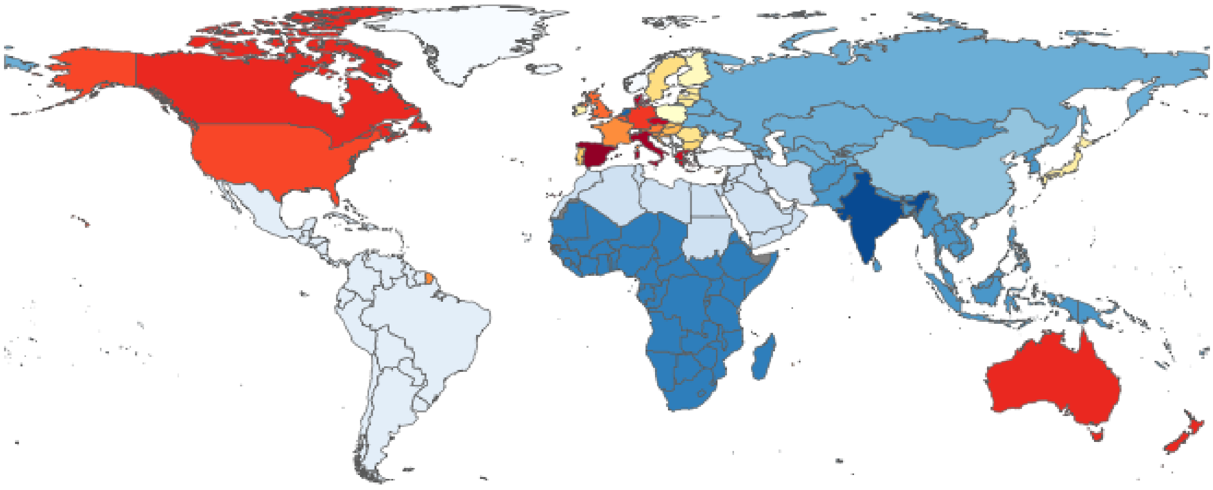

Figure 35. Regional disaggregation in OPEN-PROM.

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 or slightly updated multi-country aggregations.

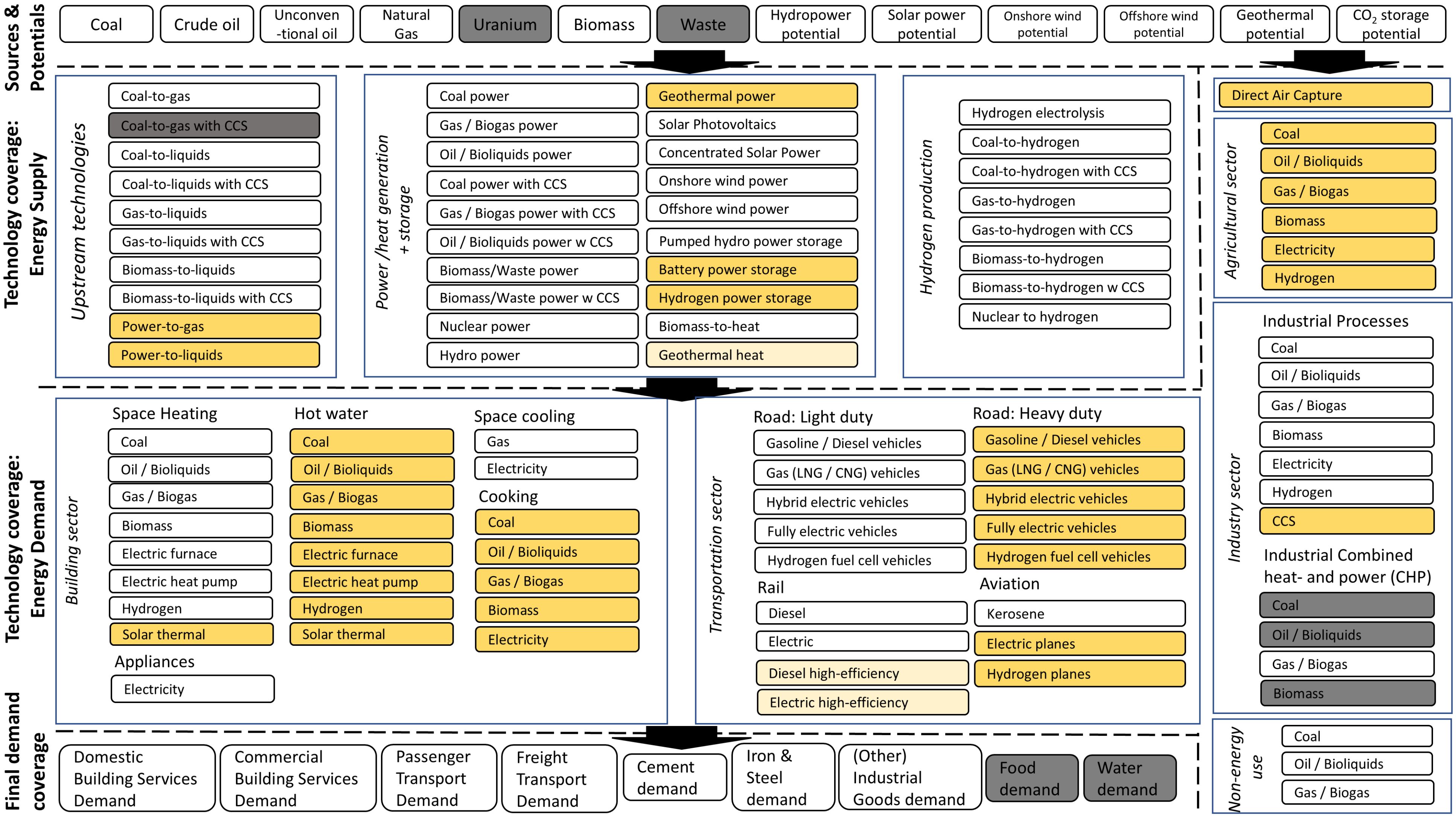

Figure 36. Summary of the resource, technology, and end-use demand representation in OPEN-PROM.

White boxes indicate features already part of the original model. Grey boxes indicate features not part of the core nor the updated model. Dark yellow boxes indicate the features that will be, and light-yellow boxes features that might be (still to be decided), explicitly developed for OPEN-PROM in the DIAMOND project, and which are not in the core version of the model.

3.6.2 Model development timeline

1. Development of a transparent, well documented, and reproducible model (ongoing) M4-M43
2. Transparent, well documented, flexible, and reproducible input data generation (ongoing) M5-M43
3. Extend time horizon to 2100 M6-M14
4. Calibration M13-M25
5. Hindcasting M35-36
6. Validate reference scenario (current policies) M33-34
7. Policy scenarios M18-M23
8. Validation against AR6, etc. M35-36
9. Output routines and dashboards M15-M20
10. Soft-coupling with other models (WP4) M10-M43
11. Scenario/sensitivity/uncertainty analyses M35-M43
12. Modularisation M35-M43

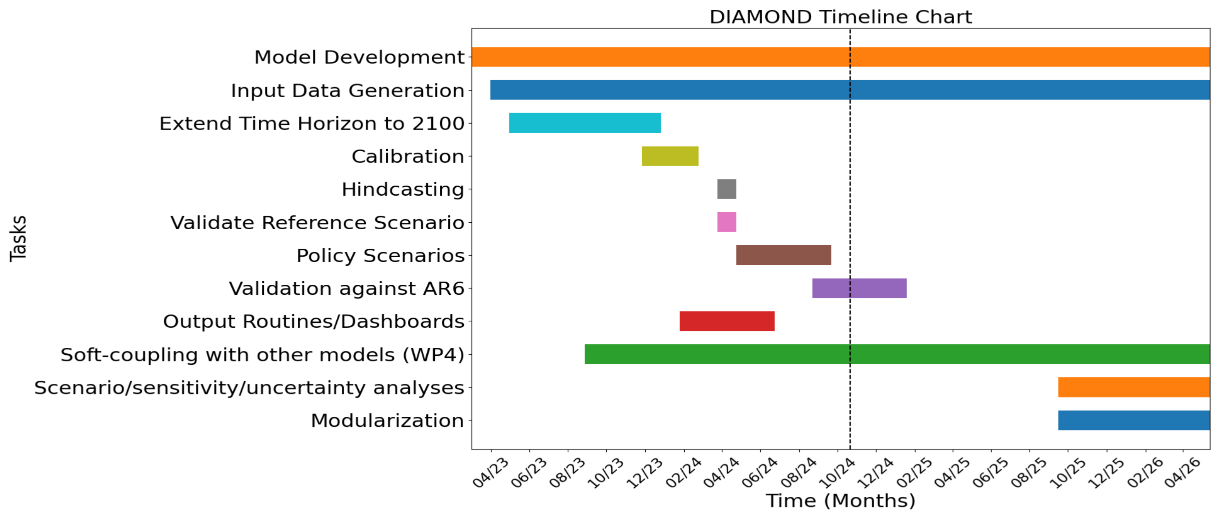

Figure 37. Timeline for the development of OPEN-PROM

3.6.3 Meetings (internal modelling team and external)

The core modelling team of OPEN-PROM holds meetings daily, with the purpose of discussing model development progress, coordinating and assigning tasks to the suitable team members, and allocating resources in an optimal manner. Apart from that, regular meetings with other ICCS/E3M teams take place in an ad-hoc manner to discuss data and modelling issues.

3.6.4 Completed model development steps

- July 2023:
  Start migrating everything to GitHub to make a full open model version;
  Automate data handling and management;
  Defined new regions and sectors;
  Development of new naming conventions;
  Identify list of technologies to be integrated;
  Identify the use of data sources;
- August 2023:
  Create model wiki: https://github.com/e3modelling/OPEN-PROM/tree/main/Tutorials
  Open Github repo: https://github.com/e3modelling/OPEN-PROM
  Developoment of R package "mrprom", for use with MADRat (open input data framework):

https://github.com/e3modelling/mrprom

- September 2023:
  Load data for: Activity in sectors (GEM-E3), Fuel consumption & price (per country, sector, fuel) (ENERDATA);
- October 2023:
  Incorporate more data on technology costs (EU Reference Scenario 2020 of the European Commission);
  Develop model results validation tools against historical and reference data
- November 2023:
  initial version of transport module with 6 transport modes and various consumer groups implemented,
- December 2023:
  Started validating the model results.
- January 2024:
  Completed the initial preparation and processing of input data.
  Completed the power generation module.
- February 2024:
  Added current carbon prices for the default scenario.
- March 2024:
  Testing the validation tool of I2AM PARIS.
- April 2024:
  Discussion on how to approach trade modelling.
  Started working on outprom: a suite of tools containing the OPEN-PROM output routines.
- May 2024:
  Derivation of targets of calibration.
  Testing and developing different calibration approaches.
- June 2024:
  Switched to the updated Shared Socioeconomic Pathways (SSP) scenarios.
- July 2024:
  Constantly improving and updating the model input data.
  Tested the Initial approach for scaling.
- August 2024:
  Tried a second approach for scaling.
  Started working on the power module documentation.
- September 2024:
  Conducted preliminary model runs for the 1.5C scenario.
- October 2024:
  Added a selection mechanism for different scenarios, i.e. NPi default, 1.5C and 2C.
  Added carbon prices for the 1.5C and 2C scenarios.

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3.6.5 Current State of OPEN-PROM

At this point, OPEN-PROM consists of the electricity generation, transportation, and industry modules, based on the PROMETHEUS model architecture. The OPEN-PROM model is currently functional, and generates preliminary results for all regions, until the year 2100. In addition, we have recently implemented a mechanism to run the main model scenarios, i.e. NPi ("National Policies implemented"), and deeper mitigation scenarios, consistent with the 1.5C and 2C temperature targets. Each scenario loads different exogenous carbon prices and consequently outputs the respective pathways for the global energy system. Our focus right now is on model calibration, with the purpose of aligning output with specific climate mitigation targets. Furthermore, we are also validating model results, and comparing them to other leading IAMs, such as REMIND and WITCH. As seen in Figure 40, the model can generate final energy projections for all the main scenarios. The team also included the same projections from other external IAMs, including REMIND-MAgPIE and IMACLIM, for demonstration and comparison purposes. Furthermore, CO_2 emissions projections generated by OPEN-PROM and other IAMs for comparison are also included in Figure 38. It should be noted that OPEN-PROM remains under heavy development, hence the output is only shared to demonstrate its current progress and state of functionality.

3.6.6 Planned model development steps

The calibrated model at the state described in the previous paragraph is expected to be the content of the initial model version to be included in MS8 (July 2025 – M32). Next steps and aspirations regarding the development of OPEN-PROM include:

- Expansion of the fossil fuel production representation by use of fossil fuel extraction curves. M33-M36
- Improvement and expansion of trade representation to simulate trade of new clean energy forms (e.g., hydrogen, synthetic fuels) and to allow analysis of geopolitical implications of the transition to net zero. M33-M38
- Introduction of new mitigation options for the transition to net zero, like hydrogen, synthetic e-fuels, direct air capture (DAC), advanced biofuels, and carbon capture, utilisation and sequestration (CCUS). M33-M43
- Integration of abatement cost-supply curves for all major non-CO2 gases by region. M33-M7
- Improved sectoral coverage (various industrial subsectors, building types, transport modes including international shipping and aviation). M33-M43

Concerning soft-links, discussions are already underway for linking OPEN-PROM with MAgPIE, a leading land use and agricultural model, the MAGICC modelling suite, and the OpenTEPES electricity model, all of which are currently in the planning phase—see also detailed progress of WP4. Similar discussions are currently formulated regarding the potential links between OPEN-PROM and the circularity (i.e., ENGAGE), household heterogeneity, and the financial dimensions.

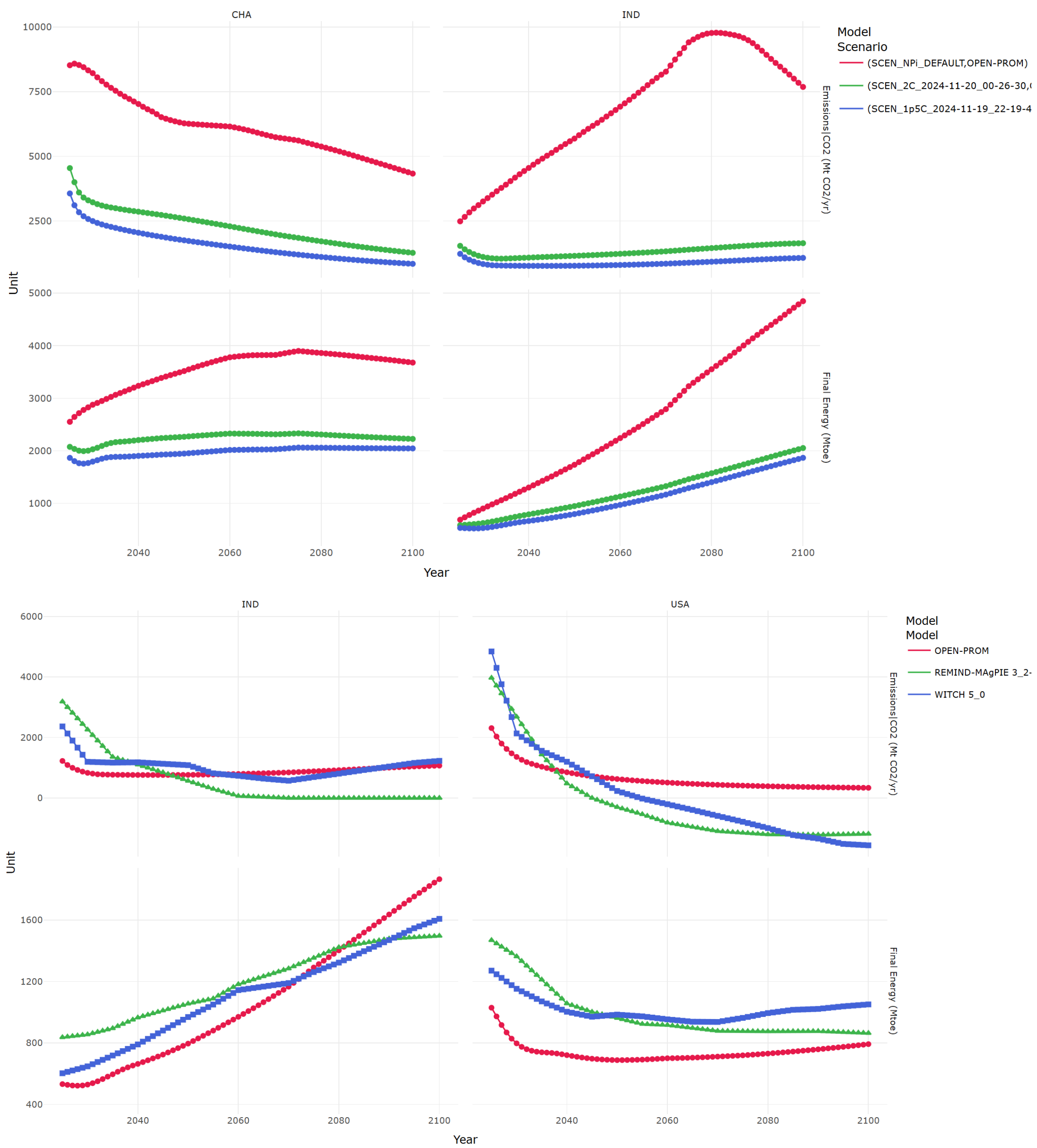

Figure 38. Comparison of preliminary OPEN-PROM pathways for CO2 emissions and final energy with different policy scenarios (upper graph) and with other IAMs for the 1.5C scenario (lower graph)

4 MODEL HARMONISATION PROTOCOL

4.1 Context

To align model development efforts with their potential use in future modelling exercises, including model comparison tasks such as previsioned in DIAMOND WP5 ("Apply & Explore"), but also beyond the project´s deadlines, harmonisation of key model input parameters is recommended. Harmonisation procedures are common in multi-model IAM studies. A clear and transparent harmonisation process promotes a consistent interpretation of divergences in modelling outcomes, isolating different outputs caused by intrinsic model behaviour instead of, e.g., diverse assumptions (Giarola et al, 2021).

While harmonisation is crucial for model outcome interpretation, harmonisation exercises can be labour-intensive, depending on model structures and model solution sensitivity. Therefore, throughout modelling communities, predefined sets of input parameters are defined that avoid repetitive harmonisation procedures, while maintaining a defined set of parameters representing a certain narrative (O´Neill et al, 2017) or following a well-informed and balanced representation of future developments, which may be aligned with national or regional public institutions (European Commission, 2021).

4.2 Relevant harmonisation context in DIAMOND WP3 development exercises

The development of the six multi-sectoral models participating in WP3 of DIAMOND is headed towards different directions (e.g., increasing the regional disaggregation of global models or contrary going from EU-focused to global models), with the aim to participating in a variety of model (comparison) exercises within and also beyond the duration of the project. Therefore, within the context of model development, it is crucial to decide which parameters to harmonise and what values to use. While it may yet be unknown which scenarios to run with each model, adapting to widely accepted harmonised values may ease model preparation for future modelling exercises. Concretely, the regional focus of modelling exercises is important for the selection of these values: global modelling exercises are commonly using a different set of parameters than national or regional (e.g., for the EU) exercises, and require assumptions in distinctive regions to be consistent with one another. Out of 6 models in WP3, 5 are aiming to have a global representation of all regions (all except CLEWs-EU). At the same time, 3 models are specifically focusing on expanding detail within the EU (CLEWS-EU and GEMINI-E3 EU) or Europe (GCAM-Europe). Therefore, despite 2 of them maintaining a global representation, their aim within or beyond the duration of the project may be to participate in EU-specific modelling (comparison) exercises. Also, apart from geographical representation, differences in sectoral representation also affect the relevant parameters that may be subject to harmonisation. For example, Computable General Equilibrium (CGE) or Macro-economic models (e.g. GEMINI-E3 EU and Nemesis-World) may have different exogenous parameters than Partial Equilibrium (PE) models. Meanwhile, models that hard-link a wide set of systems (CLEWs-EU, GCAM-Europe) like energy, land, water and climate, may be subject to harmonising input parameters throughout all these systems.

4.3 Recommended parameter input values

Based on the model differences outlined in the previous section, a wide set of potential input parameter values is shared to modelling teams in the context of task 3.1, with the aim to coordinate model development exercises. It is up to the individual modelling teams which parameters to harmonise or not, including the exact values selected. The prime purpose of this protocol, therefore, is not to oblige any sort of strict harmonisation at this point (which is bound to be updated once specific exercises and their protocols will be pursued within the context of WP5), but to avoid unnecessary (double) efforts in the development stage and future usage stages of each model. Table 1 outlines a set of existing databases that can feed into potentially harmonisable input variables, as well as an explanation of the scope, and potential future updates that can be expected. The table considers the specific needs of teams with different focus within the model development strategy, notably providing sources for both global and regional (e.g., at the EU level) datasets. All referenced datasets are uploaded to DIAMOND´s SharePoint folder here.

Table 29. Relevant potential input data for WP3 model projections. All data is available through DIAMOND SharePoint

Dataset	Input parameters covered	Geograp. focus	Projected years	Ref.	Expected update
SSP Basic drivers v3.1	For all 5 SSP pathways, projections for: - Population by gender, age group and education level - GDP PPP - Urbanisation (separate file)	Global (by individual country)	Historical data for 1950/1980 to 2020, projections 2025-2100	[1]	No update expected (recent release)
SSP Income Inequality projections	For all 5 SSP pathways, projections for: - Gini coefficients - Poverty headcounts	Global (by individual country)	2011-2100	Rao et al (2019)	Unknown, possibly 2025
Qualitative SSP assumptions	Qualitative SSP assumptions for energy demand, supply and conversion, and agriculture and land use (tables A1-A5) for relative input definitions per SSP.	Global (by low, medium, high income)	N/A	O´Neill et al (2017)	No update expected
IEA GEC Model technology dataset	For 3 levels of climate action: - Power technology costs and capacity factors - Costs of other mitigation technologies - Fossil fuel price projections (oil, coal and natural gas)	Global / USA, EU, China, India	2023-2050	IEA (2024)	2025
IMF WEO Oct. 2024	Short-term GDP growth projections	Global (by individual country)	1980-2029	IMF (2024)	April 2025
EU Ageing Report 2024	- Population by gender, age group, and participation rate - GDP growth rate, labour productivity, and interest rate	EU (by individual country)	Projections 2022-2070 (Eurostat for hist. data)	EC (2023)	2027

EU Reference Scenario	Reference scenario results [2] for: - Energy, transport and GHG emissions - Non-CO2 emissions and air pollution - LULUCF Technology assumptions for: - Energy technologies - Transport technologies	EU (results by country, tech assumptions for entire block)	2005-2050 for results, 2020 ("current") to 2050 for technology projections	EC (2021)	First half of 2025
Eurostat Energy Balances	Energy balance data for extensive list of energy commodities and sectors.	Most European countries (by country)	1990-2022	[3]	February 2025 (to include 2023 as last estimate)
[1] https://data.ece.iiasa.ac.at/ssp/#/workspaces [2] May be useful for partial calibration of values that are exogenous in some models [3] https://ec.europa.eu/eurostat/cache/infographs/energy_balances/enbal.html					

Furthermore, for historical emissions of all GHGs and pollutants, there are two well covered collections with emission estimates by country, fuel, sector, and gas.

- Emissions Database for Global Atmospheric Research (EDGAR), projections for 1970-2023: https://edgar.jrc.ec.europa.eu/emissions_data_and_maps (Crippa et al, 2024)
- Community Emissions Data System (CEDS), projections for 1750-2022: https://zenodo.org/records/12803197 (Hoesly et al, 2018)

Finally, for the preparation of models to specific policy modelling (as well as potentially preparing models to represent certain policies), this protocol provides a list of climate policies by major economies as well as NDC and long-term (net-zero) targets for the majority of countries, through the DIAMOND Sharepoint.

4.4 Soft recommendations by November 2024 for model harmonisation (anticipating future WP5 and beyond-project use of models)

- Models participating in global studies:
    - Calibrate representation of at least SSP2, ideally all SSPs in as many input parameters as possible (population and income at the least, further parameters where relevant, potentially through adaptions based on qualitative SSP assumptions). Overwrite GDP growth rates up to 2029 by IMF projections.
    - For technology cost and fossil fuel prices, potentially follow latest IEA assumptions as representative for SSP2. Map projections of regions beyond USA, EU, China and India to either one specific or a mix of projections for these countries.
- Models participating in EU-specific studies:
    - Calibrate representation of 2024 Ageing Report projections for population and GDP. Overwrite GDP growth rates up to 2029 by IMF projections.
    - Adapt technology costs to projections in Reference Scenario, as well as other input parameters

that are results from the reference scenario, where relevant (potentially wait for update in early 2025 to avoid double work, or use current values to set up structure, and adapt values in 2025).

- Models participating in both global and EU-specific studies:
    - Option 1 (if main focus is either on global or on EU depending on study): maintain model with 2 different versions of calibrated input data, one based on SSPs and another based on EU-specific projections, and toggle between versions depending on the study focus.
    - Option 2 (if main focus is on EU, but global impacts/context matter): use EU-specific projections for EU countries and SSP2 projections for ROW, which are relatively aligned with EU Ageing Report. Potentially use comparable techno-economic projections like IEA.
    - Option 3 (if ability to compare socioeconomic narratives is crucial): use SSPs and IEA cost estimates, also for EU countries.

4.5 SSP-Ageing Report comparison

To compare consistency between the updated SSP database and the latest EU Ageing Report projections, Figure 39 provides a comparison of population and GDP projections between all scenarios. This comparison shows that, despite a short-term mismatch in population projections, overall, the EU Ageing Report projections are quite coherent with SSP2 projections on the EU-27 level. Nevertheless, for the individual member state level, larger inconsistencies exist.

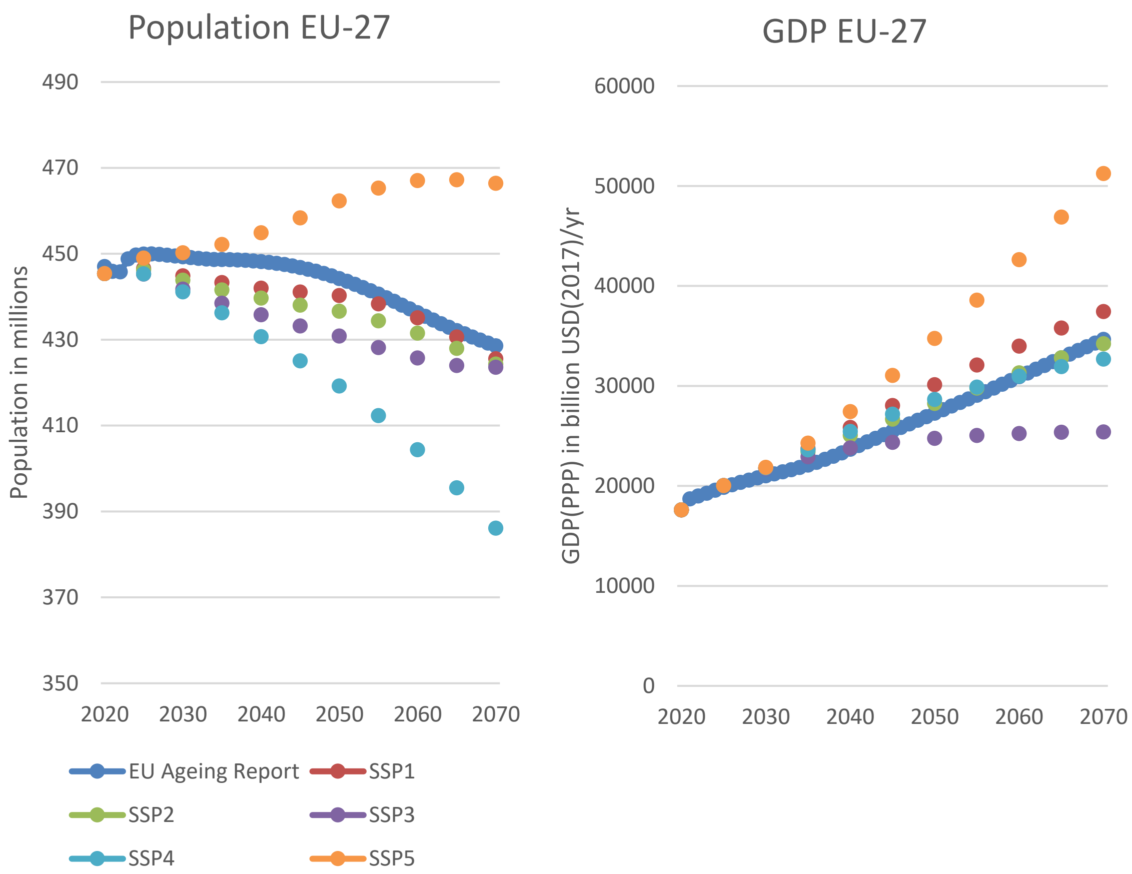

Figure 39. Comparison of population & GDP projections for EU-27 between SSPs (v3.1) & EU Ageing Report 2024

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ANNEX

Model documentation survey

The internal surveys with the updated information on the IAMs, including their regional, sectoral, policy coverage, as well as the calibration data and input assumptions, and the identified stakeholder inputs are publicly available on Zenodo here: https://zenodo.org/records/14216491

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