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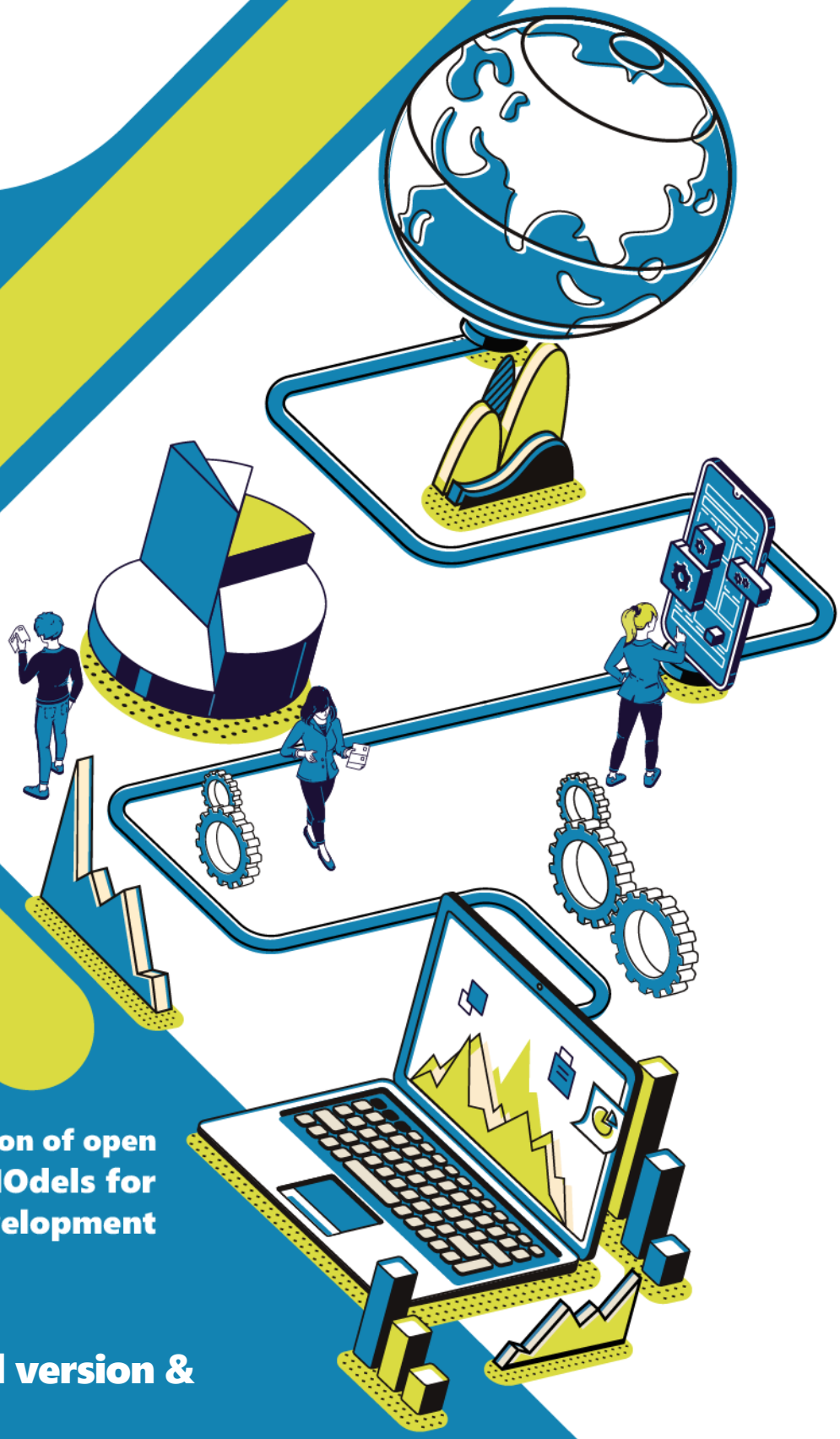

Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development

D3.5 – CLEWs-EU final version & documentation

WP3 – Update & Upgrade

27/11/2025

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Lead Beneficiary	The Cyprus Institute (CYI)			
Responsible Author	Constantinos Taliotis	**Email**	c.taliotis@cyi.ac.cy	
	CYI	**Phone**	+357 22 397 524	
Contributors	Vignesh Sridharan, Leigh Martindale, Nathan Johnson (Imperial); Anastasios Karamaneas, Thomas Nikolakakis, Sophia Kokoni, Konstantinos Koasidis, Alexandros Nikas (ICCS); Marios Karmellos, Irene Gkiouleka, Elias Kousoulos, Ioanna Konstantinou, Theodoros Zachariadis (CYI)			
Reviewer(s)	Dirk-Jan van de Ven (BC3); Panagiotis Fragkos, Alexandros Nikas (ICCS); Marie Pied (ESMIA)			
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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 development of the CLEWs-EU model aimed at the development of a fully open-source Integrated Assessment Model (IAM) for the European Union, in two versions for different purposes. The aggregated EU version of the model can be used for stakeholder engagement and capacity building, while the more detailed, nationally disaggregated model can be used for more comprehensive analyses of the CLEWs nexus in the EU. The simultaneous release of separate sectoral models (i.e., electricity and heat generation, industry, transport, buildings, land and water) also allows researchers from the broader community to take up and enhance the respective models for targeted analyses.

3. Short summary of results (<250 words)

This deliverable describes the final version of the CLEWs-EU model developed within the DIAMOND project. It provides a fully open-source tool to examine, in an integrated and internally consistent way, the European Union's energy, land, and water systems. CLEWs-EU is built within the OSeMOSYS modelling framework, while two geographical layers—an aggregated EU-wide version and a nationally disaggregated model—allow exploratory high-level analysis and detailed country-specific assessment. All relevant material (i.e., model files, scripts, input data, and assumptions) is made publicly available to support reproducibility, while an online model documentation has been developed to guide interested users in the uptake and application of the model. The final version of the CLEWs-EU model released with this deliverable provides a clear benchmark for evaluating more ambitious decarbonisation strategies and highlights the system-wide interactions that policymakers must navigate as Europe moves toward a more sustainable future. It also constitutes the base upon which integration with external modules will be pursued and scenario exploration will be applied in the final phase of the DIAMOND project.

4. Evidence of accomplishment

This report, the GitHub repository of the CLEWs-EU model (https://github.com/CLIMATE-DIAMOND/EU-CLEWS/tree/main), the model documentation in Read-the-Docs (link), and the relevant model releases available through Zenodo (link).

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
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EPFL	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	CH
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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

Executive Summary

This deliverable describes the final version of the CLEWs-EU model developed within the DIAMOND project. The CLEWs-EU model provides a fully open-source tool based on the MIT license to examine in an integrated and internally consistent way the EU's energy, land, and water systems. Built within the OSeMOSYS modelling framework, it ensures that all energy service demands across buildings, industry, transport, and electricity supply are met while identifying the least-cost combination of technologies and resources. Two geographical layers—an aggregated EU-wide version and a fully disaggregated model with member state granularity—allow exploratory high-level analysis and detailed country-specific assessment within the same framework. The national model captures differences in resource potential, land-use patterns, water constraints, and sectoral structures across all 27 EU member states, enabling analysis of cross-border electricity exchange, national decarbonisation strategies, and land-energy-water trade-offs.

The energy module integrates various key sectors in a unified architecture. Primary supply includes fossil fuels, nuclear, renewables, and hydrogen imports, with direct links to biomass availability in the land system. Electricity and heat generation include a broad technology mix of generation and storage technologies. Interconnectors between countries reflect the growing importance of cross-border flexibility and regional balancing. Buildings encompass residential and tertiary energy end-uses, with pathways covering conventional boilers, heat pumps, and renovation strategies. Industry spans multiple subsectors and represents fuel-switching, energy-efficiency improvements, and emerging hydrogen demand. Transport is the most detailed component, distinguishing aviation, shipping, rail, and a wide range of road vehicle technologies from internal-combustion engines to electric powertrains. Temporal variation is captured through seasonal and daily time slices, reflecting changes in renewable output and load profiles.

Land and water systems are represented with crop-type detail, irrigation classes, livestock numbers, forest and grassland dynamics, and water withdrawals across agricultural, municipal, industrial, and energy sectors. Land is allocated among cropland, pasture, forest, and other uses, with yield and water requirements varying by irrigation type and input level. Water withdrawal ceilings and irrigation constraints shape land allocation and influence energy pathways dependent on water availability, such as hydropower and thermal cooling. Biomass produced in agriculture and forestry flows directly into the energy sector, linking food, land, and fuel systems. Climate variables such as temperature and precipitation influence hydropower availability, irrigation demand, and crop water needs, while land-use change affects carbon sequestration in forests. Through these cross-sector interactions, the model quantifies trade-offs between land, energy, and water—highlighting, for instance, how irrigation limits can shape bioenergy availability or how energy requirements for pumping influence water use decisions.

The model is applied through a transparent pipeline: data prepared in Excel are converted using Otoole, the datafile is solved with linear optimisation, and the results are exported for analysis. All scripts, input data, and assumptions are provided openly to support reproducibility. A baseline scenario to 2050, which assumes no new decarbonisation mandates, relies on the existing policy framework on fuel pricing and taxation (the ETS), and follows current technology-cost trends and structural shifts, is developed and projects far-reaching changes across Europe's resource systems. Results show an energy system increasingly driven by electrification, energy efficiency interventions, and renewable energy deployment; a land and water system shaped by resource constraints and climate impacts; and emissions trajectories that vary sharply by sector. The final version of the CLEWs-EU model provides a clear benchmark for evaluating more ambitious decarbonisation strategies and highlights the system-wide interactions that policymakers must navigate as Europe moves toward a more sustainable future.

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Contents

1 CLEWs-EU model technical documentation 1

1.1 General introduction 1

1.2 Model overview 2

1.2.1 Energy module 3

1.2.2 Land and Water module 23

1.2.3 Time horizon and temporal resolution 34

1.2.4 Emissions accounting 35

1.2.5 Naming Convention 36

1.3 Model Manual 37

1.3.1 Software and hardware requirements 37

1.3.2 Model setup 38

1.3.3 Using the CLEWs-EU model 39

2 Model validation 40

2.1 Energy module 40

2.1.1 Electricity and heat generation 40

2.1.2 Buildings 41

2.1.3 Industry 42

2.1.4 Transport 43

2.2 Land and Water module 45

2.2.1 Crop production and area under cropland cover 45

2.2.2 Water use 48

2.2.3 Agricultural emissions 50

3 Baseline scenario outlook 51

3.1 Energy module 51

3.1.1 Electricity and heat generation 51

3.1.2 Buildings 54

3.1.3 Industry 56

3.1.4 Transport 57

3.1.5 Hydrogen supply 58

3.2 Land and Water module 59

3.2.1 Crop production and Land Use 59

3.2.2 Other Land Use 62

3.2.3 Water Use 64

3.3 Cross-sectoral linkages 67

3.3.1 Energy-Water Nexus 67

3.3.2 Energy-Land Nexus 68

3.4 Greenhouse gas emissions 71

4 Future developments 74

4.1 Limitations and potential improvements in the CLEWs-EU model 74

4.1.1 Energy module 74

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4.1.2 Land and Water module 75
4.2 Integration of CLEWs-EU with external modules 76
References 77

Table of Figures

Figure 1. Sectoral representation in the CLEWs-EU model. 2
Figure 2. Simplified representation of the CLEWs-EU energy module. 4
Figure 3. Simplified representation of electricity and heat generation in the CLEWs-EU model. 6
Figure 4. Capacity factor assumptions for different classes of wind in Spain across four seasons (S01-winter, S02-spring, S03-summer, S04-autumn). 7
Figure 5. Capacity factors for hydro dams in Spain for average vs dry year. In RoRs, generation is pre-defined at the per time-slice level, while on hydro with dams generation is capped on a seasonal level. 7
Figure 6. Simplified representation of the buildings sector in the CLEWs-EU model. 10
Figure 7. Simplified representation of industry in the CLEWs-EU model. 14
Figure 8. Simplified representation of land transport in the CLEWs-EU model. 18
Figure 9. Simplified representation of aviation and shipping in the CLEWs-EU model. 18
Figure 10. Biofuel use in transport technologies in the CLEWs-EU model. 21
Figure 11. Hydrogen supply in the CLEWs-EU model. 22
Figure 12. Primary level of land categories breakdown in the land module of CLEWs-EU. 25
Figure 13. The CLEWs land & water model structure represented in each EU member state. 26
Figure 14. Crop classification in the CLEWs EU model. 27
Figure 15. Electricity use in the CLEWs-EU water system. Red lines represent the electricity flows. 28
Figure 16. Household water withdrawal and consumption in the EU under SSP2. 30
Figure 17. Commercial and Industrial sectors water withdrawal and consumption in the EU under SSP2. 30
Figure 18. Simplified representation of livestock in the CLEWs-EU model. 32
Figure 19. Electricity generation mix comparison in selected EU countries. The graphs show modelled vs actual generation for 2021. Generation above demand indicates exports and/or T&D losses. 41
Figure 20. Final energy demand in the buildings sector in selected EU countries (top) and EU-27 (bottom). 42
Figure 21. Final energy demand in the industrial sector in selected EU countries (top) and EU-27 (bottom). 43
Figure 22. Passenger car activity by type of technology in selected EU countries (top) and EU-27 (bottom). 44
Figure 23. Final energy demand in land transport in selected EU countries (top) and EU-27 (bottom). 45
Figure 24. Validation for the area under crop land cover; modelled year 2021, nearest actual year from statistics 2022 46
Figure 25. Crop production in Germany for major categories (2021); Modelled vs Actual. 46
Figure 26. Crop production in Spain for major categories (2021); Modelled vs Actual. 47
Figure 27. Crop production in France for major categories (2021); Modelled vs Actual. 47
Figure 28. Crop production in EU-27 countries for major categories (2021); Modelled vs Actual. 48
Figure 29. Modelled share in the drinking water supply sources (2021). SUR: Surface Water, GWT: Ground Water, DSA: Desalinated Water 49
Figure 30. Actual share in the drinking water supply sources (2021) from EurEau. 49
Figure 31. Water withdrawal for thermal power plant cooling in EU-27 countries. 50
Figure 32. Agriculture and Livestock Methane (CH4) emissions in 2021 across the EU 50
Figure 33. Total electricity generated in the EU-27 52

Figure 34. Total installed electricity generation capacity in EU-27. 52
Figure 35.Total electricity generated in France. 54
Figure 36. Generation per time slice in first season of the year over a typical day in year 2050 for France. 54
Figure 37. Evolution of final energy demand in the buildings sector in EU27. 55
Figure 38. Evolution of heat pump contribution in the buildings sector for space heating and space cooling in EU27. 55
Figure 39. Energy savings achieved through building renovations in EU27. 56
Figure 40. Evolution of final energy demand in industry in EU27. 56
Figure 41. Useful energy provided by Carbon Capture and Storage (CCS) technologies in industry in EU27 57
Figure 42. Evolution of passenger car activity by type of technology in EU27. 57
Figure 43. Evolution of final energy demand in land transport (i.e., rail and road) in EU27. 58
Figure 44. Hydrogen consumption in the road transport sector by mode of transport - EU27 total. 58
Figure 45. Evolution of hydrogen supply across the EU. 59
Figure 46. Projected hydrogen consumption for energy purposes in each EU member state. 59
Figure 47. Wheat Production by land use type. Left (2021-2050), Right (Snapshots for 2021 and 2050). 60
Figure 48. Barley production by land use type. Left (2021-2050), Right (Snapshots for 2021 and 2050). 61
Figure 49. Land use change for crop production (by crop type). 61
Figure 50. Land use change for crop production in Germany (by Land use type). 62
Figure 51. Land-Use Change across the modelling period. 63
Figure 52. Germany Land-Use Change. 64
Figure 53. Water Withdrawal in the EU-27 by sector in 2021(left) and 2050 (right). 65
Figure 54. Water withdrawal by sector in Germany (left) and Sweden (right). 65
Figure 55. Water withdrawal by sector in Spain (left) and Slovenia (right). 66
Figure 56. Change in water withdrawal between 2021 and 2050 across the EU-27 countries. Positive figures reveal higher water withdrawals, negative lower. 66
Figure 57. Energy Intensity of Water Infrastructure vs Water Demand by Country (2021). 67
Figure 58. Water Withdrawal Intensity vs Thermal Generation by Country (2021). 68
Figure 59. Energy consumption by fuel type and country in the agriculture and forestry sectors. Left (2021) and Right (2050). 69
Figure 60. Total energy consumption in the agriculture and forestry sector by fuel type. 69
Figure 61. Energy consumption by crop type across the EU-27 countries. 70
Figure 62. Energy consumption by country in the agriculture and forestry sector. 70
Figure 63. Diesel Consumption in selected countries in the AFOLU sectors. 71
Figure 64. Energy-related carbon dioxide emission projections in the EU27. 72
Figure 65. AFOLU sector carbon dioxide emission by country. 72
Figure 66. Agriculture and livestock sector methane emissions by country. 73

Table of Tables

Table 1. International fuel and ETS price projections (NCV= net calorific value; WEM= with existing policies & measures; WAM = with additional policies & measures). 5
Table 2. CAPEX and Fixed O&M costs of electricity & heat generation technologies. 8
Table 3. CAPEX and Fixed O&M costs of solar and wind technologies based on solar and wind potential. 9
Table 4. Units for the capacity and cost characteristics of electricity and heat technologies in the CLEWs-EU model.

..... 9
Table 5. Technoeconomic assumptions of buildings technologies in the CLEWs-EU model. 11
Table 6. Regional variation in savings and cost for renovation measures in the buildings sector of the CLEWs-EU model (adapted from the EU Reference Scenario 2020). 12
Table 7. Technology aggregation by end-use service and fuel, based on JRC-IDEES 2021 data. 13
Table 8. Units for the input and output of building technologies in the CLEWs-EU model. 14
Table 9. Units for the capacity and cost characteristics of building technologies in the CLEWs-EU model. 14
Table 10. Industrial sector representation in the disaggregated CLEWs-EU version. 15
Table 11. Technoeconomic assumptions of industrial boiler technologies in the CLEWs-EU model (adapted from EU Reference Scenario 2020). 16
Table 12. Units for the input and output of industrial technologies in the CLEWs-EU model. 17
Table 13. Technology options in the transport module of CLEWs-EU. 17
Table 14. Capital cost of transport technologies in the CLEWs-EU model (adapted from EU Reference Scenario 2020). 19
Table 15. Cost characteristics of electric recharging in the CLEWs-EU model (adapted from EU Reference Scenario 2020). 20
Table 16. Units for the input and output of transport technologies in the CLEWs-EU model. 22
Table 17. Units for the capacity and cost characteristics of transport technologies in the CLEWs-EU model. 22
Table 18. Technoeconomic characteristics of hydrogen production technologies (adapted from EU Reference Scenario 2020). 23
Table 19. Annual growth rates (%) in crop production from the EU-Agricultural Outlook (2024-2035) 24
Table 20. Thermal electricity generation and water withdrawal in 2021 across the EU-27 countries. 31
Table 21. Woody biomass energy intensity in EU27 countries. 33
Table 22. Key data requirements of the CLEWs-EU land and water modules. 34
Table 23. Intra-year temporal breakdown of CLEWs-EU. 35
Table 24. Naming convention sample for technologies and commodities in the energy module (CLEWs-EU). 36
Table 25. Naming convention sample for technologies in the land module (CLEWs-EU). 37
Table 26. Naming convention sample for technologies in the water module (CLEWs-EU). 37
Table 27. Key hardware requirements to run the disaggregated version of the CLEWs-EU model and its sectoral components. 38
Table 28. Contribution of variable generation technologies to firm capacity. 53

1 CLEWs-EU model technical documentation

This report provides the technical documentation for the CLEWs-EU model, which corresponds to the final version of the model released under D3.5 of the DIAMOND project. Section 1 presents the core part of the technical drafts for CLEWs-EU, including features and characteristics of the released model, the sectoral design and input data used, and a manual to guide new users, also elaborating on hardware and software requirements to run the model. Section 2 describes the testing phase, which accompanied this release of the model. Section 3 presents sample scenario outputs with an outlook to 2050 from the various key sectors represented in the model; the associated scenario consists of the baseline setup of the model, which has no specific decarbonisation targets defined. Finally, the limitations of the model and potential future improvements, both within and beyond the DIAMOND project's duration, are proposed in Section 4.

1.1 General introduction

The CLEWs-EU model is developed within the OSeMOSYS (Open-Source Energy Systems Model) modelling framework. OSeMOSYS is a long-term cost-optimisation energy system model (Howells et al., 2011). OSeMOSYS has been used in numerous studies with a focus ranging from a global, regional and national scale (Gardumi et al., 2018; Peña Balderrama et al., 2018; Sridharan et al., 2019). It is a bottom-up technoeconomic model that is demand-driven, meaning the exogenously defined demand must be met, regardless of the cost. The choice of technologies and energy mix is based on the adopted technoeconomic assumptions (e.g., fuel costs, technology costs, resource availability, emission limits). The model's objective function is the minimisation of the total discounted system cost over the entire modelling horizon.

The CLEWs-EU model builds on the structure of the Global CLEWs model (Beltramo et al., 2021), with several enhancements being implemented. Two separate main modules, i) energy and ii) land with water, have been developed with several interlinkages between them. Greenhouse gas (GHG) emissions are tracked across the modules; in turn, the assumptions within the modules are affected by climate assumptions. For instance, temperature affects water demand in agriculture, while precipitation affects hydropower output and crop yield. In the energy module, a large set of technologies are used to represent primary energy supply, electricity generation, transport, buildings, and industry. In addition, the suite of technologies has been expanded to include a broader range of decarbonisation options. For instance, the use of hydrogen—either imported or locally produced—is an option that was not available in the Global CLEWs but is 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 has a more explicit representation of water demand and supply. More information on the structure of each module is provided in the subsequent sections.

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 allows the exploration of climate change mitigation pathways by a broad range of stakeholders. This ensures consistency with the philosophy behind the initial development of the Global CLEWs model.

b. **Disaggregated model**[1], in which the level of spatial resolution has been extended to the national level, 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 provides more focused insights and can be used to support the development of national policies within the context of mutual EU or national obligations/targets. Interaction between the countries is also enabled in this model, for instance through electricity trade. As expected, the development of the disaggregated model has entailed a larger volume of input data compared to the aggregated model. For the land and water module, mostly country-specific data has been incorporated in this version. However, in certain cases, like groundwater usage shares or livestock numbers (to name a few), EU-27 averages have been used for countries that do not report explicit numbers. These assumptions can be revisited in future model developments, and country-specific data will be updated wherever possible.

The CLEWs-EU model (including both versions) is licensed under the MIT License.

1.2 Model overview

The development of the various sectors of the model was parallelised, based on separate entities, which also offer the possibility of running specific sectoral models in isolation (Figure 1). The latest version of the disaggregated CLEWs-EU model is made available, but also the first versions of the sectoral modules (land & water, electricity & heat, buildings, industry, and transport) are released with this version of the model.

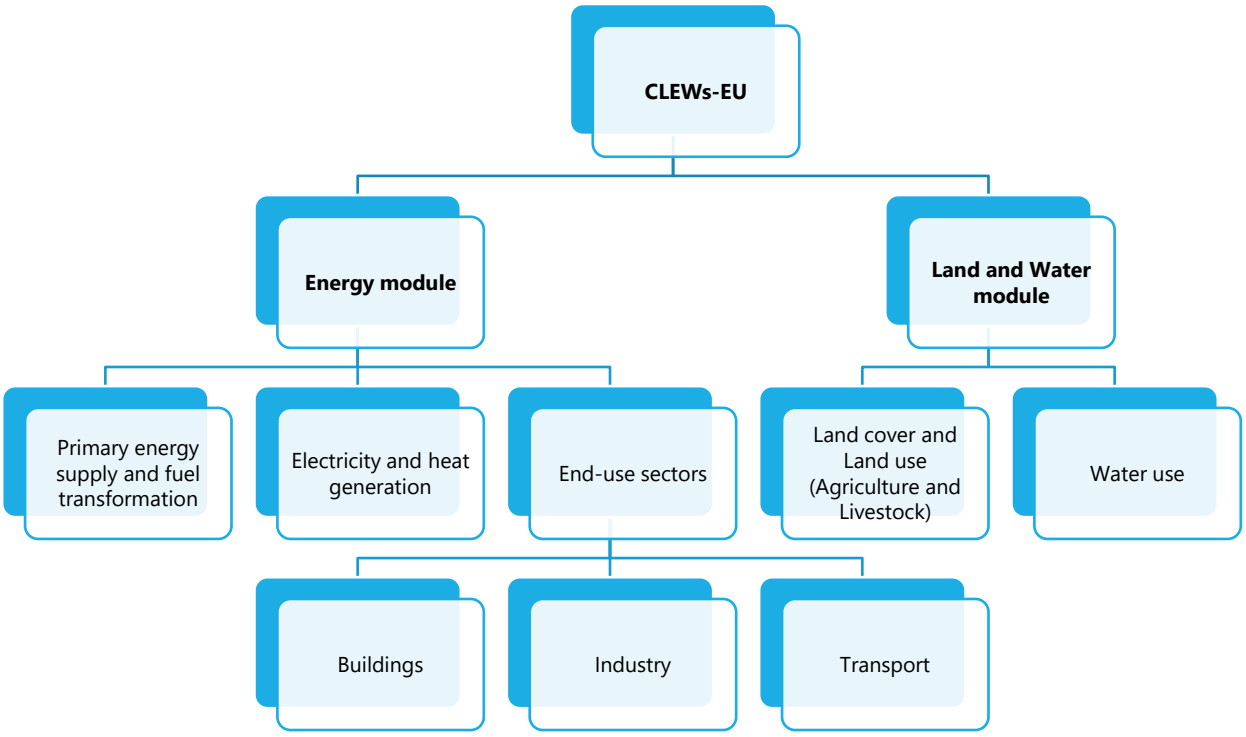

Figure 1. Sectoral representation in the CLEWs-EU model.

[1] The latest version of the disaggregated CLEWs-EU model is available on GitHub. An integrated version of the model is available, but also the standalone sectoral modules (land & water, electricity & heat, buildings, industry, and transport) will be separately released, in case community users would like to focus on a specific sector without running the entire model.

1.2.1 Energy module

Five overarching sectors are developed to represent the broader energy system. Each of these includes a large set of technologies to capture the status of the current energy mix, as well as future technology options for decarbonisation. Specifically, the following sectors are 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.) is not modelled explicitly, with the only exception of electricity interconnectors between countries in the disaggregated version of the CLEWs-EU model and hydrogen production. Supply of biomass into the energy system occurs via an interlinkage with the land module of the model.

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

c) **Transport** – the transport sector includes road transport, which is 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. It is worth mentioning that no distinction between national and international transport is made for each of these sectors, as they are aggregated in a single category.

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

e) **Industry** – up to four distinct industries, based on the most energy-consuming sectors (per country), are represented separately for each country, while the rest of the industries are lumped together in a fifth category[2]. The output of each of the industries is represented in generic energy terms (i.e., PJ of useful energy services).

[2] The breakdown of the industrial sector is 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.

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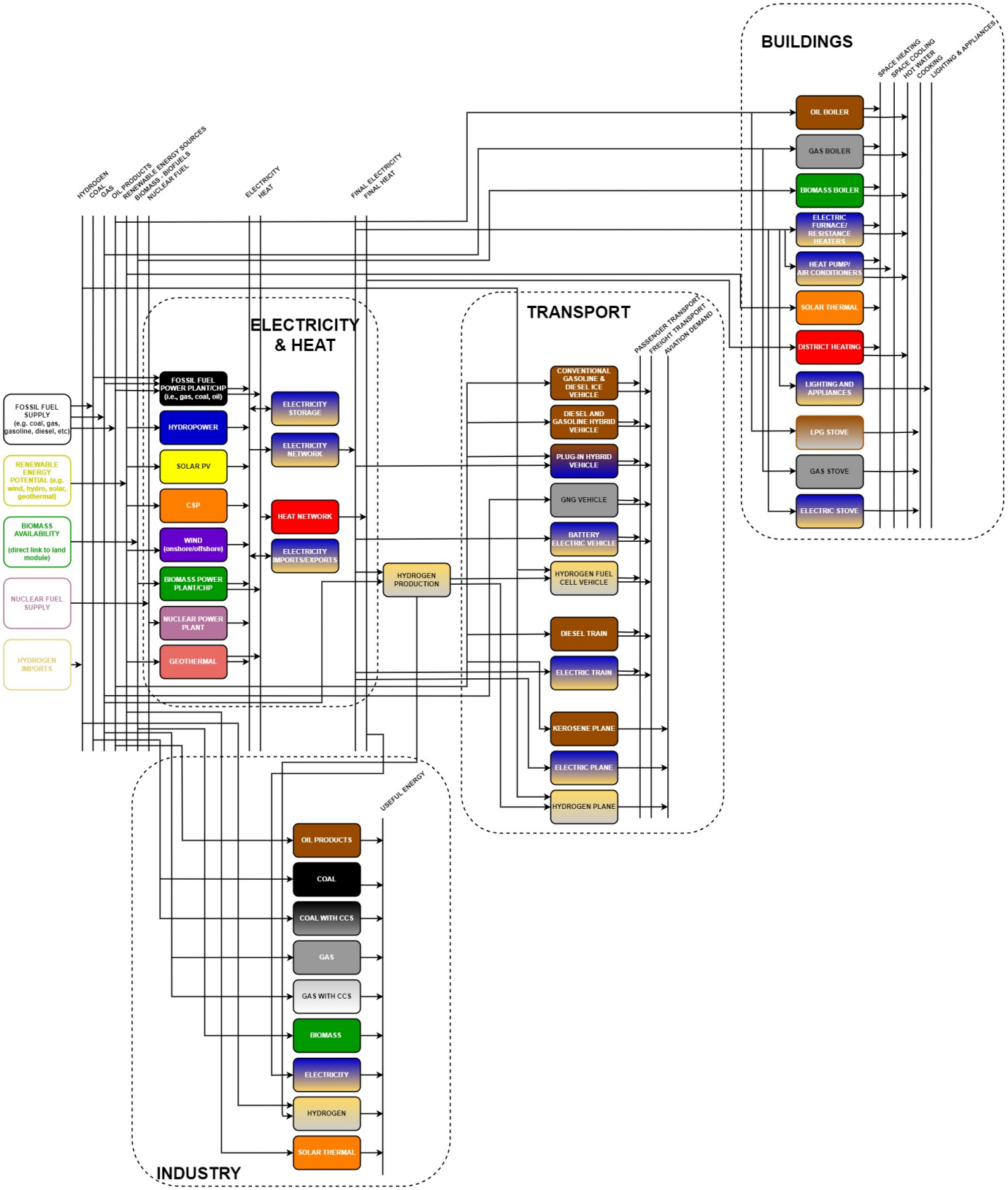

Figure 2. Simplified representation of the CLEWs-EU energy module.

It should be noted that the energy demands in all sectors are inputs to the model and there is no endogenized

impact of energy supply price changes to demand[3]. A simplified representation of the structure of the energy module is provided in Figure 2. Further disaggregation of technologies is available in the model than is depicted. For instance, the various vehicle technologies are further broken down into passenger cars, buses, light commercial vans, and heavy trucks. Similarly, the structure of the industrial sector is constructed for each of the four key industries (and other industries) to be represented in each country. Finally, interlinkages with the land and water modules are presented in Section 1.2.2.

1.2.1.1 Overarching assumptions

Among the most crucial assumptions adopted in the model are the international fuel price projections. The model uses as a base the international fuel price projections of the European Commission recommendations (European Commission - DG CLIMA, 2024). The same source provides projections on the existing Emission Trading System (ETS) and the new ETS (Table 1). The existing ETS initially applied only to electricity and heat generation and energy-intensive industries. The new ETS (ETS2) will be expanded to include buildings, road transport, and smaller industries (i.e., those not already covered by the existing ETS) and become fully operational in 2027 (European Commission - Directorate-General for Energy, 2025a). Both the ETS and the ETS2 are included in the baseline setup of the CLEWs-EU model.

Table 1. International fuel and ETS price projections (NCV= net calorific value; WEM= with existing policies & measures; WAM = with additional policies & measures).

	Unit	2021	2025	2030	2035	2040	2045	2050
Oil	EUR2018/GJ	10.24	10.16	11.39	12.62	12.95	14.10	16.14
Gas (NCV)	EUR2018/GJ	14.83	7.70	7.38	6.72	8.28	8.11	7.87
Coal	EUR2018/GJ	3.69	3.36	3.28	3.11	3.11	3.28	3.28
ETS WEM	EUR2018/tCO2	53.27	77.85	77.85	81.95	81.95	131.12	155.71
ETS WAM	EUR2018/tCO2	53.27	77.85	77.85	114.73	237.66	352.39	401.56
ETS2 WEM	EUR2018/tCO2	0	0	0	0	0	0	0
ETS2 WAM	EUR2018/tCO2	0	0	45.07	114.73	237.66	352.39	401.56

1.2.1.2 Electricity and heat generation

Representation of electricity and heat generation is crucial in the CLEWs-EU model as it defines the long-term cost-competitiveness of these commodities as alternatives to fuel combustion at the final consumer level. A large set of technologies is used to represent this sector (Figure 3). The following subsections discuss the structure and key assumptions adopted in this sector.

[3] 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.

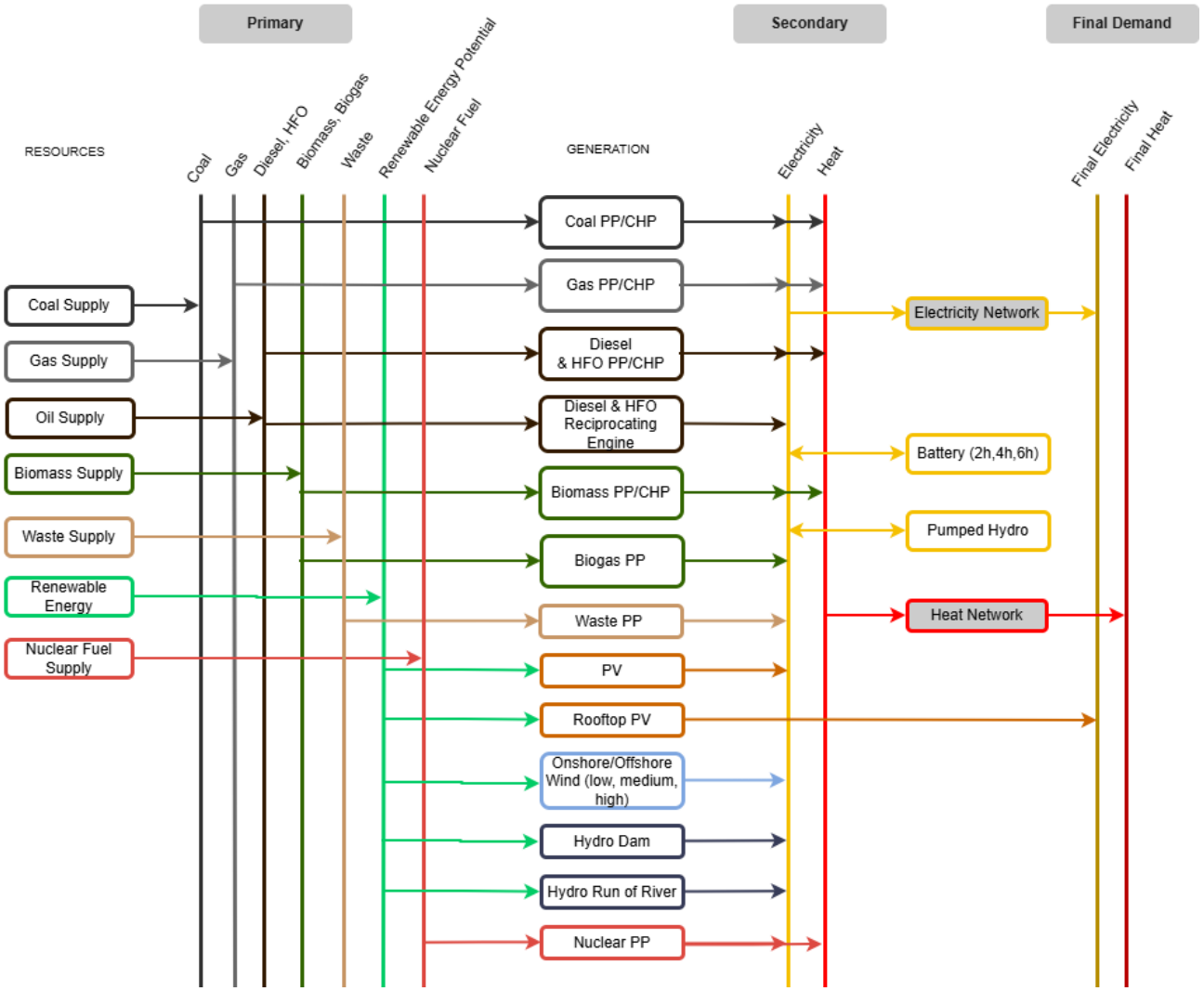

Figure 3. Simplified representation of electricity and heat generation in the CLEWs-EU model.

1.2.1.2.1 Electricity

The development of the electricity supply module has been based on detailed historical data for total final electricity demand, PV and wind profiles, as well as hydro availability. Data on existing installed capacity has been retrieved primarily from the Joint Research Centre of the European Commission (JRC) Integrated Database of the European Energy System (IDEES) 2021 database (Rózsai et al., 2024) and cross-verified with data from ENTSO-E. Furthermore, demand profiles have been downloaded from the ENTSO-E website for the year 2022 for all member countries (ENTSO-E, 2025). Moreover, an important constraint is set, related to the maximum total installed capacity of renewable energy power plants: for hydropower, these values are adopted from each country's National Energy and Climate Plan (NECP) projections from the final revisions of 2024 or the draft revisions of 2023 if the final revision was not available, whereas for solar and wind energy, they are taken from the JRC ENSPRESO database (Ruiz et al., 2019).

PV and wind generation profiles have been downloaded from Renewables-Ninja (Pfenninger & Staffell, 2025) and adjusted to get the average annual capacity factor based on Eurostat (Eurostat, 2025c). Wind and PV resources have been broken into high, average, and low potential, based on data from the JRC-IDEES database (Rózsai et al., 2024) (Figure 4). For each country, there are 3 PV and wind technologies/resources associated with a different capacity factor (%) and economic potential (in GW).

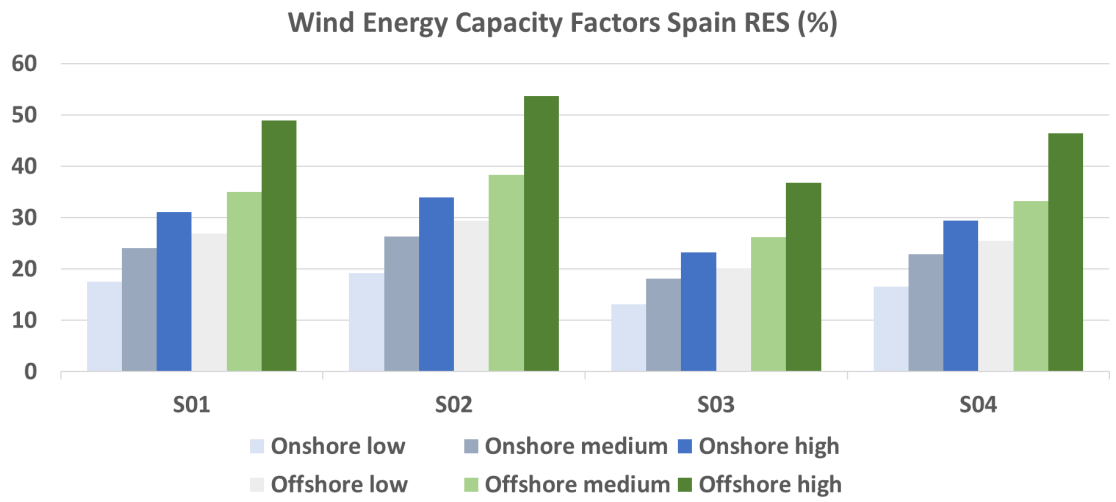

Figure 4. Capacity factor assumptions for different classes of wind in Spain across four seasons (S01-winter, S02-spring, S03-summer, S04-autumn).

Run-of-River (RoR) hydro generation is modelled similarly as in the case of PV and wind, using a historical profile of generation, retrieved from ENTSO-E (ENTSO-E, 2025) and adjusted to get the average capacity factor based on historical data by Eurostat (Eurostat, 2025c). The hourly profiles of demand, as well as generation from PV, wind, and RoR have been treated and adjusted to the agreed temporal resolution that is used across the CLEWs-EU model (see Section 1.2.3).

Hydro plants with dams are modelled as generators running on water (represented as a "fuel"), while the maximum capacity factor is capped based on historical generation. The main difference between RoR and hydro with dams is that hydro with dams can operate flexibly, subject to a seasonal cap on generation that is based on statistical analysis of historical hydro generation data for seven consecutive years. To better reflect the annual fluctuations of hydropower generation, the model considers 7-year cycles where 6 years with average hydrological data are followed by a single "dry" year (Figure 5). All adopted profiles for hydro, PV, and wind have been compared with historical data based on Eurostat (Eurostat, 2025c) and have been treated to represent an average year. For this purpose, historical annual averages have been obtained from 1980-2019 for PV and Wind and 2015-2022 for hydro.

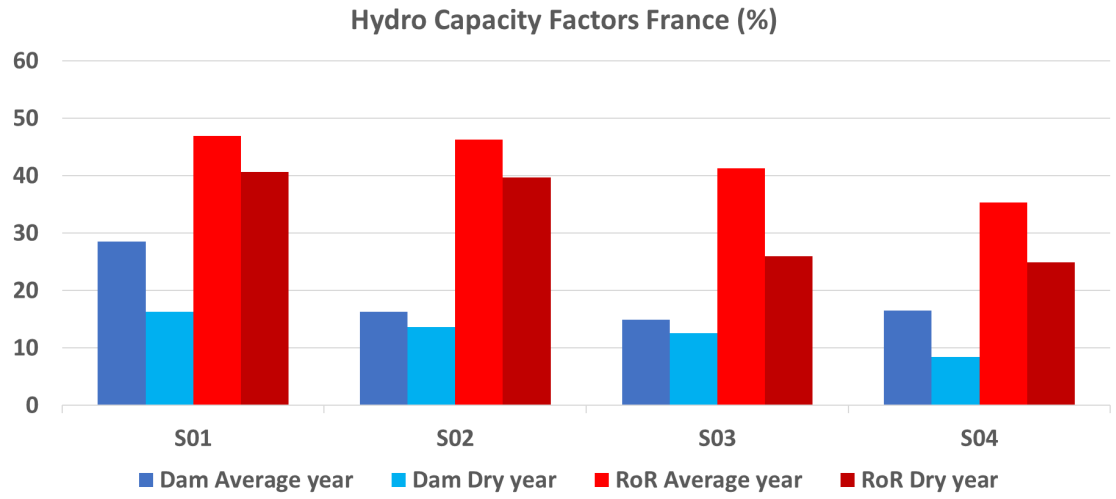

Figure 5. Capacity factors for hydro dams in Spain for average vs dry year. In RoRs, generation is pre-defined at the per time-slice level, while on hydro with dams generation is capped on a seasonal level.

The model accounts for a wide range of technologies, which comprise a portfolio of projects to be considered in the optimisation. The technological mix of conventional generators can be distinguished based on the thermodynamic cycle (steam (ST) vs gas, open vs. closed cycle vs combined cycle (CCGT), and on the fuel (biomass, nuclear, coal, natural gas, liquid fuels, waste, biogas etc.). The model also includes CCS for specific technologies, coal-ST with CCS, gas CCGT with CCS and biomass-ST with CCS (which leads to net-negative emissions).

Utilising data from ENTSO-E (ENTSO-E, 2025), grid interconnections between the EU member states are represented in the model. Specifically, the existing and potential future capacities of all relevant interconnections have been incorporated in the model. The level of electricity trade between the systems is endogenously calculated in the model, considering the marginal electricity cost differential between the countries, which depends on the technoeconomic assumptions adopted for each scenario.

The technoeconomic parameters of electricity generation technologies (efficiency, capital cost, operation and maintenance cost, etc.), presented in Table 2 and Table 3, are based on the latest available EU Reference Scenario (European Commission - Directorate General for Energy. et al., 2021). The CLEWS-EU model considers two types of electricity storage, namely battery energy storage systems (BESS) and pumped hydro. The technoeconomic parameters and trajectories for these storage options have been based on the Annual Technology Baseline (ATB) documentation of NREL (NREL, 2024). The model assumptions include capital cost trajectories for all technologies; this is especially important for technologies where the capital cost is expected to be reduced with time as in the case of PV, wind, and BESS. The OSeMOSYS code used to run the CLEWs-EU model contains modified storage equations to ensure proper representation of the operation of these technologies.

Table 2. CAPEX and Fixed O&M costs of electricity & heat generation technologies.

Technology	**CAPEX (EUR/kW)**			**Fixed O&M (EUR/kW)**		
	2021	**2030**	**2050**	**2021**	**2030**	**2050**
Nuclear Generation III	4,770	4,500	4,500	120	115	105
Coal supercritical	1,650	1,650	1,650	33-41	31-36	28-31
Coal Supercritical with CCS	3,432	3,270	3,075	69	66	62
Biomass Steam Turbine	1,980	1,800	1,700	47	40	38
Biomass Steam Turbine with CCS	4,013	3,675	3,205	80	69	61
Steam Turbine CHP	1,980	1,800	1,700	46	40	38
Gas Turbine CC	598	579	570	22	21	19
Gas Turbine OC *	399-497	386-465	380-450	12-29	12-24	12-24
Reciprocating engine	1,897	1,897	1,897	35	35	35
Natural Gas CC with CCS	1,738	1,625	1,500	41	38	34
Geothermal	3,211	2,807	2,614	102	95	99
Waste PP	1,647	1,615	1,600	52	45	39
Hydro reservoir PP	2,100	2,100	2,100	26	26	26
Run of river PP	1,711	1,670	1,650	9	8	8
Batteries **	578-1734	380-1140	300-900	48	31	21
Pumped Hydro Storage	3,062	30,612	3,062	19	19	19

** Ranges in both CAPEX and Fixed O&M are due to different values using the same technology, leading to cost variations.*

*** Ranges on batteries depend on different hours of storage capacity*

Table 3. CAPEX and Fixed O&M costs of solar and wind technologies based on solar and wind potential.

Technology	CAPEX (EUR/kW)			Fixed O&M (EUR/kW)		
	2021	2030	2050	2021	2030	2050
Wind onshore Low	1198	1175	1100	13	13	12
Wind onshore Medium	1045	1000	925	14	14	12
Wind onshore High	995	950	880	21.9	21	20
Wind offshore Low	1778	1650	1503	32.4	27	26
Wind offshore Medium	1756	1622	1468	32.4	27	26
Wind offshore High	1734	1593	1432	32.4	27	26
Solar PV Low	470	400	367	14.8	12.6	8.2
Solar PV Medium	455	387	355	14.8	12.6	8.2
Solar PV High	447	380	348	14.8	12.6	8.2
Solar PV Rooftop Low	470	400	367	18.6	14.9	9
Solar PV Rooftop Medium	635	543	500	18.6	14.9	9
Solar PV Rooftop High	625	536	493	18.6	14.9	9

1.2.1.2.2 Heat

The heat module of the power section of the CLEWs-EU model contains CHP plants with the main purpose of producing electricity, while heat is directed as a by-product into district heating networks. The existing capacity of CHP plants and the level of district heating demand are retrieved from the JRC-IDEES 2021 database (Rózsai et al., 2024). CHP units that are part of industrial facilities are excluded from this module, as end-use energy demand in the industry sector is accounted for separately.

To vary the level of electricity and heat production throughout the model horizon and the intra-annual timesteps, we have added two modes of operation for each CHP technology. The first mode represents the maximum rate of electricity production for the CHP unit, while the highest heat-rate production is accounted for in the second mode. The electricity and heat efficiency ranges of CHPs for these two modes are taken from IEA ETSAP (IEA ETSAP, 2010). Depending on the level of electricity versus heat demand in the end-use sectors, the model chooses which of the two modes to prioritise.

1.2.1.2.3 Units of electricity and heat generation technologies

OSeMOSYS models do not have a specific unit definition, so the decision on the units to be used is entirely up to the modeller. The parameter "CapacityToActivityUnit" is used to relate the rate of activity of each technology to its capacity. In the energy module of CLEWs-EU, this parameter is either 1 or 31.536. In the former case, this means that the activity is in PJ and the capacity is in PJ/year, while in the latter case, the capacity is in GW.

Table 4. Units for the capacity and cost characteristics of electricity and heat technologies in the CLEWs-EU model.

Capacity	Activity	Capital cost	Fixed cost	Variable cost
GW	PJ	Million EUR2018/GW	Million EUR2018/GW	Million EUR2018/PJ

1.2.1.3 Buildings

The buildings module aggregates the residential and commercial services sectors. It splits demand for energy services into four primary end-uses: heating (i.e., space heating & hot water), space cooling, cooking, and electrical appliances.

For space heating, the module incorporates several technologies to reflect the heterogeneity of heating systems in buildings. These include solid fuel furnaces for solid fuels, oil boilers for LPG and gas/diesel oil, gas-based systems (including gas heat pumps and heaters), biomass boilers for biomass and waste, district heating systems, heat pumps (indicated as advanced electric heating in JRC-IDEES database (Rózsai et al., 2024), electric furnaces (representing conventional electric heating and circulation systems), and solar thermal installations. Energy renovations of buildings are also included as technology options that can mitigate final energy demand for space heating and cooling.

Space cooling is represented by electric space cooling systems due to the predominance of electricity-based cooling technologies in both residential and commercial buildings. Deployment of heat pumps, as a single technology, can be used to satisfy both space heating and space cooling demands. Cooking is represented using three primary technologies: LPG stoves, gas stoves, and electric stoves, capturing the most common cooking appliances across the sectors. Lighting and electrical appliances are treated as a single, aggregated category without further technological disaggregation, as they only consume electricity.

As in all modules of CLEWs-EU, to facilitate the independent development and testing of the buildings module, we introduce additional dummy technologies for electricity and centralised heat provision, as well as dummy technologies that can directly satisfy the defined energy service demands at an exceptionally high cost. These temporary additions allow for standalone operation of the module during development phases. However, it's important to note that these dummy technologies are also included in the final integrated model version, where electricity and heat are endogenous to the model via the dedicated "Electricity & Heat generation" module, as they allow identification of potential modelling faults.

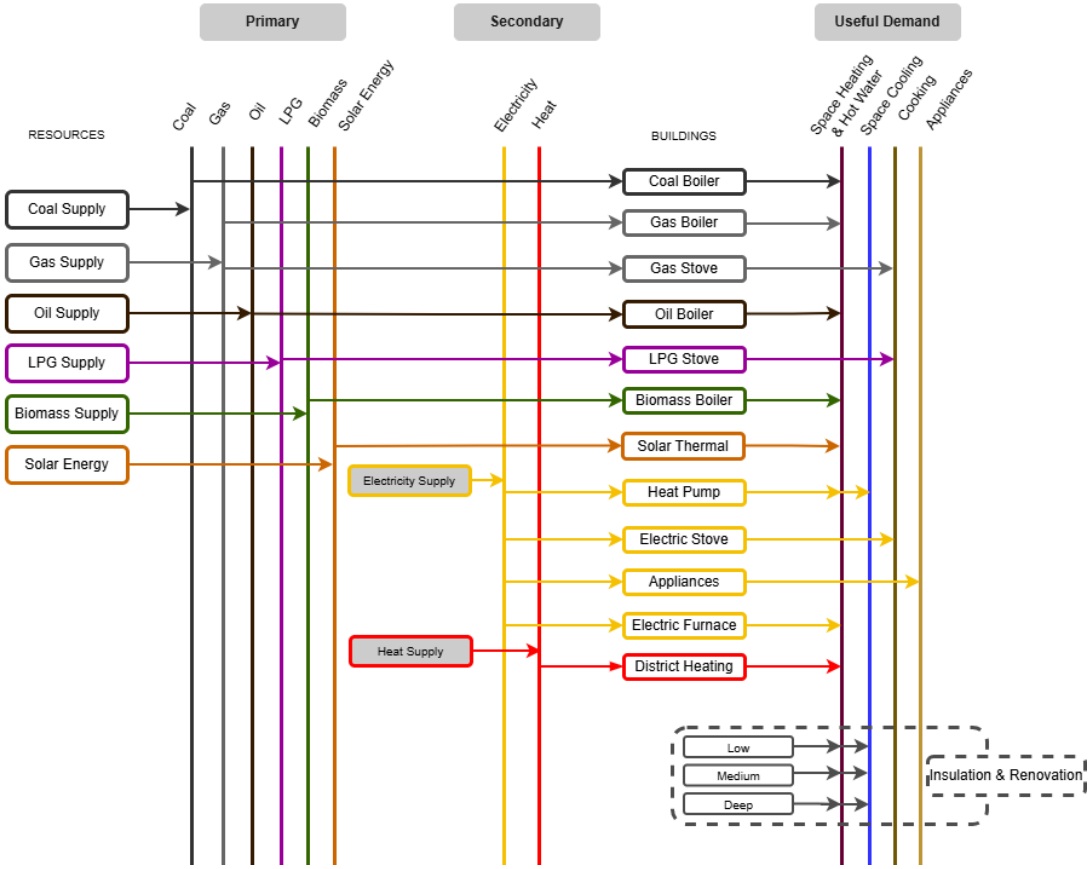

Figure 6. Simplified representation of the buildings sector in the CLEWs-EU model.

1.2.1.3.1 Technoeconomic characteristics of building technology options

The development of the buildings module was based on data from the JRC-IDEES database. The latest version of the publicly-available dataset, JRC-IDEES-2021 (Rózsai et al., 2024) was published in May 2024 and covers the timeframe from 2000 to 2021, making it suitable for the calibration of the model. The release introduces several methodological refinements and incorporates new statistical sources as well as feedback from the user community.

As an analytical database, it goes beyond raw statistical data by processing and decomposing energy consumption into specific processes and end-uses, allowing for in-depth analysis of energy system dynamics. JRC-IDEES was created by harmonising existing statistics with technical assumptions. For the buildings sector (both commercial and residential), JRC-IDEES (Rózsai et al., 2024) offers highly disaggregated data on energy demand, breaking it down by end-use (e.g., space heating, cooling, lighting) and fuel type and is aligned with Eurostat energy balances.

As per the overarching model assumptions (Table 5), capital costs are derived from the EU Reference Scenario 2020 technology assumptions (European Commission - Directorate General for Energy. et al., 2021), with the exception of solid fuel boilers/furnaces, which are taken from IEA ETSAP (IEA ETSAP, 2012), which is also consulted to derive operation and maintenance costs.

Table 5. Technoeconomic assumptions of buildings technologies in the CLEWs-EU model.

Technology	Capital cost (EUR2018/kW)			Fixed O&M cost (EUR2018/kW)			Energy Intensity Index (2021=100%)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050
Space heating & water heating									
Oil boiler	170	192	180	5.08	5.08	5.08	100%	100%	100%
Gas boiler	165	187	185	5.08	5.08	5.08	100%	88%	88%
Coal boiler	165	187	185	5.08	5.08	5.08	100%	100%	100%
Biomass boiler	431	488	457	13.22	13.22	13.22	100%	94%	91%
Electric furnace	64	78	71	5.08	5.08	5.08	100%	100%	100%
Heat pump*	817	865	697	5.08	5.08	5.08	100%	81%	63%
Solar thermal	1308	1432	1119	5.08	5.08	5.08	100%	95%	92%
District heating	96	111	104	---	---	---	100%	99%	99%
Space cooling									
Heat pump*	817	865	697	5.08	5.08	5.08	100%	81%	66%
Cooking									
LPG stove	198	202	195	---	---	---	100%	95%	91%
Gas stove	198	202	195	---	---	---	100%	95%	91%
Electric stove	189	194	186	---	---	---	100%	96%	91%
Lighting & electrical appliances									
General appliances	---	---	---	---	---	---	100%	93%	91%
Building renovations**									
Low renovation	1134	1134	1134	---	---	---	100%	100%	100%
Medium renovation	705	705	705	---	---	---	100%	100%	100%
High renovation	900	900	900	---	---	---	100%	100%	100%

**Air-to-air heat pumps are used as representative technologies.*

***The capital cost unit of building renovations is in terms of Million EUR2018/PJ yearly savings. Furthermore, the cost provided here is indicative, as both the renovation cost and the achieved energy savings vary by country.*

Efficiency factors are projected to evolve and are, therefore, inserted in the model as time series. For the period 2018-2021, these calculations were based on the JRC-IDEES-2021 database. Since both Final Energy Consumption (FEC) and Useful Energy Consumption (UEC) data for the Households (HH) and Services (SER) sectors are available in the database for all EU Member States and the European Union as a whole, we computed the efficiency factors

as:

$$Efficiency = \frac{Total\ UEC}{Total\ FEC}$$

For 2022-2050 projections, efficiencies are indexed to the estimated efficiencies for 2021 from JRC-IDEES as:

$$Efficiency\ (y_n) = Efficiency_{2021} \times Energy\ Intensity\ Index$$

Where $Energy\ Consumption\ Index = \frac{Efficiency\ in\ Reference\ Scenario\ (y_n)}{Efficiency\ in\ Reference\ Scenario\ _{2021}}$, derived from the EU Reference Scenario 2020 technology assumptions.

Some technologies, such as oil and coal-based systems, are assumed to maintain constant efficiency over time. For lighting and electrical appliances, the model incorporates projected efficiency improvements due to equipment replacement and anticipated technological advancements with the increasing adoption of more efficient technologies. This is implemented by gradually improving the relevant efficiency parameters over time, reflecting the expected enhancement in energy conversion efficiency for these end-uses.

Furthermore, according to the adopted technoeconomic assumptions, building renovation costs and savings potential are assumed to be different for every geographical region of the EU; both climatic and socioeconomic conditions matter in this case. Thus, the EU member states are grouped as shown below:

- **South**: Greece, Cyprus, Italy, Spain, Malta, Portugal
- **East**: Bulgaria, Estonia, Latvia, Lithuania, Romania
- **Centre/West**: Austria, Belgium, Czech Republic, Germany, France, Croatia, Hungary, Ireland, Luxembourg, Netherlands, Poland, Slovenia, Slovakia.
- **North**: Denmark, Finland, Sweden

It should be mentioned that a limitation on the rate of building renovations has been adopted for each country. Specifically, in the baseline scenario setup of CLEWs-EU up to 1.5% of the building stock is allowed to be renovated on an annual basis (0.75% light, 0.5% medium and 0.25% deep). These limits can be adjusted accordingly based on the respective scenario to be assessed by the model.

Table 6. Regional variation in savings and cost for renovation measures in the buildings sector of the CLEWs-EU model (adapted from the EU Reference Scenario 2020).

Regions	Extent of renovation	Energy savings (%)	Capital cost (Million EUR 2018/PJ annual savings)
Centre/West	Light renovation	15.8%	1134
	Medium renovation	68.7%	705
	Deep renovation	78.0%	900
North	Light renovation	22.3%	897
	Medium renovation	67.4%	749
	Deep renovation	86.6%	870
South	Light renovation	16.1%	853
	Medium renovation	56.5%	682
	Deep renovation	75.3%	802
East	Light renovation	12.9%	780
	Medium renovation	55.5%	452
	Deep renovation	68.6%	566

Finally, technology lifetimes are also sourced from available technology briefs (IEA ETSAP, 2012), which provide standardised estimates for the operational lifespan of various heating and cooling technologies in residential and commercial buildings.

1.2.1.3.2 Input data transformation

Due to the lower technological complexity adopted in CLEWs-EU, aggregation from the relevant input data is pursued. Specifically, we group similar technologies together to keep the model complexity low and to create meaningful categories for analysis. Energy service demands for the tertiary and residential sectors are aggregated together. JRC-IDEES (Rózsai et al., 2024) provides data for the use of hot water separately, but we group this thermal demand with space heating.

Table 7. Technology aggregation by end-use service and fuel, based on JRC-IDEES 2021 data.

Space heating & hot water	**OSeMOSYS code**	**Technology aggregation**
Oil boiler	*EUEBDOILBR00*	*SER(Diesel Oil(SP&HW)) + RES(Diesel Oil(SP&HW))*
Gas boiler	*EUEBDNGSBR00*	*SER(Gas heat pumps(SP) + Conventional gas heaters(SP) + LPG(SP&HW) + Natural gas(HW)) + RES(Natural gas(SP&HW) + LPG(SP&HW))*
Coal boiler	*EUEBDCOABR00*	*SER(solids(SP&HW)) + RES(solids(SP&HW))*
Biomass boiler	*EUEBDBIOBR00*	*SER(Biomass(SP&HW)) + RES(Biomass(SP&HW))*
Electric furnace	*EUEBDELCFC00*	*SER(Conventional electric heating(SP)+ Electricity in circulation and other use(SP&HW) + Electricity(HW)) + RES(Conventional electric heating(SP) + Electricity in circulation and other use(SP&HW) + Electricity (HW))*
Heat pump	*EUEBDELCHP00*	*SER(Geothermal(SP) + Advanced electric heating(SP)) + RES(Geothermal(SP&HW) + Advanced electric heating(SP))*
Solar thermal	*EUEBDSTHRP00*	*SER(Solar(HW)) + RES(Solar(HW))*
District heating	*EUEBDHEADH00*	*SER(Distributed Heat (SP&HW)) + RES(Distributed Heat(SP&HW))*
Space cooling		
Heat pump	*EUEBDELCHP00*	*RES(Air conditioning) + SER(Gas heat pumps + Electric space cooling)*
Cooking		
LPG stove	*EUEBDLPGSV00*	*SER(LPG) + RES(LPG)*
Gas stove	*EUEBDNGSSV00*	*SER(Natural gas) + RES(Natural gas)*
Electric stove	*EUEBDELCSV00*	*SER(Electricity) + RES(Electricity)*
Lighting & electrical appliances	EUEBDELCAP00	SER (Summary Specific Electricity Uses) + RES (Summary Specific Electricity Uses)

1.2.1.3.3 Building demand projections

Demand projections in the baseline scenario of CLEWs-EU are based on final energy demand projections for the residential and commercial sectors, retrieved from the EU Reference Scenario 2020 (European Commission - Directorate General for Energy. et al., 2021). For consistency with the JRC-IDEES-2021 data used for the calibration of the model, we indexed the values of the final energy demand projections to the base year 2021 and calculated coefficients relative to this baseline.

Specifically, in the baseline setup of the CLEWs-EU model, the growth rate of useful energy demand for each of the energy service demands in the period 2022-2050 resembles the collective final energy demand growth rate of the residential and tertiary sectors from the EU Reference Scenario 2020 (European Commission - Directorate General for Energy. et al., 2021). This implies that the overall efficiency will remain at current levels until mid-century. However, since the model allows building upgrades for improved energy efficiency, as well as assumes partial improvement of the energy efficiency of the technology stock for the various energy services, the baseline scenario of CLEWs-EU is expected to result in lower final energy demand projections than the EU Reference Scenario 2020. This can be adjusted in the scenario exploration phase of the DIAMOND project (i.e., in WP5).

More details on the exact demand projections by country and energy service are provided in the Supplementary

Material within the model's GitHub repository.

1.2.1.3.4 Units of building sector technologies and commodities

Since OSeMOSYS models do not have a specific unit definition, the adopted units must be defined externally prior to model development. As indicated in the tables below, the output of building technologies is defined in terms of their activity. The existing capacity of technologies is estimated based on the activity of technologies as extracted from the JRC-IDEES 2021 database.

Table 8. Units for the input and output of building technologies in the CLEWs-EU model.

Energy service technologies	Input	Output
Space heating & hot water	PJ fuel	PJ of useful energy for heating
Space cooling	PJ electricity	PJ of useful energy for cooling
Cooking	PJ fuel	PJ of useful thermal energy for cooking
Appliances	PJ electricity	PJ of useful energy for appliances
Energy efficiency upgrades	---	PJ of useful energy savings (cooling & heating)

Table 9. Units for the capacity and cost characteristics of building technologies in the CLEWs-EU model.

Mode of transport	Capacity	Capital cost	Fixed cost
Space heating & hot water	GW	Million EUR2018/GW	Million EUR2018/GW
Space cooling	GW	Million EUR2018/GW	Million EUR2018/GW
Cooking	GW	Million EUR2018/GW	Million EUR2018/GW
Appliances	PJ/year	---	---
Energy efficiency upgrades	PJ/year	Million EUR2018/PJ yearly savings	---

1.2.1.4 Industry

Representation of industry in the CLEWs-EU model is largely based on data retrieved from the JRC-IDEES 2021 database (Rózsai et al., 2024). Specifically, the database provides statistics on the final energy demand and useful energy demand for each sector by process and by technology/fuel for the period 2000-2021 but, for the purposes of CLEWs-EU, we only focused on the period 2018-2021.

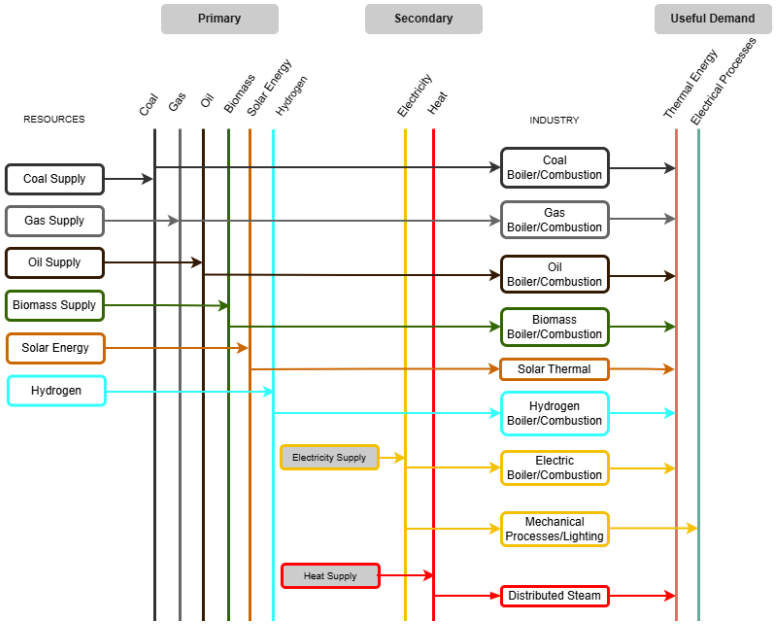

Figure 7. Simplified representation of industry in the CLEWs-EU model.

As a first step, the key industrial sectors in each country are identified based on the level of final energy demand in 2021 (Table 10); for each country, up to 4 main sectors are represented separately, while the rest of the sectors are aggregated into an "Other industrial sectors" category. Instead of representing the same key industrial sectors in each country (e.g., iron and steel, cement, non-metallic minerals, pulp and paper) and then aggregating the remaining industries in a separate category, this approach is chosen because in some countries such key industries are non-existent or have very little impact on the final energy demand. This may not allow comparability across countries, but it captures national heterogeneity and enables nationally relevant outlooks for each EU member state. Also, in this manner, a base is built upon which further detail can be included in future enhancements of the CLEWs-EU model, where the relevant processes of the key national industries can be explicitly represented.

Furthermore, in countries where industrial energy demand is low, the number of sectors represented is lower (e.g., Cyprus, Luxembourg, Malta, etc.). As mentioned above, the output of each of the industries is represented in generic energy terms (i.e., PJ of useful energy services). As more data becomes available in the future (e.g., after completion of the DIAMOND project), a more explicit representation of key industries can be pursued.

Table 10. Industrial sector representation in the disaggregated CLEWs-EU version.

Country	ISI	NFM	CHI	NMM	PPA	FBT	TRE	MAE	TEL	WWP	OIS
Austria	X		X	X	X						X
Belgium	X		X	X		X					X
Bulgaria		X	X	X		X					X
Cyprus				X		X					X
Czechia	X		X	X	X						X
Germany	X		X	X	X						X
Denmark			X	X		X		X			X
Estonia					X	X		X		X	X
Greece	X	X		X		X					X
Spain	X		X	X		X					X
Finland	X		X		X					X	X
France			X	X	X	X					X
Croatia			X	X	X	X					X
Hungary			X	X		X		X			X
Ireland		X	X	X		X					X
Italy	X		X	X				X			X
Lithuania			X	X		X				X	X
Luxembourg	X			X							X
Latvia				X		X				X	X
Malta											X
Netherlands	X		X	X		X					X
Poland	X		X	X		X					X
Portugal			X	X	X	X					X
Romania	X	X	X	X							X
Sweden	X		X		X	X					X
Slovenia	X		X	X				X			X
Slovakia	X		X	X	X						X

Note: The industrial sectors represented are the following: Iron and Steel (ISI), Non-ferrous metals (NFM), Chemical industry (CHI), Non-metallic minerals (NMM), Pulp, paper and printing (PPA), Food, beverages and tobacco (FBT), Transport equipment (TRE), Machinery equipment (MAE), Textiles and leather (TEL), Wood and wood products (WWP), Other industrial sectors (OIS).

1.2.1.4.1 Technoeconomic characteristics of industrial technology options

Data on final energy demand and useful energy demand are aggregated for each fuel category in each of the represented sectors and an efficiency is calculated for the years 2018-2021. Specifically, the technological/fuel options for satisfaction of demand for useful energy are the following:

- **Thermal energy –** coal (with and without CCS), oil, natural gas (with and without CCS), biomass/biofuels, hydrogen, solar thermal, centralised steam, electricity.
- **Electrical processes (lighting, motor drives etc.) –** electricity.

Adopting the same approach as for the buildings sector, projections on how the capital cost and efficiencies of industrial boilers will evolve until 2050 are based on EU Reference Scenario 2020 assumptions (European Commission - Directorate General for Energy. et al., 2021). However, efficiency is indexed to the last available year's statistics (i.e., 2021) from the JRC-IDEES 2021 database (Rózsai et al., 2024). An overview of key technoeconomic assumptions in the industrial sector is provided in Table 11.

Table 11. Technoeconomic assumptions of industrial boiler technologies in the CLEWs-EU model (adapted from EU Reference Scenario 2020).

Technology	Capital cost (EUR2018/kW)			Fixed O&M cost (EUR2018/kW)			Energy Consumption Index (2021=100%)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050
Oil	232	252	252	1.32	1.32	1.32	100%	91%	91%
Coal	356	386	386	1.37	1.37	1.37	100%	91%	91%
Coal with CCS*	2203	2085	1888	38.37	35.01	30.46	115%	114%	107%
Gas	119	128	128	1.25	1.25	1.25	100%	92%	92%
Gas with CCS*	1350	1256	1133	22.75	20.14	16.09	132%	126%	121%
Biomass	771	836	836	1.37	1.37	1.37	100%	92%	92%
Electricity (heat)	701	683	673	10.36	10.36	10.36	100%	100%	100%
Electrical processes	---	---	---	---	---	---	100%	94%	87%
Hydrogen**	119	128	128	1.25	1.25	1.25	100%	92%	92%
Solar thermal	1308	1432	1119	15.54	15.54	15.54	100%	95%	92%

**Coal with CCS and gas with CCS capital and fixed cost are based on modellers' own assumptions using cost differences from relevant power generation technologies in the EU Reference Scenario 2020 assumptions. Similarly, their efficiency is estimated in the same manner; in these cases, the Energy Consumption Index refers to a comparison with the respective technology without CCS for the same year. For instance, the efficiency of gas with CCS is 32% higher in 2021 compared to the same technology without CCS.*

***Hydrogen boilers are assumed to have the same assumptions as gas boilers.*

Data extraction and preparation from JRC-IDEES statistics to data ready for direct input into the model has been conducted with specially developed Python scripts. These scripts provide detail on the technology/fuel aggregation for each industry and on how the selected industries vary across the countries and are made available on the model's GitHub repository.

1.2.1.4.2 Industrial demand projections

The useful energy demand in 2021 for the various industries is taken from the JRC-IDEES 2021 database (Rózsai et al., 2024). In the baseline setup of the model, the growth rate of useful energy demand for the period 2022-2050 resembles the final energy demand growth rate of energy-intensive and non-energy-intensive industries from the EU Reference Scenario 2020. Energy-intensive industries include iron and steel, non-ferrous metals, chemicals, non-metallic minerals and pulp and paper; these are assumed to be subject to the existing ETS. The rest of the industrial sectors are assumed to be subject to the new ETS (i.e., ETS2) from 2027 onwards (European Commission - Directorate-General for Energy, 2025a).

Adopting the same growth rate for useful demand as for final energy demand from the EU Reference Scenario 2020 entails the assumption that the overall efficiency will remain at current levels until mid-century; this can be amended in the scenario exploration phase of the DIAMOND project (i.e., in WP5). Separate demand projections are developed for each of the key industries of each member state. In turn, these are split between demand for useful thermal energy and useful demand for electrical processes; as indicated above, the latter is satisfied by a single technology option.

More details on the exact demand projections by country and industrial sector are provided in the Supplementary Material within the model's GitHub repository.

1.2.1.4.3 Units of industrial sector technologies and commodities

OSeMOSYS models do not have a specific unit definition; as such, the adopted units must be defined externally before model development. As indicated in the tables below, the output and capacity of industrial technologies are defined in terms of their activity. The existing capacity of technologies is estimated based on the activity of technologies as extracted from the JRC-IDEES 2021 database.

Table 12. Units for the input and output of industrial technologies in the CLEWs-EU model.

Technology	Input	Output	Capacity	Capital cost & Fixed cost	Fuel cost
Thermal & electrical processes	PJ fuel	PJ of useful heat	GW	Million EUR2018/GW	Million EUR2018/PJ

1.2.1.5 Transport

Similar to the other sectors of the energy system, the representation of the transport sector is constructed using data from the JRC-IDEES 2021 database (Rózsai et al., 2024). Specifically, relevant statistics are retrieved on the biofuel blending ratios in each mode of transport, existing stock of technologies, annual rate of activity (passenger and freight) and current efficiency levels of each technology. Key assumptions (e.g., efficiencies, annual mileage etc.) vary considerably between member states, hence country-specific information is adopted. Table 13 summarises the technology options represented for each mode of transport.

Table 13. Technology options in the transport module of CLEWs-EU.

Mode of transport		Technology options
Road transport	**Passenger cars**	Gasoline vehicles, Diesel vehicles, CNG/LNG vehicles, LPG vehicles, Hybrid electric vehicles, Plug-in electric vehicles, Battery electric vehicles, Hydrogen fuel cell vehicles
	Buses	Diesel bus, CNG bus, Battery electric bus, Hydrogen fuel cell bus
	Light commercial vans	Gasoline light trucks, Diesel light trucks, CNG/LNG light trucks, Hybrid electric light trucks, Plug-in electric light trucks, Battery electric light trucks, Hydrogen fuel cell light trucks
	Heavy trucks	Diesel heavy trucks, CNG/LNG heavy trucks, Hybrid electric heavy trucks, Battery electric heavy trucks, Hydrogen fuel cell heavy trucks
Rail transport	**Passenger**	Diesel train, Electric train
	Freight	Diesel train, Electric train
Aviation	--	Conventional kerosene planes, electric planes, hydrogen/e-fuel planes
Shipping	--	Oil vessels, LNG vessels, Hydrogen/syn fuel vessels

As in the case of the industrial sector, Python scripts have been used for the transport data preparation and are also made available in the model's GitHub repository.

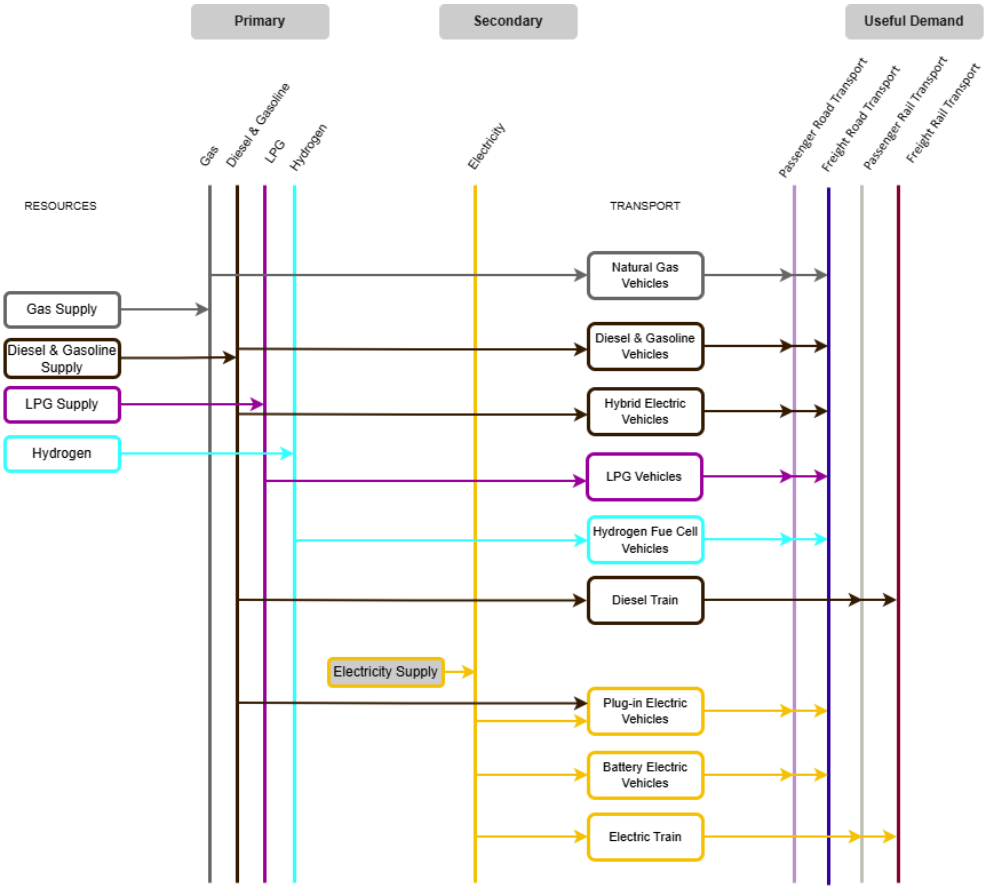

Figure 8. Simplified representation of land transport in the CLEWs-EU model.

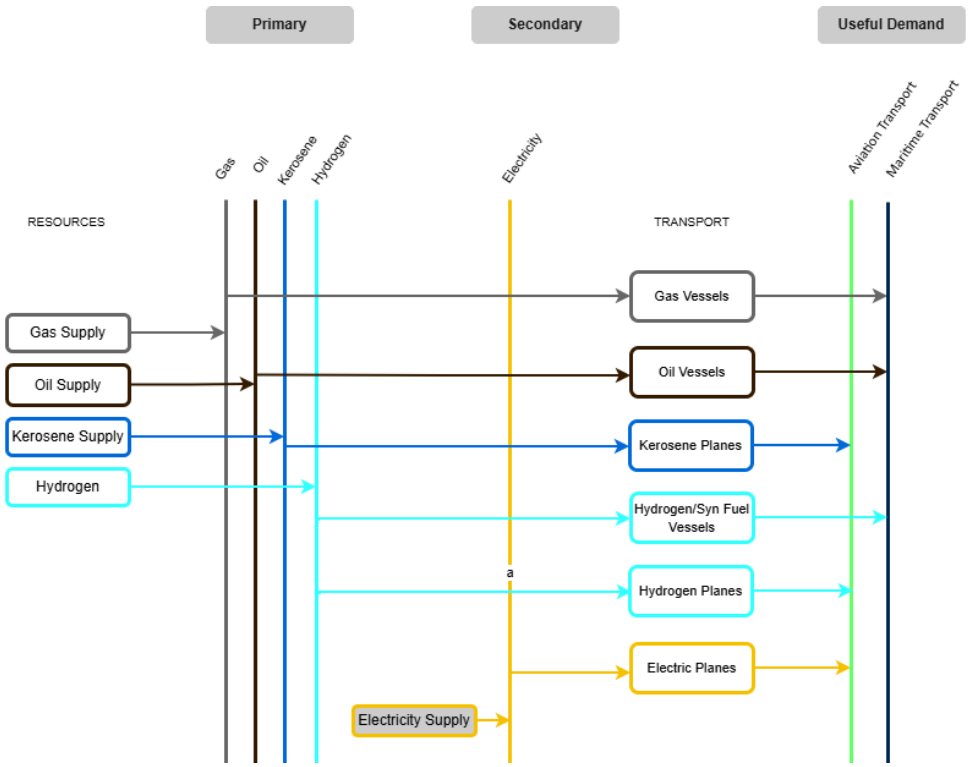

Figure 9. Simplified representation of aviation and shipping in the CLEWs-EU model.

1.2.1.5.1 Technoeconomic characteristics of mobility technology options

Technoeconomic characteristics of the various technologies and the evolution of the mobility demand for each mode of transport are based on the equivalent assumptions from the EU Reference Scenario 2020 (European Commission - Directorate General for Energy. et al., 2021), but are adjusted to agree with the base year statistics. Specifically, efficiency for each transport technology from JRC-IDEES in 2021 in each country is used as the starting point and its evolution is indexed to the growth rate projected in the EU Reference Scenario for the period up to 2050. In addition, the capital cost of transport technologies is based on the relevant technology assumptions of the EU Reference Scenario 2020, but the adopted number of technologies is lower for the sake of simplification. For instance, in the case of passenger vehicles, the corresponding values for medium cars are chosen for each technology option and these act as representative technologies.

Table 14. Capital cost of transport technologies in the CLEWs-EU model (adapted from EU Reference Scenario 2020).

Mode	Technology	Unit	2021	2025	2030	2040	2050
Passenger road	Gasoline vehicles	EUR2018/vehicle	20,084	20,140	20,794	21,553	23,431
	Diesel vehicles	EUR2018/vehicle	23,540	23,685	24,366	25,833	34,858
	CNG/LNG vehicles	EUR2018/vehicle	22,239	22,295	22,949	23,709	25,586
	LPG vehicles	EUR2018/vehicle	21,652	21,708	22,361	23,121	24,998
	Gasoline hybrid electric vehicles	EUR2018/vehicle	22,450	21,699	21,854	21,985	22,264
	Diesel hybrid electric vehicles	EUR2018/vehicle	25,750	24,957	25,079	25,254	25,492
	Plug-in electric vehicles	EUR2018/vehicle	26,673	23,419	22,296	21,967	21,973
	Battery electric vehicles	EUR2018/vehicle	37,319	34,664	24,709	22,919	22,396
	Hydrogen fuel cell vehicles	EUR2018/vehicle	49,782	37,348	31,330	29,985	30,170
	Diesel bus	EUR2018/vehicle	287,109	287,844	290,033	291,898	294,695
	CNG bus	EUR2018/vehicle	312,165	312,900	315,089	316,954	319,751
	Electric bus	EUR2018/vehicle	444,300	420,053	329,131	308,306	299,329
	Hydrogen fuel cell bus	EUR2018/vehicle	576,118	402,723	343,597	328,325	328,729
Freight road	Gasoline light trucks	EUR2018/vehicle	18,535	18,608	19,880	22,328	27,952
	Diesel light trucks	EUR2018/vehicle	23,336	23,571	25,683	31,935	31,935
	CNG/LNG light trucks	EUR2018/vehicle	20,701	20,774	22,046	24,494	30,118
	Hybrid electric light trucks	EUR2018/vehicle	25,316	24,340	24,479	24,651	24,872
	Plug-in electric light trucks	EUR2018/vehicle	29,346	25,619	24,518	24,224	24,359
	Battery electric light trucks	EUR2018/vehicle	37,489	35,018	25,755	22,940	22,117
	Hydrogen fuel cell light trucks	EUR2018/vehicle	45,010	35,109	29,449	28,300	28,633
	Diesel heavy trucks	EUR2018/vehicle	82,977	83,760	85,202	87,326	90,454
	CNG/LNG heavy trucks	EUR2018/vehicle	102,438	103,221	104,663	106,787	109,914
	Hybrid electric heavy trucks	EUR2018/vehicle	91,463	88,932	88,031	87,698	88,517
	Battery electric heavy trucks	EUR2018/vehicle	182,915	170,477	123,834	107,803	103,601
	Hydrogen fuel cell heavy trucks	EUR2018/vehicle	273,991	171,693	132,082	118,724	119,183
Passenger rail	Diesel train	MillionEUR2018/unit	9.2	9.3	9.4	9.7	10.1
	Electric train	MillionEUR2018/unit	12.6	12.7	12.8	13.2	14.3
Freight rail	Diesel train	MillionEUR2018/unit	10.1	10.3	10.6	11.1	12.0
	Electric train	MillionEUR2018/unit	12.8	13.0	13.3	13.8	14.8
Aviation	Kerosene planes	MillionEUR2018/unit	115.5	117.0	118.8	123.1	129.2
	Electric planes	MillionEUR2018/unit	---	---	319.8	247.3	228.9
	Hydrogen planes	MillionEUR2018/unit	---	---	149.8	144.8	146.1
Shipping	Oil vessels	MillionEUR2018/unit	22.3	22.3	22.3	22.3	22.3
	Gas vessels	MillionEUR2018/unit	24.9	24.9	24.9	24.9	24.9
	Hydrogen/syn fuel vessels	MillionEUR2018/unit	---	---	34.2	31.1	30.1

Due to the large variation in the efficiency and mileage of each transport technology across countries, the relevant data extracted from JRC-IDEES 2021 is substantial. For this reason, the Python scripts used to extract and prepare

the respective input data are provided in the model's GitHub repository.

1.2.1.5.2 New ETS and automotive fuel price assumptions

The model uses as a starting point the international fuel price projections of the European Commission recommendations (European Commission - DG CLIMA, 2024). Then, statistics for automotive fuel prices from the Weekly Oil Bulletin (European Commission - Directorate-General for Energy, 2025b) are used to come up with fuel price projections until 2055. The price projections are initially estimated without taxes and duties, but the relevant information on the tax regime by the end of 2023 has been used to compile fuel prices with taxes and levies. In the baseline scenario setup of CLEWs-EU, the base year's tax regime remains constant across the model horizon.

ETS2 is planned to be expanded to include road transport and will become fully operational in 2027 (European Commission - Directorate-General for Energy, 2025a). ETS2 is included in the baseline setup of the CLEWs-EU model.

In the case of electricity cost for battery electric and plug-in hybrid vehicles, the cost of electricity includes all taxes and levies. Specifically, the cost of generated electricity in each country is calculated endogenously by the model, but the relevant technologies representing transmission and distribution also include relevant taxes and levies. Statistics from Eurostat are used to extract country-specific information on this aspect. In the case of electricity for electric mobility, due to the higher number of passenger vehicles that correspond to battery electric vehicles, the relevant electricity cost figures for household consumers are adopted (Eurostat, 2025d).

1.2.1.5.3 Mobility demand projections

The activity level of each mode of transport and technology option in 2021 is extracted from the JRC-IDEES 2021 database. The level of activity for each existing road transport technology option is only allowed to decrease within a certain percentage range to prevent unrealistic drops in the usage of specific technologies; this is primarily guided by the assumed operational lifetime of the respective vehicles. Similarly, the registrations of new vehicles are constrained by the actual rate of change of the vehicle fleet stock.

In regard to the future evolution of activity for each mode of transport, the relevant projections from the EU Reference scenario are used (European Commission - Directorate General for Energy. et al., 2021). Specifically, the level of activity in 2021 is extracted from the JRC-IDEES 2021 database and used as a starting point. Then, the growth rate foreseen in the EU Reference Scenario is adopted and applied to come up with new projections until 2050. It should be clarified that the respective growth rate varies for each mode of transport and country across the EU.

1.2.1.5.4 Charging infrastructure

The future deployment of large numbers of electric vehicles will necessitate equivalent investments in charging infrastructure. A representative charging point technology is used to represent the relevant infrastructure, whose cost characteristics are based on the EU Reference Scenario 2020 technology assumptions.

Table 15. Cost characteristics of electric recharging in the CLEWs-EU model (adapted from EU Reference Scenario 2020).

	Capital cost			**Fixed O&M cost**		
	2021	**2030**	**2050**	**2021**	**2030**	**2050**
EUR2018/kW	603	440	367	7.24	5.28	4.4

1.2.1.5.5 Biofuel and alternative fuel supply

The current energy mix of the transport sector in the EU is dominated by oil products, but this is gradually changing as alternative fuels are introduced in the stock of technologies. The model has the option to invest in technologies that are powered by natural gas, LPG, hydrogen, and biofuels. The extent to which these fuels are used in the modelling horizon depends on the cost-competitiveness of the respective technology option is combination with the fuel cost and the respective emissions penalty, if applicable (i.e., through ETS2).

In the case of biofuels, we allow conventional internal combustion engine (ICE) vehicle technologies to use blended fuel (e.g., diesel with biodiesel or gasoline with bio gasoline). The blending ratio at the start of the model horizon is based on the 2021 fuel statistics as retrieved for each country from the JRC-IDEES 2021 database. In the Baseline scenario setup of the CLEWs-EU model, this ratio is kept constant, but in future scenarios it can be increased according to the relevant scenario narrative. Similarly, if one would like to explore the possibility of vehicles run by 100% biofuels, this adjustment can easily be accommodated in the model either through the aforementioned blending ratio or by altering the input fuel of ICE vehicles to the respective biofuel supply. A similar approach is followed for road transport, rail transport, and shipping.

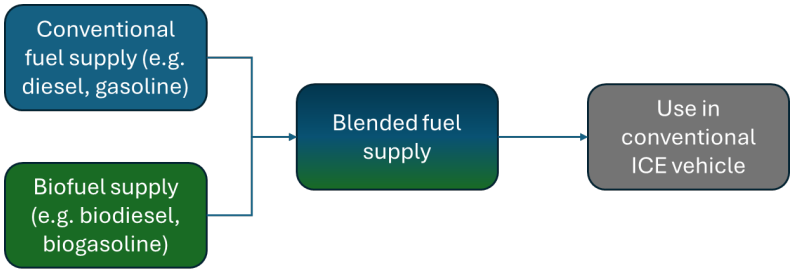

Figure 10. Biofuel use in transport technologies in the CLEWs-EU model.

In the case of aviation, due to the very specific requirement of the ReFuelEU Aviation regulation, the provision for Sustainable Aviation Fuels (SAF) is included in the model but is kept deactivated in the Baseline Scenario setup of CLEWs-EU. SAF can refer to (a) synthetic aviation fuels, (b) aviation biofuels, or (c) recycled carbon aviation fuels; only the first two are represented in the CLEWs-EU model. Similar to the blending of biofuels in land transport, a minimum use of SAF is enforced based on the relevant legislation (Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on Ensuring a Level Playing Field for Sustainable Air Transport (ReFuelEU Aviation), 2023). It should be noted that the respective future minimum requirements for synthetic aviation fuels are not forced in the Baseline scenario of the CLEWs-EU model but are included as optional shares. The defined minimum shares of SAF according to the ReFuelEU Aviation regulation are as follows:

a) From 1 January 2025, each year a minimum share of 2 % of SAF.
b) From 1 January 2030, each year a minimum share of 6 % of SAF.
c) From 1 January 2035, each year a minimum share of 20 % of SAF.
d) From 1 January 2040, each year a minimum share of 34 % of SAF.
e) From 1 January 2045, each year a minimum share of 42 % of SAF.
f) From 1 January 2050, each year a minimum share of 70 % of SAF.

1.2.1.5.6 Units of transport sector technologies and commodities

As mentioned previously in the CLEWs-EU model documentation, OSeMOSYS models do not have a specific unit definition, and the adopted units must be defined externally prior to the model development. This is comparatively more complicated in the transport sector than for the rest of the energy module. As indicated in the tables below,

the output and capacity of transport technologies is defined in terms of their activity. The stock of technologies is converted externally into the required units by multiplying the stock with the annual usage of each technology (i.e., mileage), which is extracted from the JRC-IDEES 2021 database.

Table 16. Units for the input and output of transport technologies in the CLEWs-EU model.

Mode of transport	Input	Output
Road transport	PJ	Billion vehicle kilometres (G-veh km)
Passenger rail	PJ	Billion passenger kilometres (Gpkm)
Freight rail	PJ	Billion tonne kilometres (Gtkm)
Aviation	PJ	Million vehicle kilometres (M-veh km)
Shipping	PJ	Billion tonne kilometres (Gtkm)

Table 17. Units for the capacity and cost characteristics of transport technologies in the CLEWs-EU model.

Mode of transport	Capacity	Capital cost	Fuel cost
Road transport	G-veh km/year	Million EUR2018/G-veh km/year	Million EUR2018/PJ
Passenger rail	Gpkm/year	Million EUR2018/Gpkm/year	Million EUR2018/PJ
Freight rail	Gtkm/year	Million EUR2018/Gtkm/year	Million EUR2018/PJ
Aviation	M-veh km/year	Million EUR2018/M-veh km/year	Million EUR2018/PJ
Shipping	Gtkm/year	Million EUR2018/Gtkm/year	Million EUR2018/PJ

1.2.1.6 Hydrogen

Hydrogen is a fuel whose role may be critical to the decarbonisation of certain sectors, especially in industry and some transportation modes. As such, the supply and production of this fuel have to be represented in the CLEWs-EU model. This fuel enters the energy module of the CLEWs-EU model either through imports or domestic production. Production of hydrogen can occur through steam methane reforming (SMR) with (blue) or without CCS (grey) using natural gas as feedstock, or through electrolysis (green). Hydrogen can then be used in the transport sector or in industry. For use in the aviation sector, hydrogen is first converted into jet fuel.

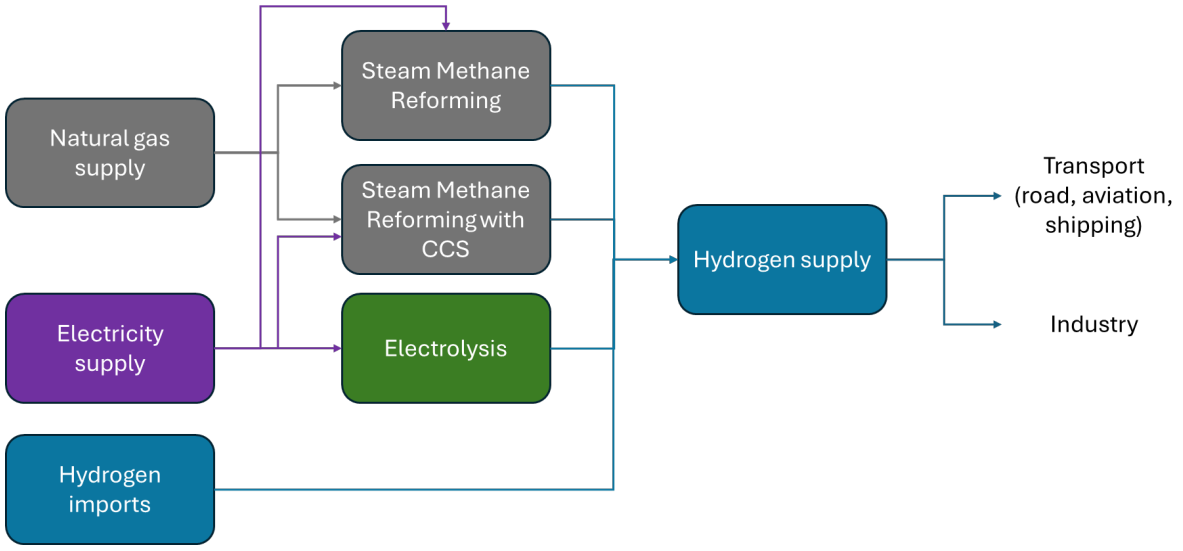

Figure 11. Hydrogen supply in the CLEWs-EU model.

The technoeconomic assumptions for the relevant hydrogen production technologies are drawn from EU Reference Scenario 2020 assumptions (European Commission - Directorate General for Energy. et al., 2021). Specifically, the adopted input is shown in Table 18.

Table 18. Technoeconomic characteristics of hydrogen production technologies (adapted from EU Reference Scenario 2020).

Technology	Capital cost (EUR2018/kW)			Fixed O&M cost (EUR2018/kW)			Efficiency (energy output vs input)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050
Electrolysis	1241	621	186	27.5	14.5	9.3	72%	79%	85%
SMR	564	518	466	22.6	20.7	18.6	70%	72%	73%
SMR with CCS	927	880	829	37.1	35.2	33.1	41%	42%	42%

1.2.2 Land and Water module

The land use and water modules are effectively interlinked. Although we use different naming conventions and technologies to represent the two modules in CLEWs-EU, their inputs and outputs are interdependent. The water module represents the following primary sources: water from precipitation and snowmelt (represented as a single entity); water from existing surface and groundwater sources; water from neighbouring geographies through transboundary river exchanges; and water from desalination and secondary sources, such as treatment plants in some countries. The model includes a simplified representation of the water balance for each country. In the land module, the total land available in the continent (in the aggregated model) and in each country (in the disaggregated model) is divided into eight major land categories based on the European Space Agency's land cover classifications (Eurostat, 2025a). These are: grassland, cropland, barren land (including snow-covered areas), water bodies, shrubland, forest cover, built-up land, and wetlands (including mangroves, lichens, and other types of wetlands). Representing land and water systems in a generic systems optimisation setup involves using relevant assumptions to simplify their characterisation while ensuring that little 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 they involve detailed subsurface flow modelling, which is outside the scope of the model. Additionally, detailed hydrological water routing across countries is outside the scope of this work. In the following sections, the overarching assumptions and the technology representation in the land and water module are presented.

1.2.2.1 Overarching assumptions

In the land and water module, the central assumptions concern the simplifications used to represent the actual setup in each country. In each of the following sections, the country-specific assumptions used in the model are detailed. One common assumption that holds across countries is the growth rate of crop production, which is used as a demand driver in this model. These growth rates (presented in Table 19) are obtained from the European Union's agricultural outlook 2024-2035 (DG Agriculture and Rural Development, 2024). For crops without a specific growth rate in the outlook, we use an average of all crops, which is also applied to the other (OTH) crop category, which aggregates the crops other than the top ten in each country by planted area. We have maintained the same growth rate between 2035 and 2055, as no specific projections were available for that period.

Table 19. Annual growth rates (%) in crop production from the EU-Agricultural Outlook (2024-2035).

Crops	Code	Average annual growth rate (2024-2035)
Wheat	WHE	-0.10%
Barley	BRL	0.10%
Rape seed	RAP	-0.40%
Rye	RYE	0.20%
Maize	MAI	0.40%
Sugar beet	SUG	-0.70%
Potatoes	POT	-0.80%
Oats	OAT	0.20%
Grapes	GRP	-0.80%
Olives	OLI	-0.40%
Other crops	OTH	-0.23%

1.2.2.2 Module structure and technological representation

Figure 12 represents a diagrammatic illustration of the land component within the broader CLEWs systems framework. The diagram breaks down "Total land" into various land uses and their subsequent products or services. The diagram is a schematic and should be used only as an example of how land cover/use is split in a typical CLEWs model.

Land Uses:

This includes various land classifications, such as cropland, barren land, forests, pastures/grasslands, Built-up land, water bodies, and wetlands. Each land-use category is dedicated to a specific type of production or ecosystem service.

Production:

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

- Cropland is associated with the production of agricultural commodities like maize, rice, wheat, sugarcane, and other crops. The crops represented in the model vary by country. The choice is based on the area under cultivation by each crop. Crop residues constitute a share of the biomass used in the energy sector.
- Forests contribute to the production of woody biomass.
- 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.

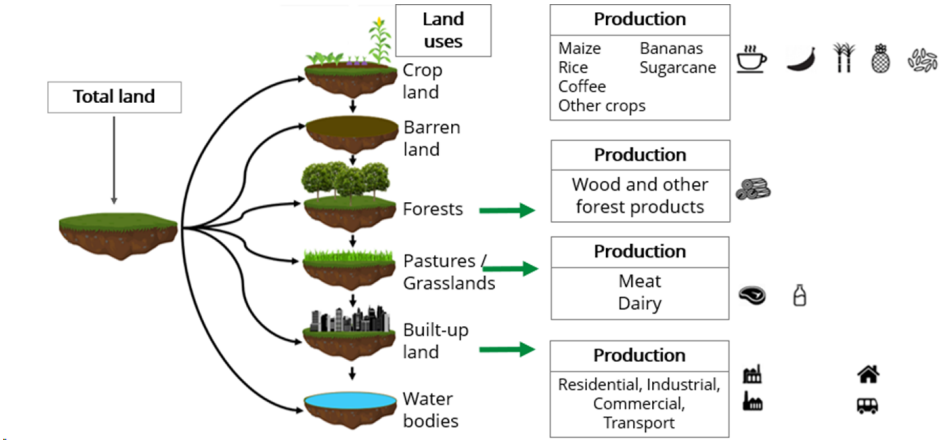

Figure 12. Primary level of land categories breakdown in the land module of CLEWs-EU.

A more complex system diagram is illustrated in Figure 13 and portrays how the CLEWs-EU land and water modules are represented, along with key interactions with the energy module. Solid lines show the actual links, and dotted lines show potential links that exist but are temporarily disabled to reduce the computation load during optimisation.

The diagram is classified into different colours, each representing different components of the CLEWs systems:

1. *Land Use (Green):* This group lists various types of land uses such as agricultural land (which is divided into up to 10 different crop types), barren land, forests, built-up land, water bodies and wetlands. Each land type is linked to specific outputs, i.e., specific crops and the different aspects of the water system. In Figure 13, only maize has been included to simplify the representation of crop cover.

2. *Precipitation and Sea Water (Blue):* 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.

3. *Energy Supply and Use (red and black):* The diagram includes the links with the energy module. These predominantly include energy use in the agriculture and forestry sectors, as well as in the water module for pumping and water treatment activities.

4. *Interlinkages (arrows and lines with different colours):* 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. Runoff (water) from each land cover category contributes to the surface and groundwater resources.

5. *Backstop technologies (Pink):* The pink circular entities are modelling specific structures and are included in the model to identify errors and resource insufficiencies.

6. *Fertiliser (Orange):* The fertilisers utilised to increase crop yields are also presented here. It is worth noting that some of these fertilisers are produced outside the EU27.

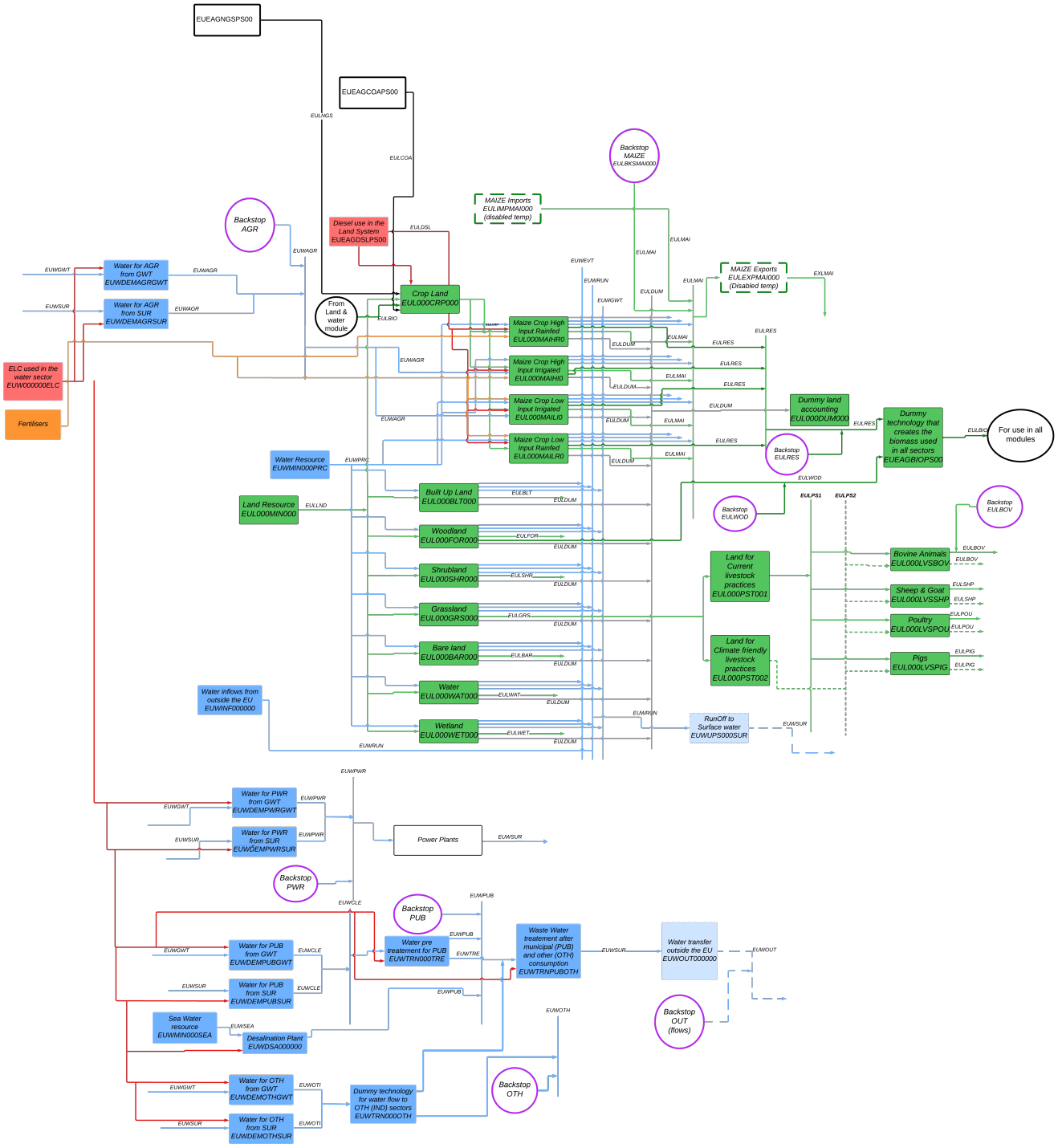

Figure 13. The CLEWs land & water model structure represented in each EU member state.

Note: High resolution image can be accessed here.

A detailed naming convention for the technologies (in shapes) and commodities (lines) is available on the GitHub repository.

1.2.2.3 Modelling crop selection and demands

As described earlier, within the cropland category for each country, we rank crops by cultivated area in 2018 and select the top 9, which are represented individually. The remaining crops are grouped together and included in a

bundled category. Therefore, there are effectively 10 crop categories, with 9 unique ones represented in each country. The number of crops is lower for countries like Malta and Luxembourg, owing to the total number of crops grown. In the majority of EU27 countries, the top nine crops account for more than 85% of cultivated cropland (FAO, 2024). The crops selected for each country can be accessed in the country-specific input files for the land and water module (on GitHub).

For each of these selected crops, two input levels and two water supply options are considered. The input levels (high and low) refer to the degree of mechanisation and the use of fertilisers in the farming techniques, both of which directly influence yield. The water supply options refer to whether the crop is irrigated or rainfed. The water requirement for irrigation is derived from the Global Agro-Ecological Ecological Zoning (GAEZ) crop water deficit, which is specific to each crop and the climatic pattern and the country (Fischer, 2021). The different input and water supply combinations available for each crop are presented in Figure 14.

As the exact area under irrigation per crop per country is not available, we use the EU-wide average percentage of irrigated area for each crop. We decided to use this value to simplify the representation of irrigation inside the model. For example, crops such as olives have a higher irrigation share (19% of total cultivated area), while crops such as wheat may have a lower share (~2–3%). Overall, the share of cultivated land under irrigation is approximately 7% (Eurostat, 2019).

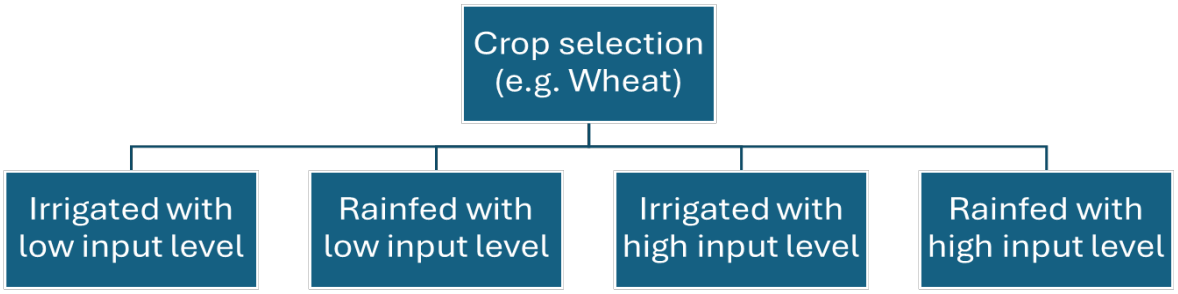

Figure 14. Crop classification in the CLEWs EU model.

The EU agricultural outlook (European Commission, 2025b) provides projections for major EU agricultural markets until 2035. In this model, the actual production numbers are presented as crop demands until 2023. From 2024, the crop production projections from the outlook have been used to estimate demand for each crop in each EU member state. These growth rates and the assumptions are presented in Table 19. It must be noted that the import and export of crop commodities have not been included in this model. Owing to the uncertainty in price projections and to avoid computational complexity, it has been decided to represent only local production. Having said that, the model provides for the inclusion of exports and imports of any commodity.

1.2.2.4 Modelling other land categories.

The model also considers other landcover types: forests, grasslands (includes pasture), wetlands, built-up lands, barren land, water bodies, and shrublands. In this model, the focus is on croplands, forests and grasslands. Therefore, as a common practice in similar modelling frameworks, we keep the shares of other categories, except built-up land, constant.

1.2.2.4.1 Built up land

To represent urban growth on artificially built-up land, we use the OECD's land cover change dataset between 2000 and 2020 and use the 20-year compounded annualised growth rate (CAGR) for each country (Vladimir Tesnière, Mikaël J. A. Maes, Ivan Haščič, 2024). This process involves using the raw GIS data to compute the final

numbers. The country-specific values are available on the public GitHub repository.

1.2.2.4.2 Forests and grasslands expansion

Forested and grassland areas are provided with an economic incentive to keep the land under these land-cover types. It is also essential to highlight that they have GHG sequestration potential, which varies by country. The incentive presented as negative variable costs is basically a way to represent the opportunity cost of removing the forests and grasslands for agriculture and other purposes. We have maintained these costs unchanged across all countries, as it was not possible to estimate an opportunity cost for each country. This is also one of the limitations of the model, as highlighted in Section 4.1. Additionally, the forests and grasslands in each country have maximum growth rates aligned with national policies. These values are derived from national projections. The maximum annual growth rate is limited from 2024 onward, as actual land cover values are only available through 2023.

1.2.2.5 Energy use in the land and water module

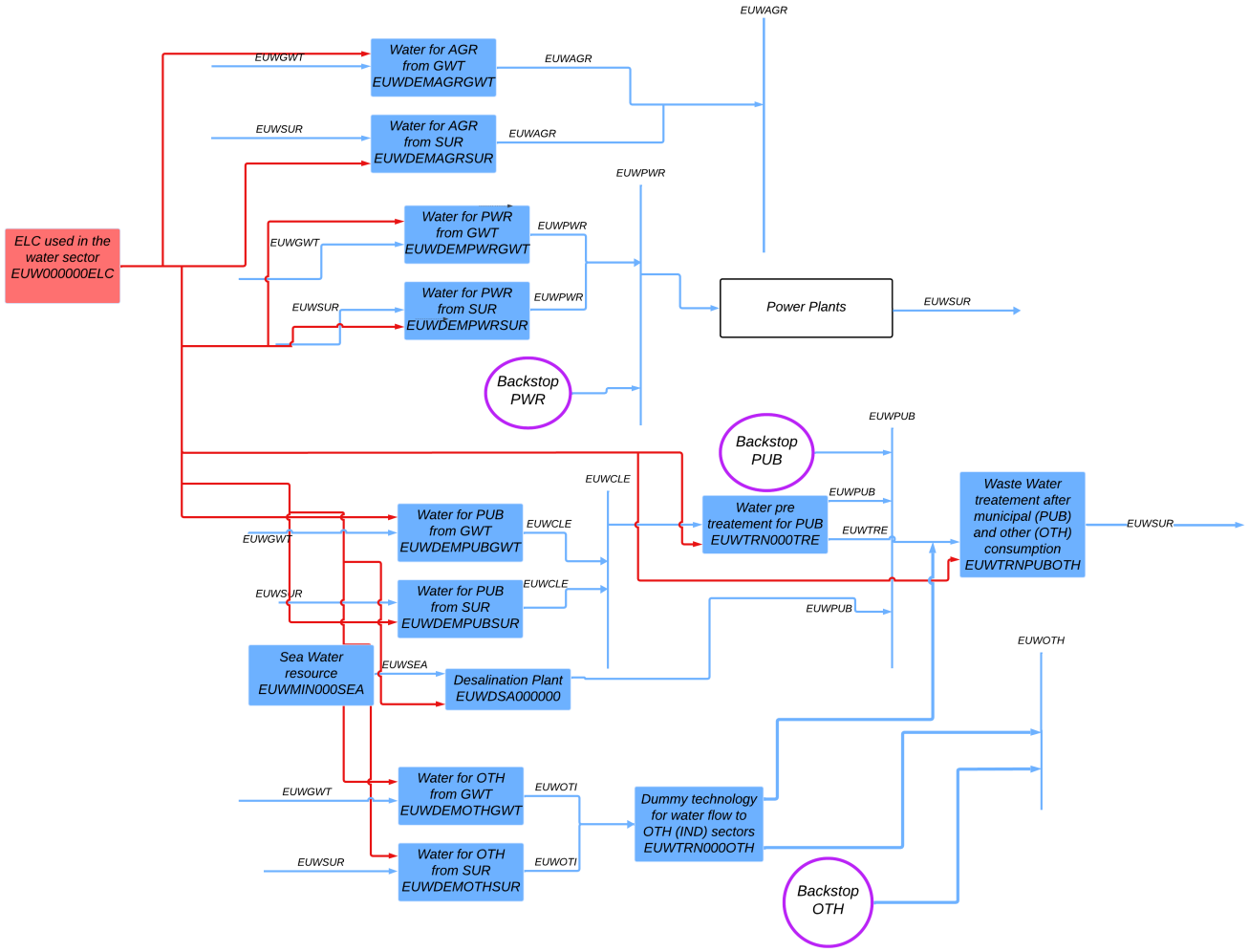

Figure 15. Electricity use in the CLEWs-EU water system. Red lines represent the electricity flows.

Energy used in the water and land use module is modelled by linking the energy inputs (fossil fuels and electricity) from the energy module with the respective end-use sectors. Electricity is used in the agricultural sector for pumping water from surface and groundwater sources, for treating water before sending it for household consumption, and for treating water after use before releasing it into surface water bodies. Figure 15 presents the section of the system where the electricity flows from the energy module are provided as inputs to the pumping technologies that supply water for irrigation, cooling in thermal power plants, and supply to other commercial

and industrial needs. The energy use factors for pumping were obtained from (Plappally & Lienhard V, 2012). The efficiencies and the cost of both types of treatment mentioned above are obtained from ((Paraschiv et al., 2023; Schiller & Dirlich, 2015; *Urban Waste Water Directive Treatment Plants Data Viewer*, 2017). We assume a uniform energy intensity for all the countries. The cost of treatment always includes an energy component. We have attempted to remove this component to prevent double-counting. However, this section could be improved with more actual project-specific costs.

Additionally, the national-level energy balances (Rózsai et al., 2024) have been used to account for all other energy flows to the agriculture and forestry sectors. To simplify the representation of these energy inputs, we subtract the total energy for pumping and diesel consumption in the land-use sector from the total energy used (by fuel) in the agricultural and forestry sector. This resulting value is divided by the total cropland area to derive the energy intensity per unit area of cultivated cropland in each EU-27 country. These fuels are disaggregated into diesel, natural gas, coal, and biomass fuel (which also includes biofuel and other bio-based energy commodities found in the energy balance). We used these intensities to calibrate energy consumption in the agriculture and land-use sector.

1.2.2.6 Water use and consumption

In the CLEWs-EU model, water demand in the power, agriculture, and domestic use sectors is explicitly modelled. All other water use, predominantly the commercial and industrial sectors, is grouped into the "Other" category. Water used for cooling thermal power plants and for irrigation of cropland is endogenously determined within the model. Figure 15 highlights the structure of the water supply to the respective end uses. For household use, water is first treated before supply, and wastewater is channelled through a technology that represents post-use treatment before being returned to surface water sources.

1.2.2.6.1 Water use in the residential sector

The demand (withdrawal and consumption) for water in the residential sector was obtained from (Fridman et al., 2024). These values are calibrated against Eurostat data. The dataset includes projections available through 2100. We assume a median projection from SSP2 for the base scenario. Figure 16 presents the values for all the EU27 countries together. The values are expected to decline owing to an expected decline in the population and lower per capita water use.

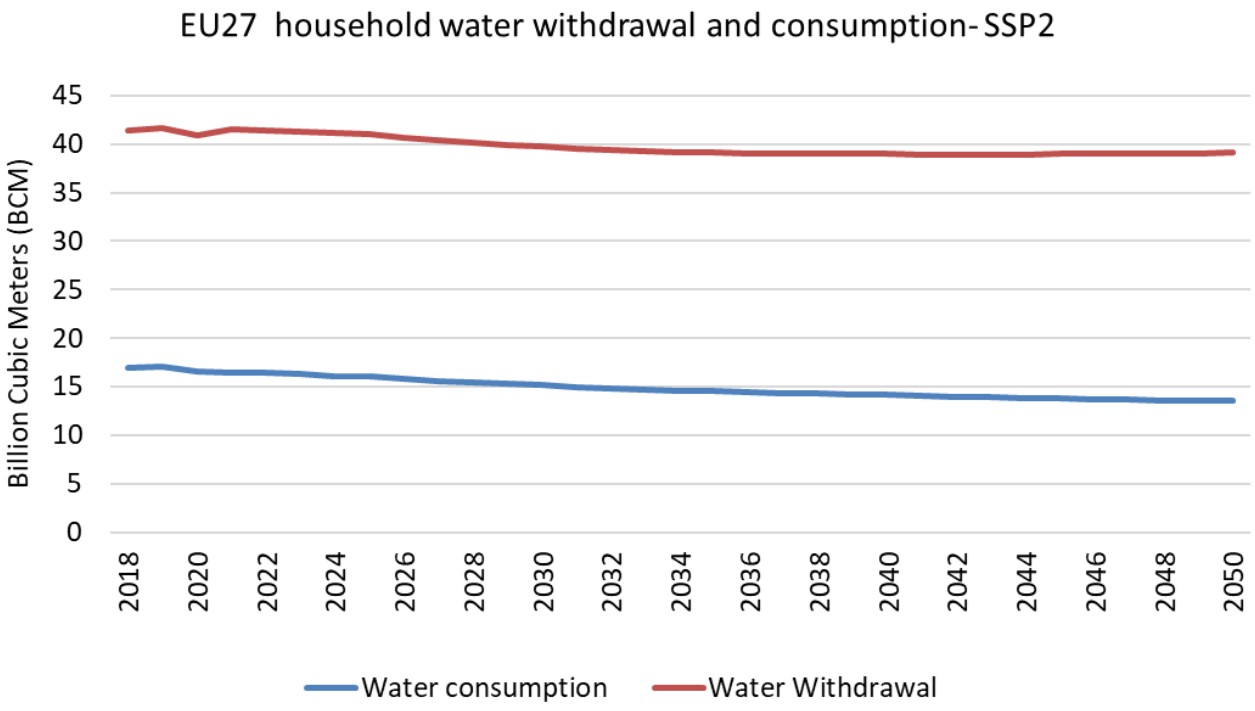

Figure 16. Household water withdrawal and consumption in the EU under SSP2.

1.2.2.6.2 Water use in the commercial and industrial sectors

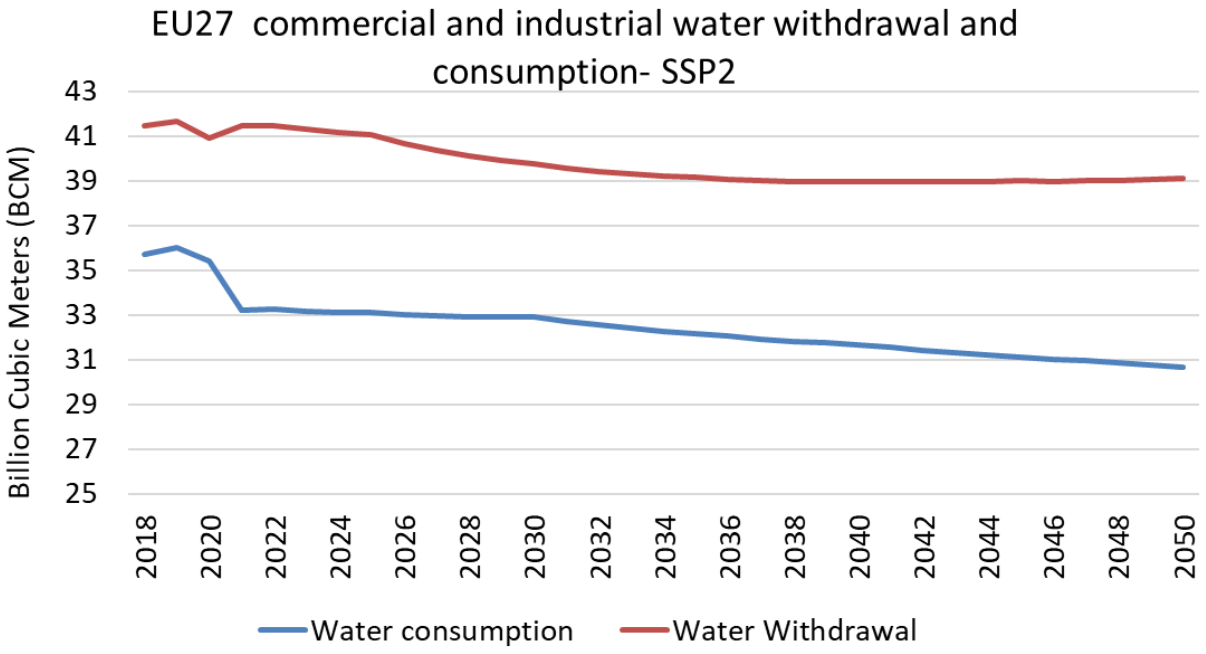

Figure 17. Commercial and Industrial sectors water withdrawal and consumption in the EU under SSP2.

The demand (withdrawal and consumption) for water in the commercial and industrial sectors is obtained from (Fridman et al., 2024). These values are calibrated against actual numbers from Eurostat. The data set has different projections available until 2100. We assume a median projection from SSP2 for the base scenario. Figure 17 presents the values for all EU27 countries together. The values are expected to decline due to a projected decrease in population and lower per capita water use. Like the household projections, the demand for water in these

sectors is also expected to decline.

1.2.2.6.3 Water use in the power sector

Thermal power plants (fossil fuel, biomass, nuclear, etc.) need to be cooled, and water is used in most of them. There are two primary types of water-based cooling technologies: once-through cooling (direct) and wet-recirculating/closed-loop (indirect). Sometimes the water used for cooling is from a nearby river, pond, or even seawater. In our model, we simplify the representation of water for cooling in thermal power plants. We calibrate the water used for cooling (obtained as a single number per country and year) from Eurostat with the total electricity generation from thermal power plants to calculate a cooling water withdrawal and consumption intensity, presented per unit of electricity produced. This methodology provides us with good accuracy in water withdrawal and consumption, eliminating the need to represent cooling technologies and thereby reducing the computational load. Table 20 presents the water withdrawal for cooling in thermal power plants in the EU27 countries. The data was obtained from Eurostat.

Table 20. Thermal electricity generation and water withdrawal in 2021 across the EU-27 countries.

Country	Thermal electricity generation (PJ)	Water withdrawal (MCM)
Austria	291.61	1495.1
Belgium	142.44	2256.5
Bulgaria	20.45	3471.7
Croatia	15.86	167.3
Cyprus	282.27	14.8
Czechia	56.42	264.5
Denmark	21.94	3.5
Estonia	170.17	681.7
Finland	1575.11	405.4
France	1444.75	14368.4
Germany	118.87	13321.6
Greece	112.65	Data not available
Hungary	75.49	3586.7
Ireland	680.88	359.2
Italy	10.76	4594.2
Latvia	8.06	2.6
Lithuania	2.27	87.5
Luxembourg	7.05	Data not available
Malta	331.68	Data not available
Netherlands	562.6	3183.3
Poland	78.82	5216
Portugal	120.41	786.9
Romania	89.02	566
Slovakia	37.52	50.4
Slovenia	291.61	717.1
Spain	547.23	4682.7
Sweden	248.77	113.4

1.2.2.7 Livestock representation

In the CLEWs-EU model, the land used for livestock farming and the corresponding GHG emissions are modelled. The livestock representation includes bovine animals (cattle, etc.), pigs, sheep, goats, and poultry (Figure 18). The demands for livestock are exogenously defined in the model. Livestock demand is defined as a function of the live head count for each animal category. Additionally, the demand is specified in Livestock Units (LSU) rather than individual animal categories. The assumptions for the conversions were derived from a European Commission study on livestock GHG emissions (Leip & Weiss, 2010). The assumptions for the land footprint of the livestock are obtained again from a modelling study conducted by the European Commission (De et al., 2022). The figure below provides a simplified representation of the livestock sector. We have made provisions in the model to develop an analysis that takes into consideration more climate-friendly agricultural practices. The main objective of representing livestock is to capture the GHG emissions and account for the land used to maintain them.

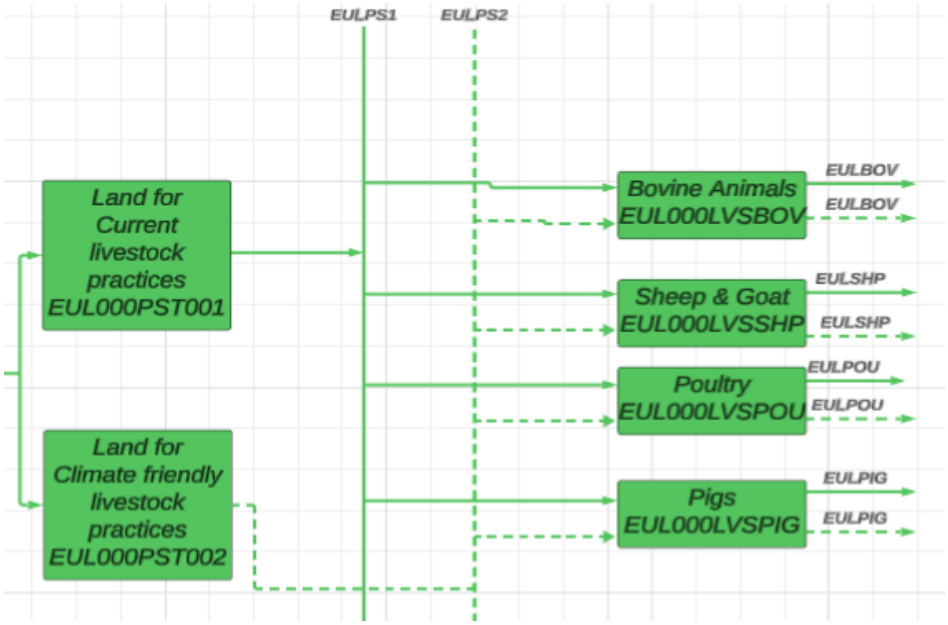

Figure 18. Simplified representation of livestock in the CLEWs-EU model.

1.2.2.8 Biomass production

Biomass (woody biomass, crop residue, biofuels, biodegradable waste and other bio-derived sources of energy) is used in all energy and transport sectors in varying amounts. Approximately 96% of all the biomass used in EU-27 countries is sourced within its borders. However, this share varies by country. For example, Cyprus imports a significant share of its biomass used in various local sectors, whereas the import share is much lower in Ireland. The National Renewable Energy Action Plans (NREAPs) for each EU-27 country specify the share of woody biomass, agricultural residue, and other sources of biomass supply (Scarlat et al., 2019). In this model, to simplify the representation of biomass availability, we have two main categories: woody biomass from forests and all other sources represented as agricultural residue. The woody biomass energy potential for each member state is calculated using the forested area in each country, the country-wide average wood intensity, the lower heating value (LHV) value, and the availability factor of wood for energy purposes (Avitabile et al., 2024). These values are calibrated for the base year, and an intensity of woody biomass per unit of forested area is calculated. Table 21 presents the potential for each EU member state.

Table 21. Woody biomass energy intensity in EU27 countries.

Country	Woody biomass energy potential-Intensity (PJ/1000sqkm/year)
Austria	1.68
Belgium	2.125
Bulgaria	1.123
Croatia	1.634
Cyprus	0.333
Czechia	2.308
Denmark	3.169
Estonia	1.527
Finland	1.11
France	1.608
Germany	2.783
Greece	0.867
Hungary	1.587
Ireland	2.588
Italy	0.947
Latvia	1.55
Luxembourg	2.03
Malta	0.333
Netherlands	2.087
Poland	2.125
Portugal	1.4
Romania	1.184
Slovakia	1.847
Slovenia	1.894
Spain	0.68
Sweden	0.897
Lithuania	1.905

The component of biomass from agricultural residues is calculated using the Residue-to-Product-Ratio (RPR), the LHV for each crop and the surplus availability factor (SUAF). These are calculated for each crop type and used in the model as output activity ratios for each crop-producing technology in each country. The detailed methodology for the calculation is provided in (Singhal et al., 2024) and the associated GitHub repository.

1.2.2.9 Data sources

The construction of the Land and Water modules within the CLEWs-EU framework requires extensive data collection and processing. Table 22 provides a summary of the primary data requirements for the land and water components of the model. In alignment with the approach adopted for the energy module, we are collecting data at the individual country level, despite that the initial development focused on a regional EU aggregate. For land, this includes data on land use patterns, agricultural productivity, and forest cover policies, among others. For water, we gather information on water availability, usage statistics across sectors, withdrawal limits, and water use intensities. 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 is still 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	Primary Source
Land Cover	Area under different land cover classes	FAO, Eurostat, European Space Agency (WorldCover2021)
	Area under crop cultivation	Aquastat & Eurostat
	Emission Factors	Eurostat and European GHG inventory
Agriculture	Crop yields and production statistics	GAEZ (FAO/IIASA) & interactions with the Magpie modelling group
	Fertiliser usage in Crop production	Eurostat, Peer-reviewed literature
	Crop import statistics	Faostat
	Costs involved in crop production	National Statistics, Eurostat & Derived entity in some cases
	Fuel usage in the agriculture and forestry sector	JRC IDEES- Energy balances
Water Availability and Use	Precipitation statistics	Eurostat and GAEZ
	Groundwater potential	Perr Reviewed Journals and Eurostat
	Water use factors in different sectors	Eurostat
	Evapotranspiration under different land categories	GAEZ
	Demand projections for water in different sectors	IIASA projections calibrated with Eurostat

1.2.3 Time horizon and temporal resolution

Considering the climate neutrality goal of the European Union by 2050, analysis by the model is performed up to **2050**[4]. The extension of the modelling horizon beyond this point implies great uncertainty as to the technological advances and relevant cost assumptions, climatic conditions, and energy demand projections required as input in the CLEWs-EU model. The base period is 2018-2021, with statistics up to 2021/2022 accounted for, and these years are calibrated accordingly, wherever possible. To reduce the computational effort required to run CLEWs-EU, a modified OSeMOSYS code version has been developed to allow scenario development with multi-year steps instead of adopting an annual resolution (e.g., one could choose to adopt an annual resolution for the period 2018-2035, and then the years 2040, 2045 and 2050). This same OSeMOSYS code can also be used for an outlook with annual resolution and is made available on the GitHub repository. The individual sectoral models of the disaggregated CLEWs-EU version are built with an annual resolution. However, the integrated CLEWs-EU model represents 2021 as a base year, then 2025 and the remaining horizon is in 5-year time-steps, due to the computational effort entailed; in the case of the energy module, the years 2018-2020 are also included in the reference period.

The temporal resolution of the model is enhanced from the 3 intra-annual parts adopted in the GLUCOSE (i.e.,

[4] Even though model outputs will be reported until 2050, the model horizon is extended to 2055 to avoid edge effects, where the model might indicate unexpected investment behaviour in the last few years of the outlook.

Global CLEWs) model to **16 annual timesteps**, consisting of **4 seasons** (i.e., winter, spring, summer, autumn) represented by a typical day; each consisting of **4 intra-day parts** (Table 23). The goal is to capture the daily characteristics of variability across electricity demand and variable renewable electricity generation (especially for solar PV and wind power). Initially, the model is 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 model development. Such an enhancement would strengthen the model's capability to provide valuable insights regarding variable renewable energy integration and the need for storage and flexibility with increasing amounts of solar and wind power. 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.) considered this plausibility.

Table 23. Intra-year temporal breakdown of CLEWs-EU.

Seasons	Winter	Spring	Summer	Autumn
	December-February	March-May	June-August	September-October
Day parts (UTC time)	00:00-07:00	07:00-17:00	17:00-21:00	21:00-00:00
Day part duration (hours)	7	10	4	3

1.2.4 Emissions accounting

The CLEWs-EU model accounts for key GHG emissions (**CO_2, CH_4, N_2O**) separately, but also in terms of carbon dioxide equivalent (**CO_2eq**). In the context of the European Union legislation, it is important to differentiate between GHG emissions that fall under the **ETS** and those that are part of the Effort Sharing Regulation (**ESR**), as different carbon pricing mechanisms are in place, while these will also change with the introduction of the new ETS. As such, a distinction is made in the model on the sectors that are relevant to ETS or ESR. Price projections for the existing and the new ETS are taken from a communication of the European Commission on the "Recommended parameters for reporting on GHG projections in 2025" (European Commission - DG CLIMA, 2024), which was used by member states in the preparation of the final revisions of their NECPs (European Commission, 2025a). Accounting for GHG emissions in the energy module of CLEWs-EU occurs either at the fuel supply level or the use level (i.e., technology). Negative GHG emission rates are included in CCS technologies, which are available for investment in electricity & heat generation, as well as industry.

Emissions in the Land module are captured at multiple levels. All land cover categories have an emission activity ratio corresponding to their **CO_2, CH_4, N_2O** & **CO_2eq** emissions. Livestock emissions pertaining to enteric fermentation and manure management are obtained from the European GHG inventory (EEA, 2021) and divided by the total live heads of livestock in the base year to compute emission activity ratios for each type of livestock per EU-27 member state. Similarly, emissions from other AFOLU sectors are also sourced from the same source, and the factors are calculated by dividing the total GHG emissions by the area under the emitting/sequestering land cover category. The EU also declares the amount of GHG that is stored in harvested wood products. We represent this category as exogenous emission in the model. For land that has been under forest or grassland cover for a long time and changes to another land cover category (such as agriculture), an emission change factor has been implemented to specify the carbon stocks that will be released when land cover changes (*Background Guide for the Calculation of Land Carbon Stocks in the Biofuels Sustainability Scheme*, 2010). These emission activity ratios and the calculation are available in the GitHub repository.

1.2.5 Naming Convention

As the CLEWs-EU model has been built from scratch, the way in which technologies and commodities would be represented within the model and, hence, 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 followed for technologies, while a 6-character naming convention was adopted for commodities. Table 24 shows an extract of the naming convention adopted for the energy module, while Table 25 and Table 26 highlight the naming convention implemented for the land and water modules. The full explanation of the naming convention is available as part of the model documentation in the model's GitHub repository. As further additions are made, the relevant documentation will be updated accordingly.

Table 24. 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 Electricity interconnector between Austria and Germany	**AT** (Austria)	**E** (Energy)	**GN** (Grid Networks)	**ELC** (Electricity)	**DE** (Germany)	**IC** (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 25. 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 26. 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 (Groundwater)
EUWDEMAGRSUR Surface water supply technology for agricultural use	EU (Europe)	W (Water)	DEM (Demand)	AGR (Agricultural Use)	SUR (Surface water)
EUWMIN000PRC Technology to produce water from Precipitation	EU (Europe)	W (Water)	MIN (Resource Technology)	000 (Dummy)	PRC (Precipitation)

1.3 Model Manual

1.3.1 Software and hardware requirements

The input data files for the CLEWs-EU model are constructed in an excel file with multiple worksheets. Each worksheet corresponds to a particular SET or Parameter in the OSeMOSYS model. A python package, **Otoole**[5], is used to handle all data manipulations required for running the model. Users should make sure they have the latest version of Otoole installed in their computer along with the latest stable version of **Python**. To use Otoole, a configuration file (YAML) is required. A YAML file has been specifically developed for this project, and it can be

[5] Full documentation for Otoole is available at: https://otoole.readthedocs.io/en/latest/index.html

found in the relevant *model_files* folder on the model's GitHub repository. Additionally, an **optimisation solver** is required to run the model. Any one of the following solver options should be installed; some of these solvers are proprietary and others are free and open source, so users should select one based on their own needs:

- GLPSOL[6] – installation of this solver is mandatory as GLPSOL is part of the open-source GLPK package and it is needed for creating the model matrix in the first step of the model run. It should be noted that the disaggregated version of the CLEWs-EU model is computationally intensive, and it is not advised to use the GLPSOL solver for the optimisation step.
- GUROBI – proprietary, but has an academic license option
- CPLEX – proprietary, but has an academic license option
- CBC[7] – open-source

As mentioned above, the CLEWs-EU model has been developed in parallel, with the different sectors having their own separate module. As such, the computational intensity varies according to whether the entire integrated CLEWs-EU model or a separate sector is run; the main limitation in using CLEWs-EU is the availability of enough memory to run the model.

The disaggregated version of the model is computationally intensive and is thus not run with an annual resolution; instead, 5-year steps are adopted. However, an annual resolution is used for each of the sectoral models. As indicated in Table 27, the disaggregated version of the integrated CLEWs-EU model requires 310 GB of random-access memory (RAM) to run. In comparison, despite its annual resolution, the aggregated version of the model requires only 8 GB of memory due to its significantly lower complexity, which allows its use for stakeholder engagement.

Table 27. Key hardware requirements to run the disaggregated version of the CLEWs-EU model and its sectoral components.

CLEWs-EU sectoral model	Memory requirements (GB RAM)
Energy module	170 GB
Electricity supply	*38 GB*
Buildings	*12 GB*
Industry	*34 GB*
Transport	*32 GB*
Land & Water module	180 GB
Integrated CLEWs-EU model	**310 GB**

1.3.2 Model setup

The CLEWs-EU GitHub[8] repository provides the following material:

a) **OSeMOSYS code** – this is the version of the OSeMOSYS code that has been created for this project. Three separate files are provided, depending on which model is used (i.e., individual sectoral models or integrated CLEWs-EU model). The files are in the form of a text file and elaborate on all the parameters, variables and constraints (i.e., equations) that describe the relationship between input data (i.e.,

[6] GLPK is available at: https://www.gnu.org/software/glpk/
[7] CBC is available at: https://github.com/coin-or/Cbc
[8] CLEWs-EU is available at: https://github.com/CLIMATE-DIAMOND/EU-CLEWS/tree/main

parameters) and model outputs (i.e., variables).

b) **CLEWs-EU model data files** – Model data files are provided in the form of an Excel spreadsheet for the energy module and its separate sub-components, the land and water module, and the integrated CLEWs-EU model (i.e., energy & land & water) separately. These files basically constitute the structure of the model in the form of Sets (i.e., years, fuels/commodities, technologies, emissions etc.) and all the techno-economic assumptions associated with these (e.g., energy service demand projections, costs and efficiencies of technologies, etc.).

c) **Supporting data** – this folder provides information that is needed for any future CLEWs-EU user. The naming convention is included here. More detailed information regarding input data and assumptions are also made available for the final version of the model.

d) **Data preparation scripts** – these are the scripts created to automate the extraction of the required data from available databases (e.g., JRC-IDEES 2021). They have been created specifically for the transport and industrial sectors but, in the future, they may be enriched with the rest of the sectors as well. These scripts are provided for transparency as well as to enable potential future changes in the model detail in the relevant sectors.

1.3.3 Using the CLEWs-EU model

The procedure to run the CLEWs-EU model is the same as for any other OSeMOSYS model. Specifically, the following steps should be followed:

1) First, using Otoole, convert the OSeMOSYS data file from Excel data format to a text file. Users should refer to the examples page of the Otoole documentation for the syntax used to carry out the previous steps.

2) Use GLPK to create the LP file version of our model (.lp file format), using the data file and the OSeMOSYS code as input (both in .txt format). This step creates the matrix of the problem by loading the data into the relevant OSeMOSYS equations.

3) Optimise the LP file using any one of the suggested solvers. Once an optimal solution is found, the user should write the solution file (.sol file format).

4) Use Otoole to write the results from the optimised solution file to result CSV files.

5) The users can open the CSV files to view the results in a tabular format. At a later stage, visualisation scripts will be developed to automatically view results in an interactive format.

2 Model validation

In the process of developing the individual sectoral models and integrating them into a single integrated CLEWs-EU model, several test runs are conducted and a comparison with historical statistics is made. This is done to ensure that the model accurately represents the current status of the represented systems, so that it can be used for scenario exploration in the later stages of the project. Examples of the model validation process for selected countries are provided in the following sub-sections.

2.1 Energy module

The validation process of the energy module gives an initial emphasis on comparison of the fuel consumption in each end-use sector with historical data, as it is a direct indication of technology shares. Similarly, since GHG emission accounting in the model is based on the rate of fuel consumption, by focusing on the final energy demand the sectoral GHG emissions are also simultaneously calibrated. Results from CLEWs-EU for 2021 illustrate the model outcome taking into account the calibrated variables adjusted to correspond to base year statistics.

2.1.1 Electricity and heat generation

The validation of the CLEWs-EU electricity and heat generation sector has been based on a comparison of actual historical versus modelled generation per fuel type and is conducted for 2021. The comparison is based on annual volumes and the validation process accounted for a large volume of data from various sources. Hourly electricity demand data were obtained by ENTSO-E (ENTSO-E, 2025). The annual generation per fuel technology is obtained by Eurostat (Eurostat, 2025c, 2025b). The installed capacities and technoeconomic parameters of generating technologies for year 2021 are obtained by JRC. The ETS prices and costs of fuels were based on European Commission recommendations (European Commission - DG CLIMA, 2024), adjusted by data from EURACOAL and PPC regarding coal extraction percentage and relevant prices. Finally, the net transfer capacity of regional transmission interconnections between countries is based on ENTSO-E data.

For the validation exercise the capacities of generating technologies and regional interconnections are fixed at 2021 levels, while generation is optimised to meet electricity demand. It should be noted that there are some factors that contribute to experiencing deviations between actual and modelled data. First, OSeMOSYS simulates least-cost generation, while actual generation is determined by bilateral contracts and the energy markets (real-world imperfect competition). In addition, the CLEWs-EU model does not account for specific unit and system constraints as in the case of minimum generation loading, minimum up/down time of generators, and operational reserves, all of which contribute to deviations, especially in the actual dispatching of power plants. Moreover, each year in the model is populated with representative average hydrological, solar and wind conditions. In reality, however, hydrological, solar and wind conditions deviated from the averages in 2021. Considering that zero-cost renewables have priority in the dispatch, the balancing is done by conventional dispatchable technologies. Finally, there is some trade with countries external to the EU, which is not accounted for by the model. Having all the above factors in mind, one can view the results of the validation process in Figure 19.

Validation results are deemed satisfactory as the modelled and actual values are reasonably close. The weighted mean error of actual vs modelled values was calculated to be less than 10% in almost all countries with important relative contribution to EU generation (i.e., DE, FR, IT, ES, NL, PL, SE). Notably, the model presents nearly perfect match on results in countries where the hydro generation matched historical and modelled values as in the case of France and Sweden. In addition, in most countries the agreement between actual and modelled values of electricity trade (imports vs exports) was at pretty good levels, which indicates that the technoeconomic inputs in the model that define the cost of electricity generation and regional interconnections are of good quality.

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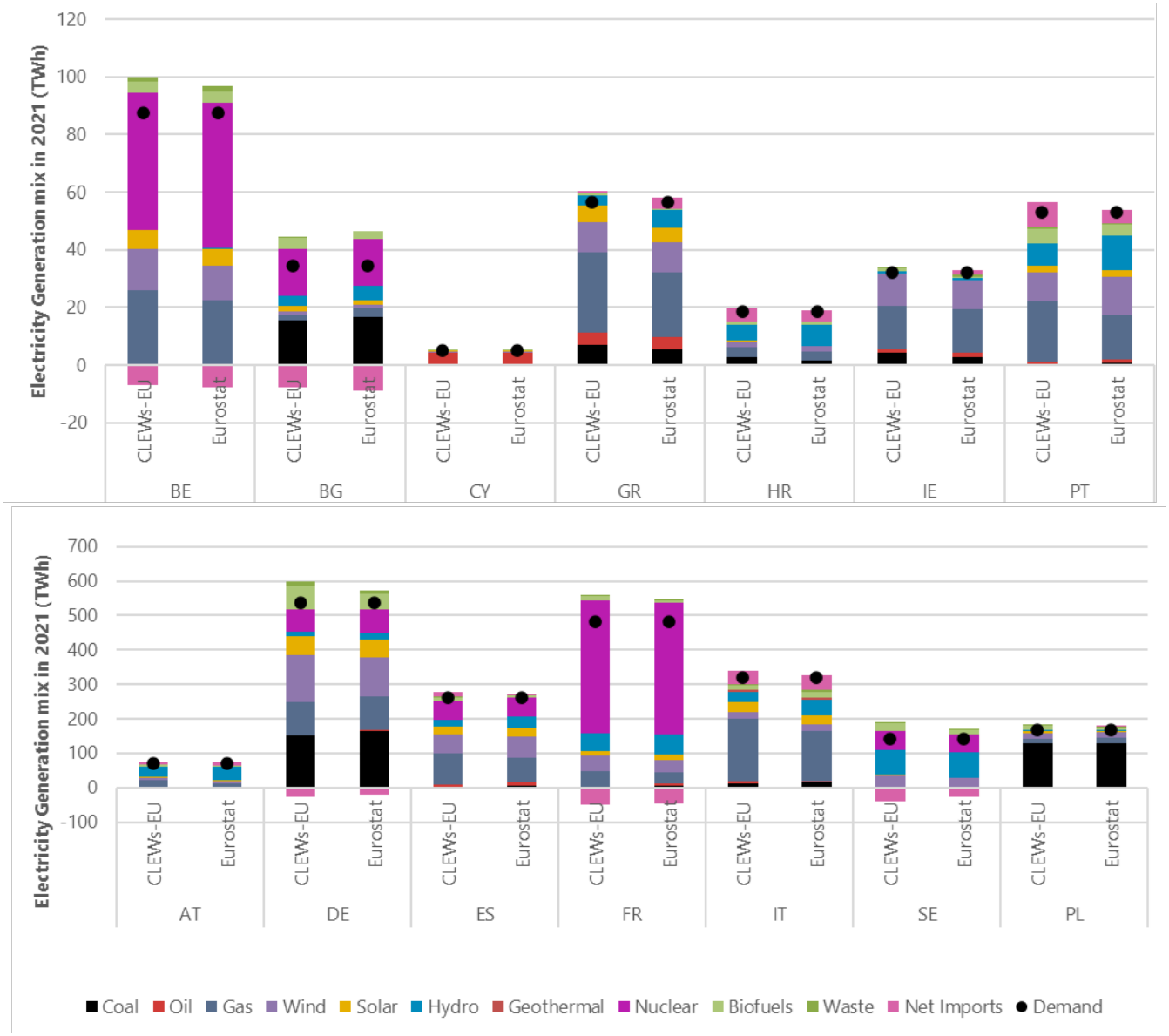

Figure 19. Electricity generation mix comparison in selected EU countries. The graphs show modelled vs actual generation for 2021. Generation above demand indicates exports and/or T&D losses.

2.1.2 Buildings

The total final energy demand in 2021, as calculated by the CLEWs-EU model, is compared to statistics from the JRC-IDEES 2021 database. It should be noted that JRC-IDEES provides data for the residential and tertiary sectors separately, but these are lumped into a single buildings sector in the CLEWs-EU model. A comparison of selected countries and the total EU27 are shown in Figure 20. As illustrated, the estimated fuel use in the buildings sector accurately represents the recorded fuel consumption in each of the sample countries. As part of the technology aggregation, some differences can be observed in terms of the exact share of each fuel. For instance, some of the oil consumed in gaseous form (i.e., LPG) for specific end-use services (i.e., space heating and hot water) is allocated to natural gas technologies, as can be more clearly noticed in the total EU27, which leads to minor differences across countries.

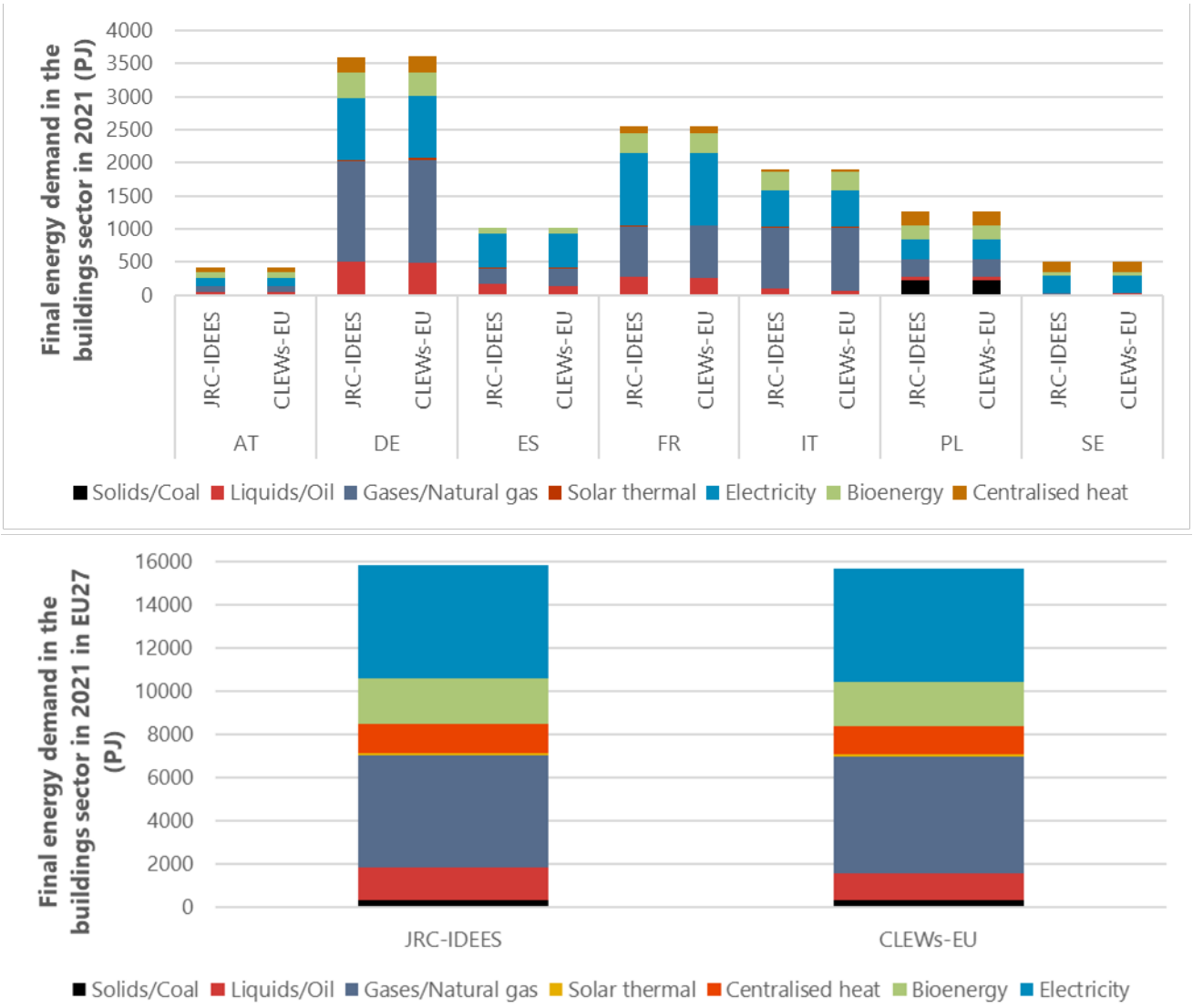

Figure 20. Final energy demand in the buildings sector in selected EU countries (top) and EU-27 (bottom).

2.1.3 Industry

As in the case of the buildings sector, the total final energy demand in 2021, as calculated by the CLEWs-EU model for the entire industrial sector in each country, is compared to statistics from the JRC-IDEES 2021 database. Selected countries are shown along with the entire EU27 in Figure 21 below. As illustrated, the estimated fuel use in the industrial sector reflects quite well the actual situation in each of the sample countries. An overestimation of centralised heat demand in industry was observed in the draft version of the CLEWs-EU model; however, the erroneous data inputs were identified and corrected for the final version of the model.

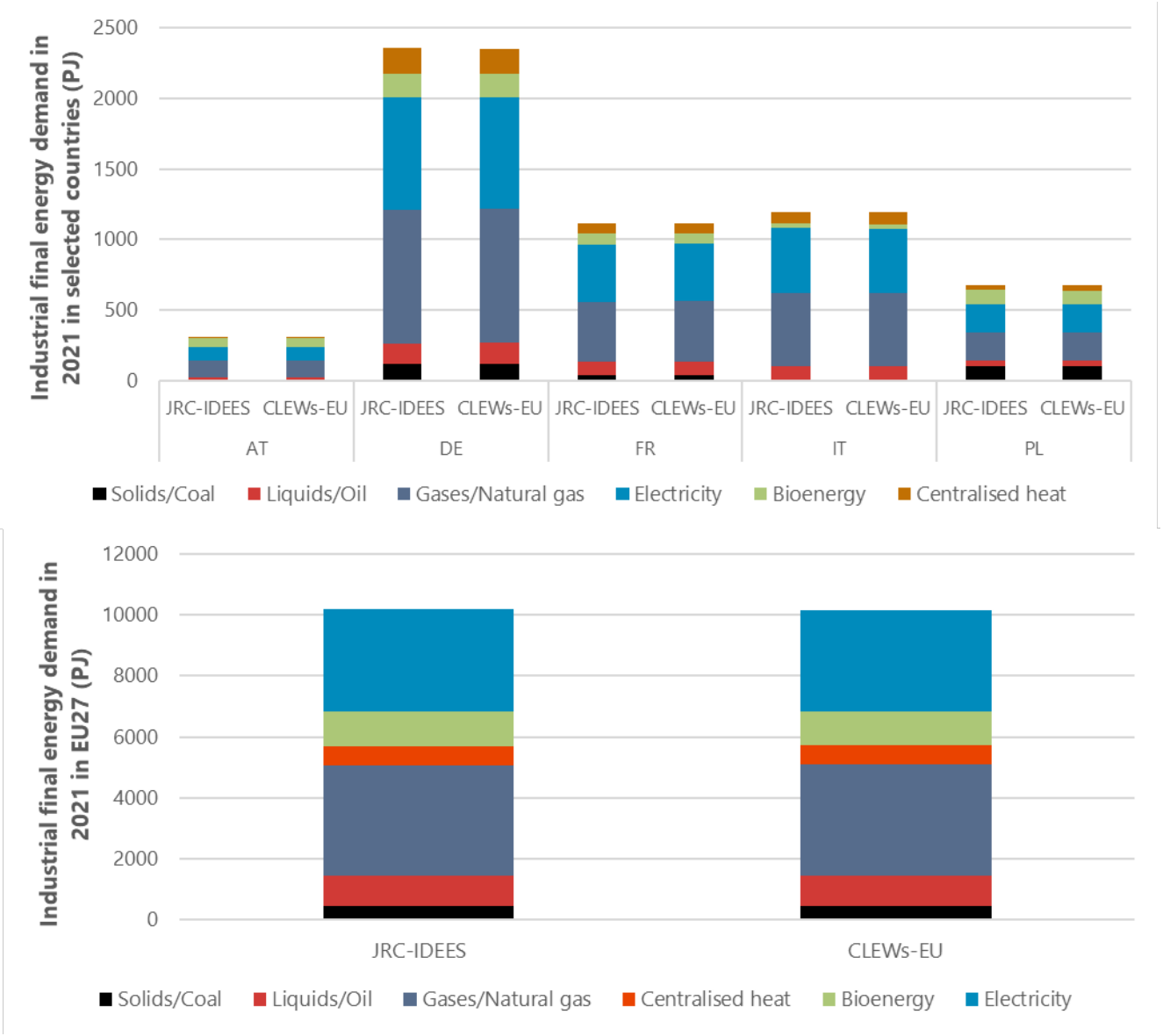

Figure 21. Final energy demand in the industrial sector in selected EU countries (top) and EU-27 (bottom).

2.1.4 Transport

The transport sector is perhaps the most detailed end-use sector in the energy module of the CLEWs-EU model, as it is broken down into aviation, shipping, rail transport, and road transport, which in turn are further broken down into several technologies. As the road transport sector has the largest number of technologies, we focus our validation on this sector. As indicated in Figure 22, the activity of vehicle technologies is sufficiently represented in the model. It should be noted that the JRC-IDEES database does not make a distinction on the number of hybrid vehicles or their energy consumption, but only on the overall gasoline/diesel engines (inclusive of hybrids) and plug-in hybrid vehicles. As such, we complement figures with data from Eurostat to arrive at a more disaggregated breakdown of vehicle technologies (e.g., as indicated in Austria, Portugal, and Romania), while the technoeconomic assumptions from the EU Reference Scenario 2020 (European Commission - Directorate General for Energy. et al., 2021) are used to also estimate the respective energy efficiency of these hybrid vehicles.



Figure 22. Passenger car activity by type of technology in selected EU countries (top) and EU-27 (bottom).

In addition, fuel consumption outputs in the broader land transport sector (i.e., road & rail) from the CLEWs-EU model are compared against the respective statistics from the JRC-IDEES database (Figure 23). As observed, the model appears to adequately capture historic fuel consumption trends.

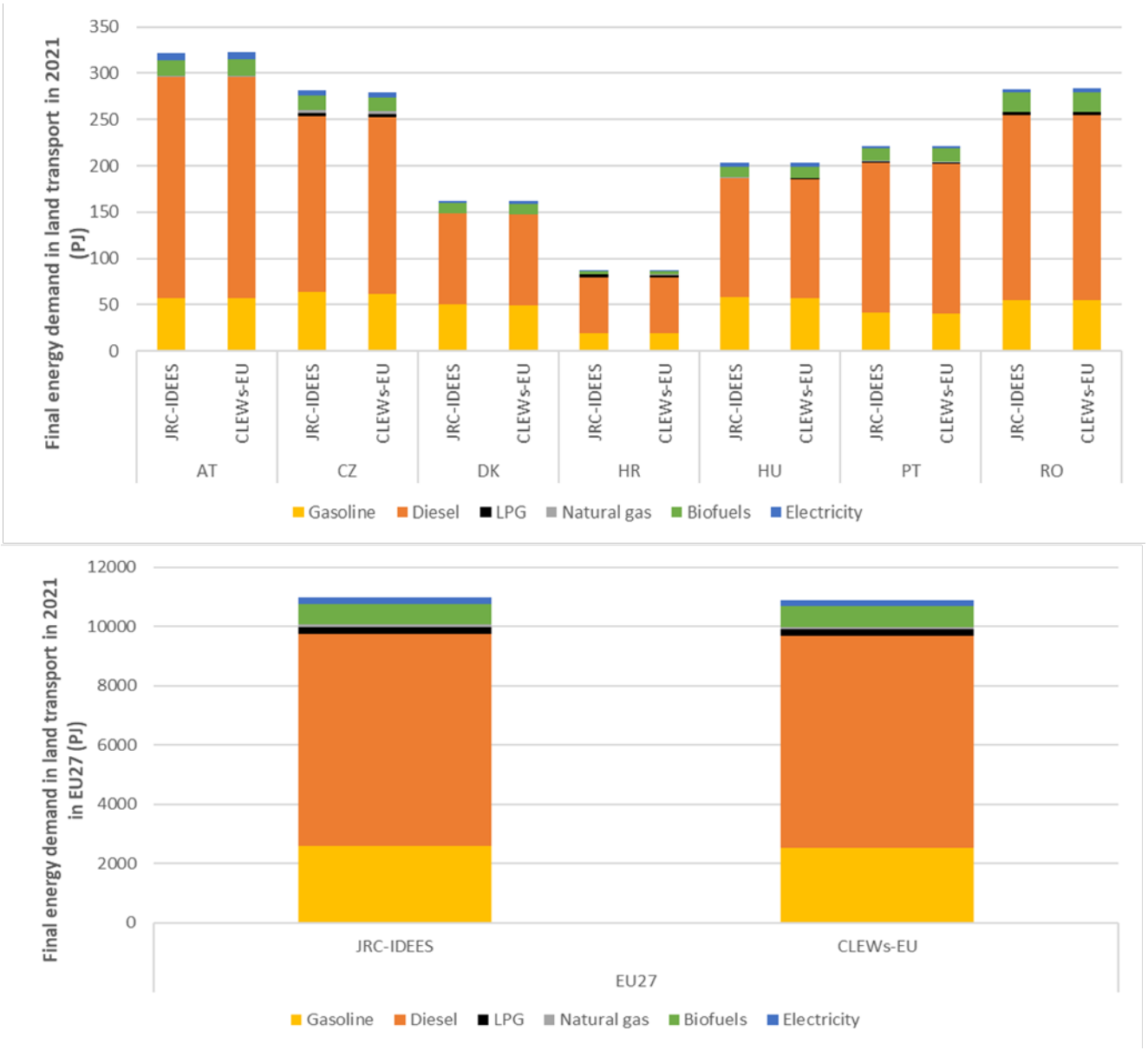

Figure 23. Final energy demand in land transport in selected EU countries (top) and EU-27 (bottom).

2.2 Land and Water module

In the land and water module, validation is carried out primarily by adjusting the input parameters to match the production of crop commodities in each EU member state.

2.2.1 Crop production and area under cropland cover

Two key parameters control total crop production: area under cultivation and average crop yield. The area under cultivation is further split based on water supply options (irrigated and rainfed) and input levels (high and low), which increase yield, such as mechanisation and fertilisers. The average yield parameter is a calculated entity based on actual area under cultivation and crop production. The key input parameters for validation are computed using data from FAOSTAT, GAEZ (Fischer et al., 2021) and Eurostat. Validation is carried out for the model's base year (2018). However, for consistency with the energy module comparison, we also validate results for 2021. EU cropland area figures are provided for 2018 and 2022; therefore, modelled cropland values in 2021 are compared with measured values for 2022. The "unpredictable" impacts of the COVID pandemic and the Russia-Ukraine war

have contributed to differences between modelled outcomes and measured data in certain countries. To minimise the effect of these events on the validity of future projections, crop yield values were averaged across years (2018-2022) and used for years after 2022. Figure 24 illustrates the differences between the modelled cropland area and the measured values from Eurostat. Across EU-27 countries, modelled cropland cover was 7.6% higher, which is of similar magnitude to expected interannual variations.

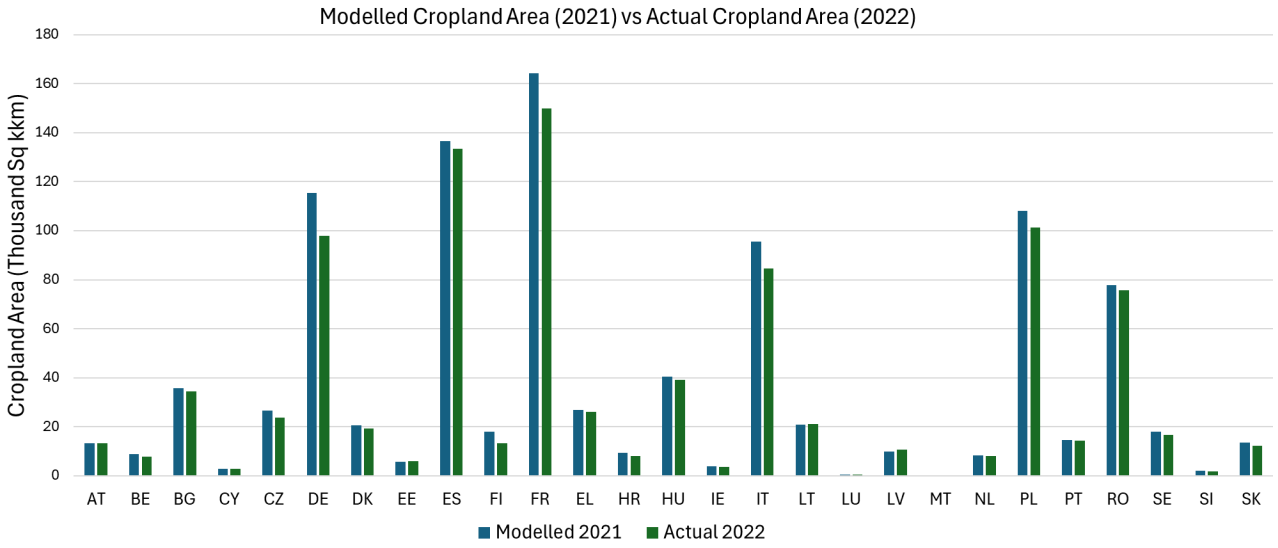

Figure 24. Validation for the area under crop land cover; modelled year 2021, nearest actual year from statistics 2022.

For actual crop production, we validate model outputs against measurements from FAOSTAT. Figure 25 presents and compares widely produced crops in Germany.

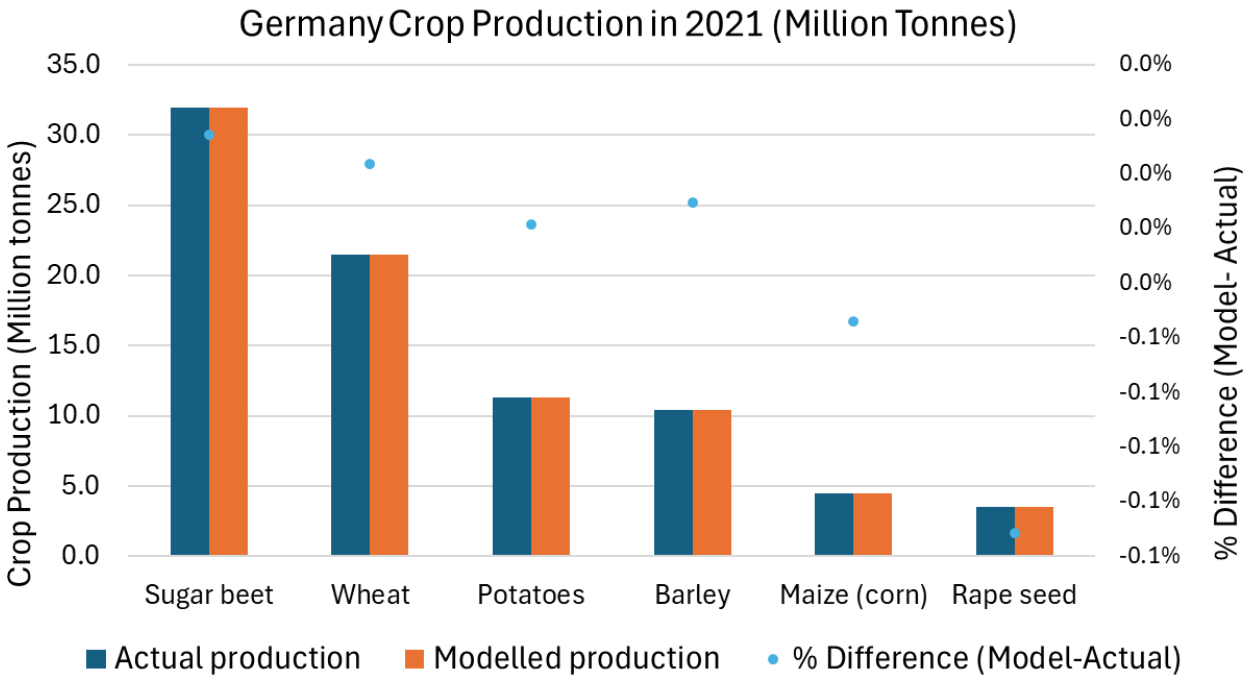

Figure 24

Figure 25. Crop production in Germany for major categories (2021); Modelled vs Actual.

Figure 26 and Figure 27Figure 26 show analogous results for Spain and France, respectively. Crop production varies by a maximum of 1% in some crops.

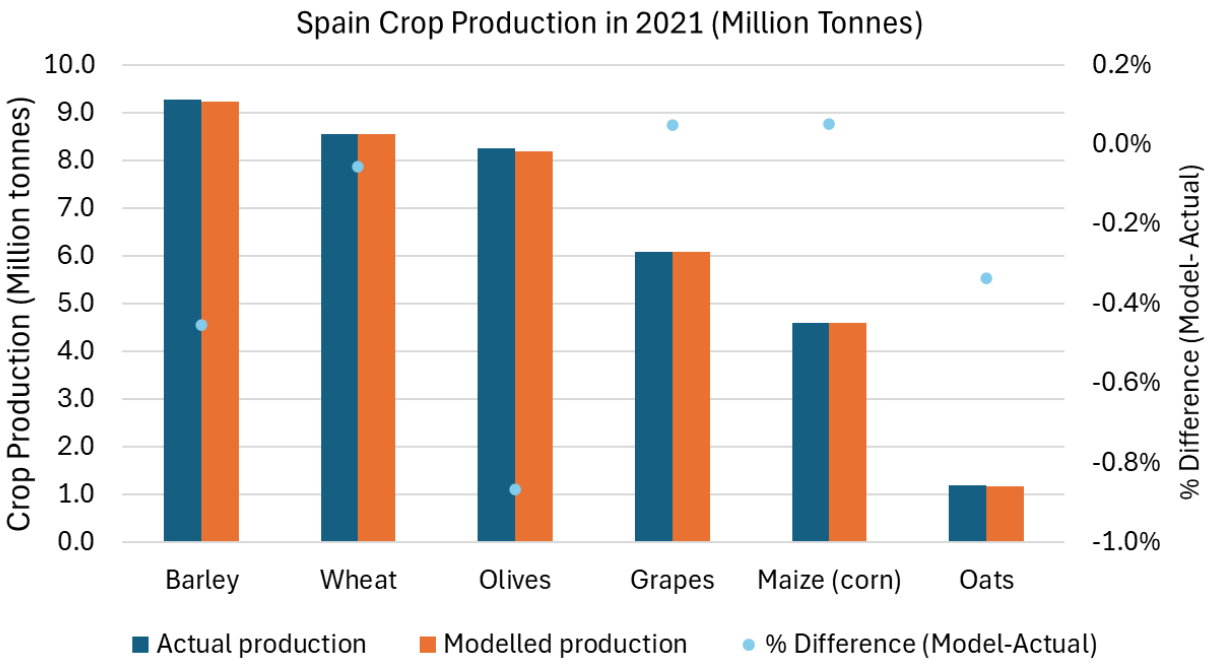

Figure 26. Crop production in Spain for major categories (2021); Modelled vs Actual.

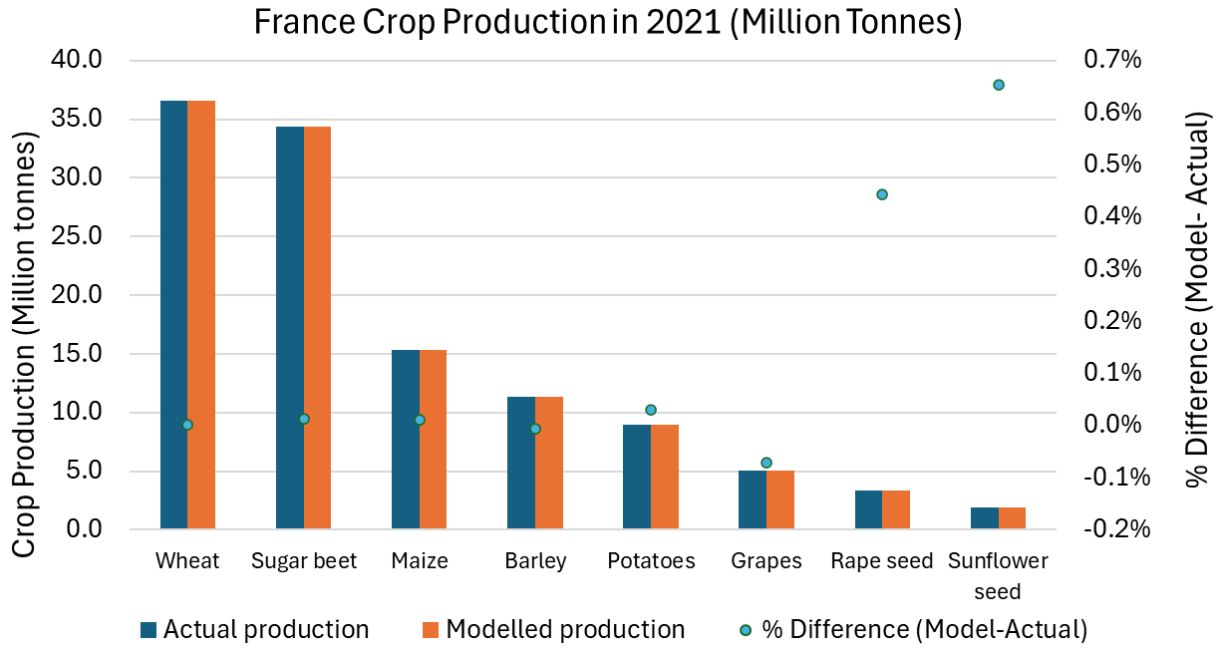

Figure 27. Crop production in France for major categories (2021); Modelled vs Actual.

Figure 28 presents the aggregated difference in crop production, for selected crops, across the EU-27 countries. For barley, wheat, and maize, which constitute 53% of cropland area, the difference is below 2%. Potatoes show the most significant deviation (12.5%) between modelled outputs and measurements. Though percentage deviation is not the most accurate measure of the differences, it gives a good idea of how closely the model approximates crop production numbers.

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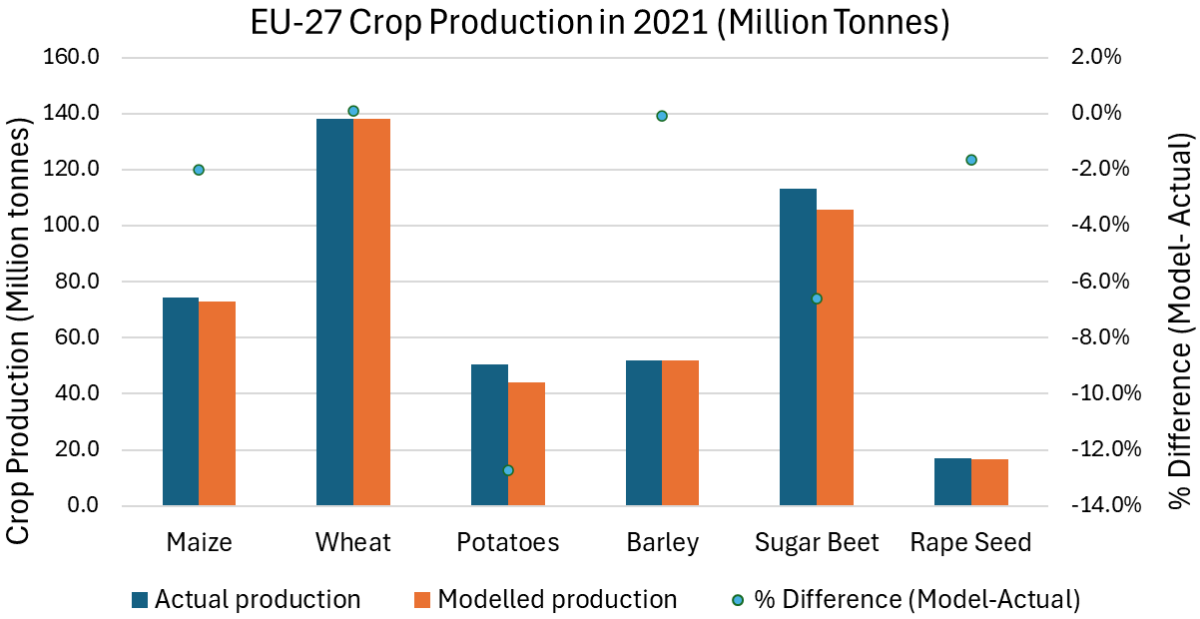

Figure 28. Crop production in EU-27 countries for major categories (2021); Modelled vs Actual.

2.2.2 Water use

Water use and abstraction are split into four sectors: public (municipal supply), power (water for cooling in thermal power plants), agriculture (irrigation), and other (commercial and industrial). For municipal supply, Figure 29Figure 29 presents the modelled share of drinking water sources in each EU-27 country and Figure 30 presents the measured share from the European Federation of National Associations of Water Services (EurEau). The EurEau data does not cover all the countries and, for those not covered, we have assumed the European average from the countries that report these numbers. Overall, for countries that report 2021 numbers, the average deviation is less than 3%. Desalination is present in Spain, Greece, Malta, and Cyprus; however, the model does not accurately represent the minor share of desalination in Greece and Malta. The model assumes that these shares persist throughout the modelling period, though these user-defined constraints can be modified in alternative scenarios. Note that desalination costs depend on electricity prices, which are determined endogenously in the power sector module.

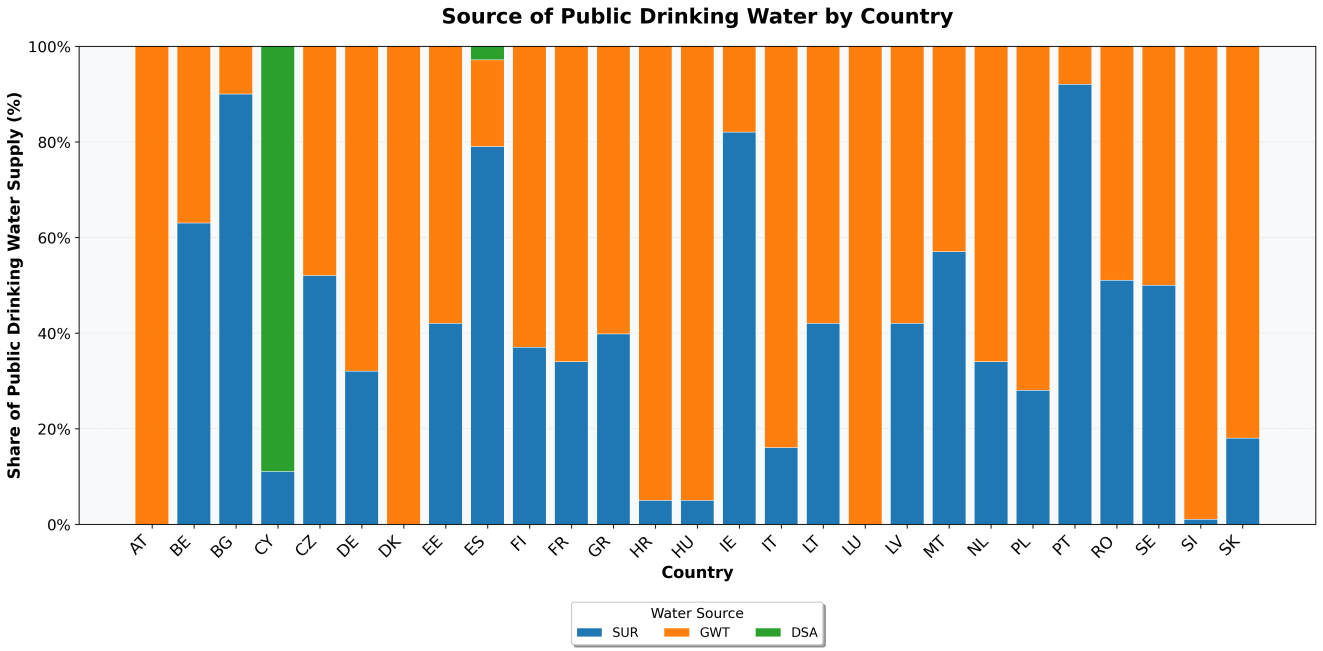

Figure 29. Modelled share in the drinking water supply sources (2021). **SUR**: Surface Water, **GWT**: Ground Water, **DSA**: Desalinated Water

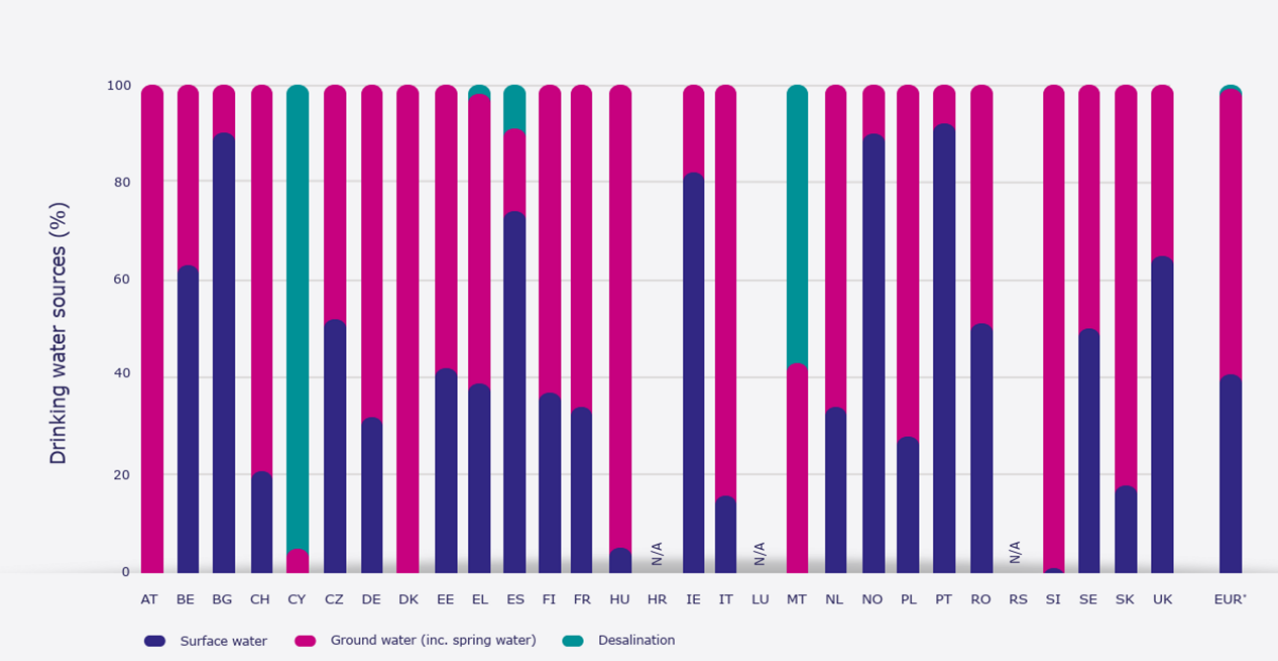

Figure 30. Actual share in the drinking water supply sources (2021) from EurEau.

Figure 31 compares modelled and measured water withdrawals from Eurostat for cooling in thermal power plants across the EU-27 in 2021. Data for several countries (IT, CY, LV, LU, and MT) are missing; for these, the weighted average value from the reporting countries was used. Overall, for all the countries that report data, our model estimates have an average deviation of ~8% from the reported values (collectively).

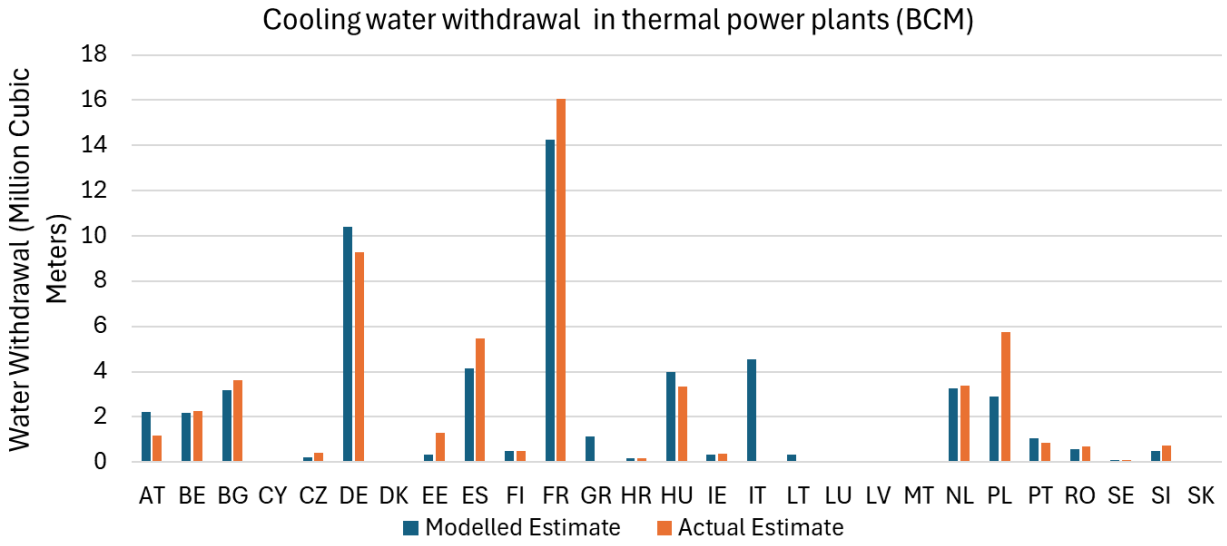

Figure 31. Water withdrawal for thermal power plant cooling in EU-27 countries.

2.2.3 Agricultural emissions

Figure 32 compares modelled methane emissions to measurements from Eurostat for 2021, showing an average deviation of ~6.6%, driven by higher-than-average deviations among key producers, such as Germany and Ireland.

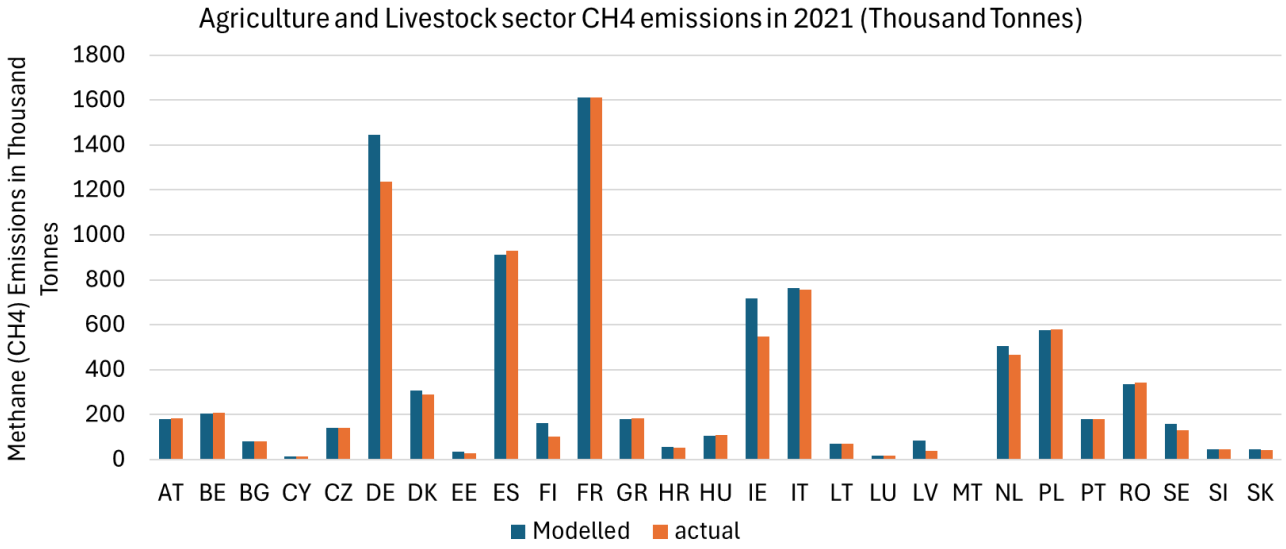

Figure 32. Agriculture and Livestock Methane (CH4) emissions in 2021 across the EU.

3 Baseline scenario outlook

As part of the scenario testing, the model development team aimed at developing a flexible baseline scenario that can easily be amended to address the stakeholder research questions and the scenarios to be explored within WP5 of the DIAMOND project. As such, the baseline scenario reflects the current policy framework regarding fuel pricing and taxation, it excludes any strict emissions and renewable energy targets, while the projections are primarily driven by cost optimisation. The baseline scenario also includes the expansion of ETS to other sectors of the economy (i.e., road transport, buildings, light industry). Scenario results for each of key sectors represented in the CLEWs-EU model are presented in this section.

3.1 Energy module

The results of the energy module are dependent on the scenario assumptions. In the absence of strict emission targets implemented in the model, the results are determined purely by the cost-effectiveness of the various energy forms and technologies in meeting the specified demands. The following subsections provide an overview of scenario results until 2050 for each of the energy system subsectors, focusing on the EU level results.

3.1.1 Electricity and heat generation

After merging the various sector models, electricity becomes one of the available energy forms to meet the various forms of end use demand (cooling, heating, lighting, km of transport, etc.) and thus is no longer an input but rather becomes output of the energy model. Electricity can directly feed some type of end-use demand or be stored in either electricity storage technologies or in the form of electrofuels (for example, hydrogen). The model optimises generation and electricity storage investments so that electricity is produced at least cost, subject to policy, system, or unit constraints[9].

At the EU level, it is observed that electricity demand grows from around 2,500 TWh in 2021 to more than 3,500 TWh by 2050 (Figure 33). This happens even though end use demands in the sectoral level are projected to remain nearly flat or decrease over the same period in some key sectors (e.g. buildings and industry). This is partly due to the effect of electrification of other sectors (sector-coupling) and the demand for electrofuels. In that respect, part of electricity production is used by electrolysers for the production of hydrogen. More specifically, around 345 and 615 TWh of electricity is used by electrolysers in 2040 and 2050, respectively.

It is also observed that PV and wind energy tend to replace coal and natural gas power plants, mainly driven by the increasing ETS prices and the continuously reduced capital cost of renewable energy sources, especially PV and wind. The share of variable renewable energy (VRE, such as PV and wind) on total generation mix is expected to grow from 25% in 2021 to 65% by 2050. Generation from hydropower plants and biofuels grows at a more moderate level with the share of above technologies reaching 8.4% for each by 2050 compared to current levels of 10% and 6% respectively. It is observed that nuclear energy remains an important aspect of EU electricity generation. Generation from nuclear power plants remains nearly flat over the study horizon, while the relative contribution slightly drops from 24% in 2021 to 19% by 2050. At the same time, coal generation, which accounted

[9] Type of policy constraints are for example carbon reduction targets or specific targets for renewable energy generation or capacities. Type of system constraints include meeting for example the system requirement for capacity reserve margin or limiting the level of trade up to account for energy security. Unit constraints are used to simulate realistically operation of technologies. Such constraints limit for example instantaneous generation up to installed capacity, or annual generation up to a given capacity factor or for example connect fuel consumption to electricity generation through efficiency of technologies)

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for nearly 8% of total generation in 2021, phases out by 2035. Natural gas related generation accounted for 24% in 2021 and phases out by the same year. It is also evident that biomass CHP plants keep their role in the electricity generation sector, mainly due to the need for heat demand; however, there is a shift from fossil-fired generation to biomass. The total investment needs in the power sector (in terms of undiscounted annualised CAPEX horizon) are equal to 876 USD billion over the study horizon. 43% and 40% of total investments are on PV and wind technologies, respectively. More specifically, total PV technology capacity will reach 804 GW by 2050 compared to 141 GW in 2021. Total onshore and offshore wind capacity was 173 GW and 15 GW, respectively, in 2021. The same capacities in 2050 will be 425 GW and 81 GW, respectively.

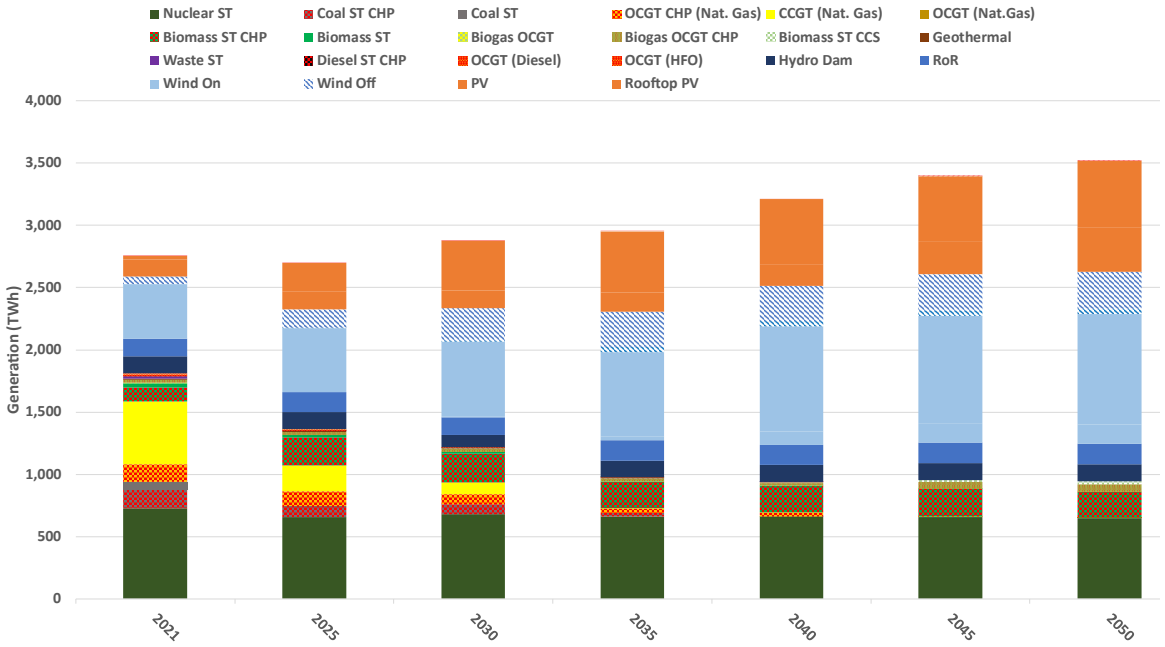

Figure 33. Total electricity generated in the EU-27.

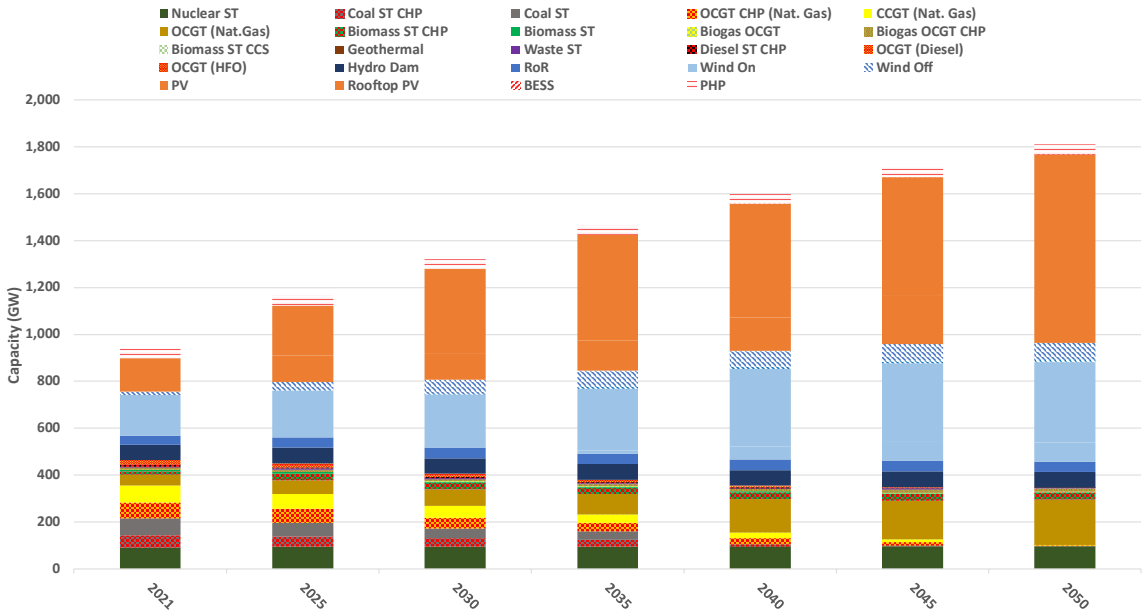

Figure 34. Total installed electricity generation capacity in EU-27.

As can be observed by comparing Figure 33 and Figure 34, there is a significant amount of gradually incoming open-cycle gas turbine capacity that is not generating electricity. This capacity is used as backup to VRE and provides firm capacity to the system (there is a country-level capacity reserve margin requirement of 10%) since

the firm contribution of solar and wind is much lower compared to dispatchable technologies. The firm contribution of PV and wind technologies has been estimated on a per-country level. In countries where peak demand occurs at night, the firm capacity contribution of PV is assumed to be 0% as highlighted in Table 28.

Table 28. Contribution of variable generation technologies to firm capacity.

Technology	Technology contribution on firm capacity (as % of installed capacity)		
	Greece	France	Sweden
Wind onshore	16%	13%	9%
Wind offshore	28%	28%	28%
Hydro RoR	50%	50%	50%
Hydro Dam	90%	90%	90%
Solar	18%	1%	0%

The development of the model included some type of parameter "tuning" to address unwanted observations on results, while some additional constraints needed to be added. Such constraints included putting a limit on biofuel availability, putting a limit on annual investments in solar and wind technologies, and putting a limit on trade volumes to account for energy security. Caps on electricity trade are being put on both imports and exports. More specifically, imports are capped based on historical trends. The cap on exports is tied to 10% of electricity demand for each country.

Results are available on the national level as well. Figure 35 shows annual generation over the study horizon for France. Figure 36 shows generation at the finest temporal resolution in the specific model setup. It shows the per-time-slice dispatch over a typical day for season 1 and for year 2050. It can be observed that hydro with water storage capacity operates flexibly to accommodate solar generation over the second time slice (7am to 5pm). It is also evident from the results that the low intraday temporal resolution contributes to not capturing the variable intraday profile of solar generation (solar generation appears flat over a period of 10 hours). As the model can only "understand" intraday effects at the level of the predefined temporal resolution, it underestimates the system's value of electricity storage in the specific case. Electricity storage could be an economic option for energy arbitrage if the model had a more refined temporal resolution. While the results presented are illustrative, a prospective user of the CLEWs-EU model could increase temporal resolution to better capture such effects based on their study needs.

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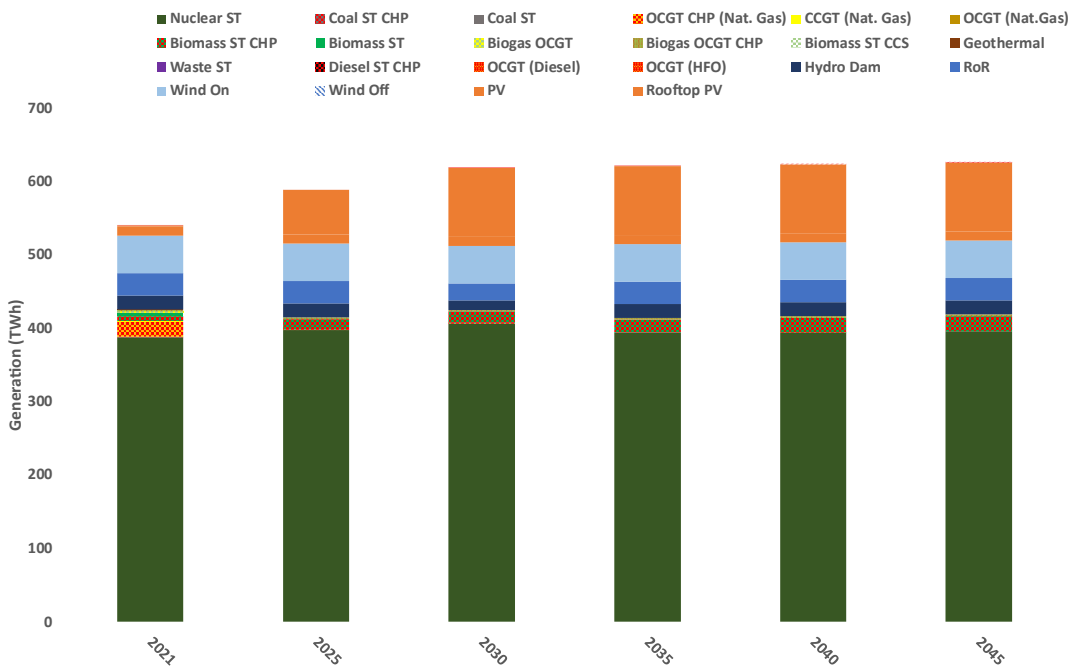

Figure 35. Total electricity generated in France.

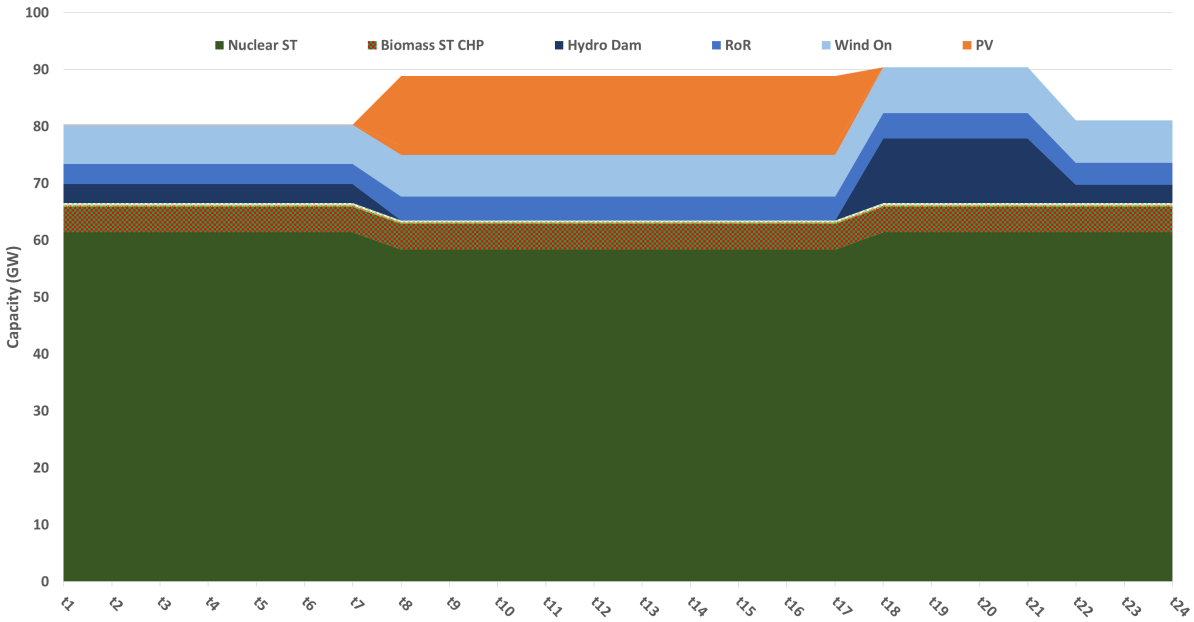

Figure 36. Generation per time slice in first season of the year over a typical day in year 2050 for France.

3.1.2 Buildings

Despite the lack of hard emission limits in the baseline scenario, the buildings sector almost completely decarbonises by 2050. At the same time, the final energy demand reduces substantially (Figure 37). This is driven mainly by aspects included in the assumptions: (a) the implementation of ETS2, which gradually increases the cost of fossil fuel use in the buildings sector, (b) the improvement in the efficiency of technologies in the building sector, and especially the decline in the purchase cost of heat pumps and their efficiency improvement, and (c) the increased renovation rates in the buildings stock across the EU already integrated in the EU Reference Scenario assumptions.

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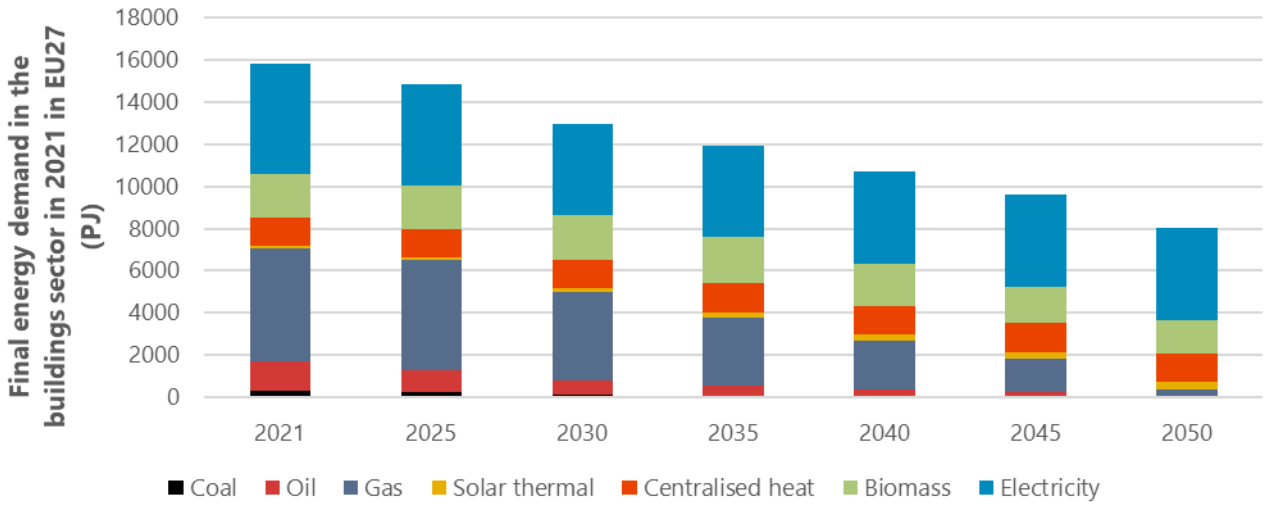

Figure 37. Evolution of final energy demand in the buildings sector in EU27.

The projected increasing importance of heat pumps is evident in Figure 38. The improvement in the cost-competitiveness of this technology option leads to a substantial increase in the contribution of this technology for space heating purposes. Due to its high efficiency, which is projected to increase even higher by 2050 according to the adopted assumptions, the deployment of heat pumps leads to a reduction in the overall final energy demand in the buildings sector. Nonetheless, in the future scenario exploration of the DIAMOND project, the useful energy demand projections adopted in the model may have to be adjusted upwards, which will have an equivalent impact on final energy demand. For instance, space cooling requirements are kept at historical levels in the baseline scenario—depending on the climate scenario to be considered, these could increase considerably across the EU in the coming decades.

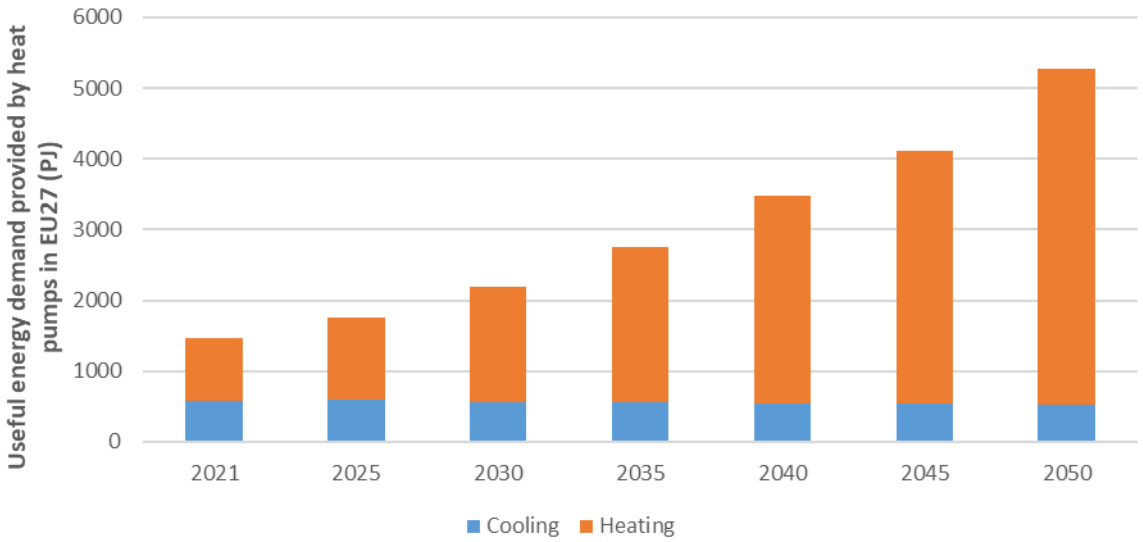

Figure 38. Evolution of heat pump contribution in the buildings sector for space heating and space cooling in EU27.

The decrease in the final energy demand in the buildings sector is also facilitated by building renovations. As illustrated in Figure 39, a reduction of approximately 640 PJ in the useful energy demand is achieved by 2050. It is interesting to observe that the most cost-competitive option is deemed to be medium-level renovations, which basically consists of improvements in the insulation of windows, walls, roof, and basement.

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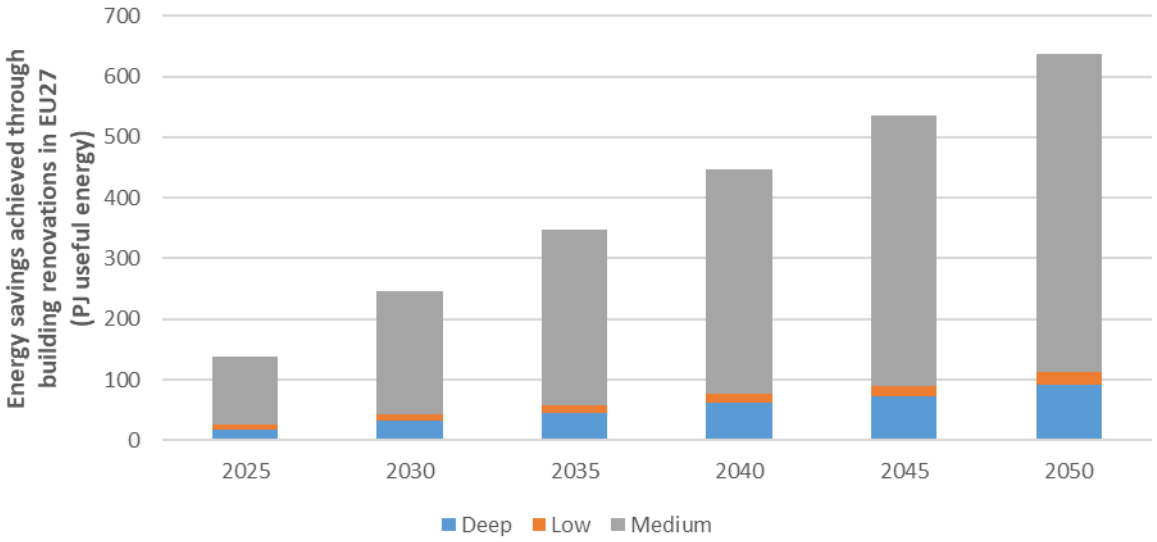

Figure 39. Energy savings achieved through building renovations in EU27.

3.1.3 Industry

The final energy demand in industry remains relatively stable for the entire model horizon with a decrease of about 6% between 2021 and 2050 (Figure 40). However, during this time, the energy mix changes a bit based on the adopted assumptions. Natural gas and oil demand decrease substantially (71% and 79% respectively), while industrial electricity demand decreases by approximately 15% during this period; this is also partially affected by assumed energy efficiency improvements in industrial equipment. However, demand for bioenergy more than doubles, while demand for coal more than triples. At the same time, hydrogen consumption appears across all EU member states during the model horizon; by 2050, the major consumers of hydrogen in industry for energy purposes are France, the Netherlands, Spain, and Finland.

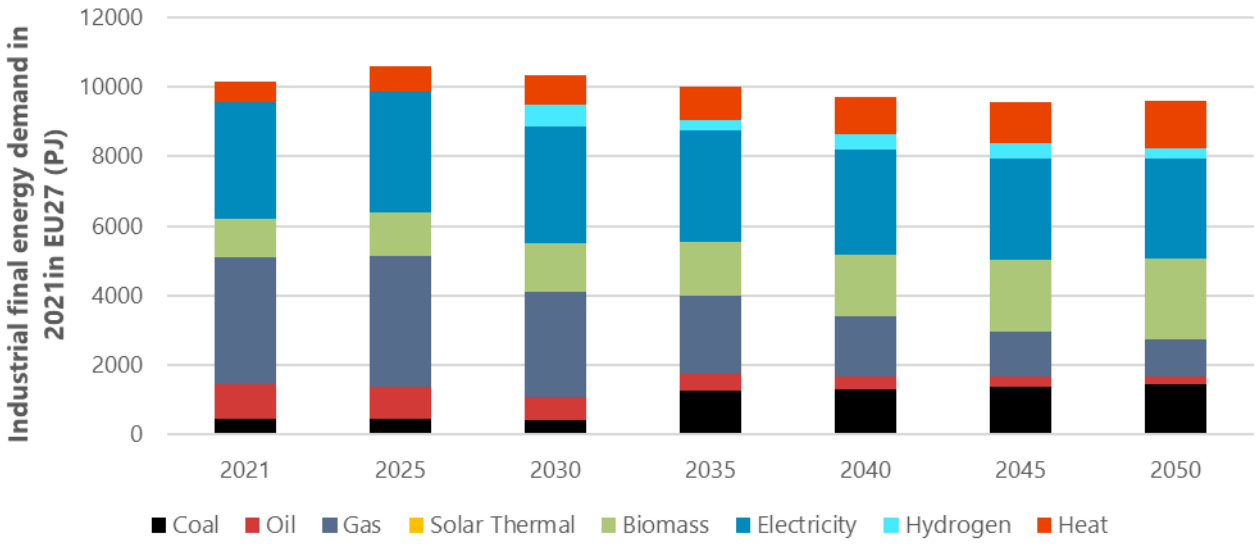

Figure 40. Evolution of final energy demand in industry in EU27.

The increase in coal consumption in industry is accompanied by the deployment of CCS technologies (Figure 41). By 2050, 91% of the industrial coal consumption is in combination with CCS—this is mainly driven by the assumed increase in ETS prices, and an improvement in the cost and efficiency of CCS-fired technologies. The major countries firing industrial coal with CCS in 2050 are France, Germany, Spain, Poland, and Italy.

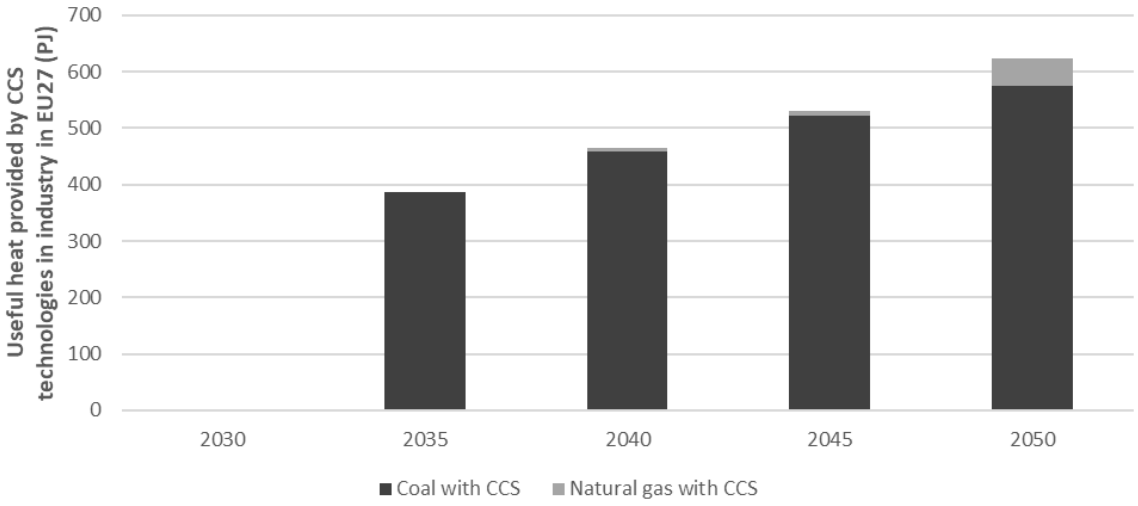

Figure 41. Useful energy provided by Carbon Capture and Storage (CCS) technologies in industry in EU27.

3.1.4 Transport

The passenger fleet changes over the model horizon away from conventional internal combustion engines to hybrid vehicles, battery electric vehicles, and alternative fuels (e.g., CNG). In addition, the baseline scenario projections appear to indicate a preference for diesel-fired hybrid passenger cars; this could be attributed to differences in fuel efficiency between gasoline and diesel hybrid cars. However, perhaps additional constraints will need to be implemented in the scenario exploration phase, as there exist more gasoline hybrid than diesel hybrid passenger car options available on the market, and this could affect consumer behaviour accordingly.

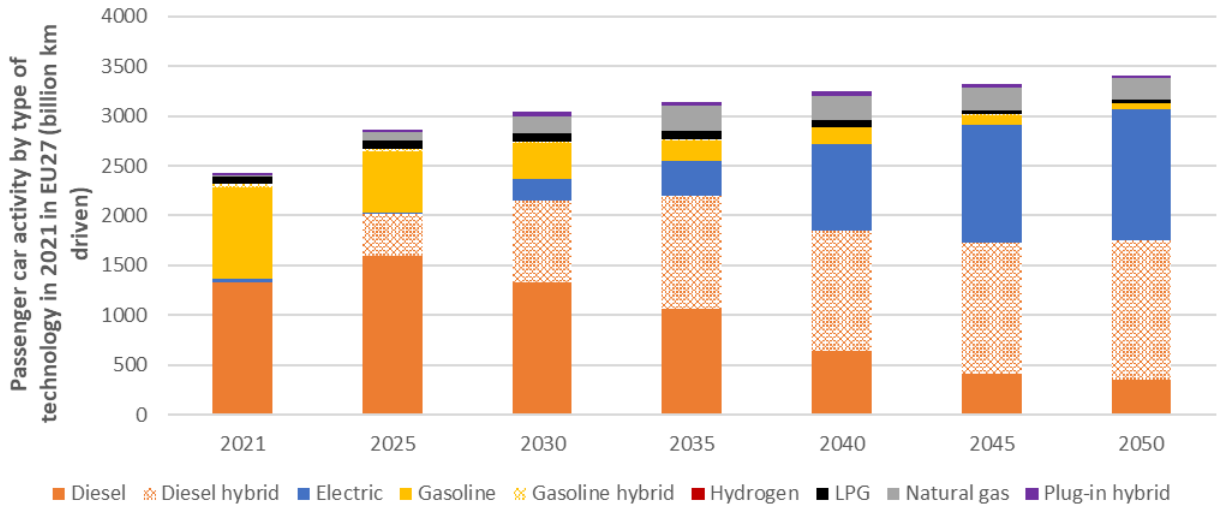

Figure 42. Evolution of passenger car activity by type of technology in EU27.

The gradual increase in hybrid and battery electric vehicles leads to a noticeable shift in the final energy demand of the entire land transport sector (i.e., road and rail transport). Consumption of gasoline and diesel decreases considerably up to 2050, with the former almost disappearing from the energy mix, while diesel retains a sizeable but diminished share of the energy mix, as it decreases by 63% from 2021 to 2050. At the same time, electricity consumption increases by an order of magnitude from approximately 205 PJ (57 TWh) in 2021 to 2,480 (690 TWh) in 2050 (Figure 43).

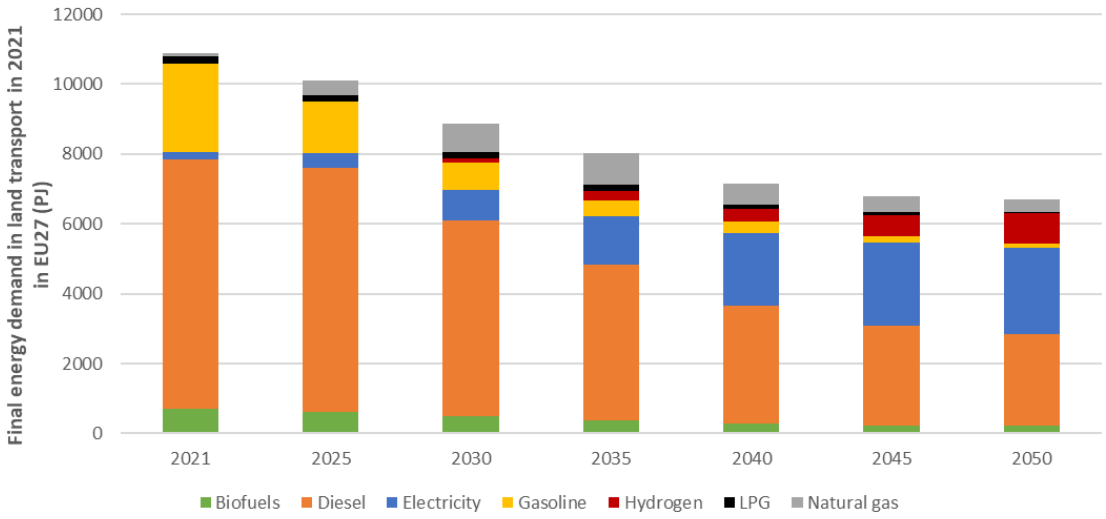

Figure 43. Evolution of final energy demand in land transport (i.e., rail and road) in EU27.

Hydrogen also gradually emerges as an important fuel in the road transport sector. The top 5 countries with the highest hydrogen consumption in this sector, in absolute terms, are Germany, Italy, Spain, France, and Austria. Hydrogen in road transport is primarily directed to heavy transport modes (i.e., heavy trucks and buses), while the vast majority is used for heavy freight vehicles (Figure 44).

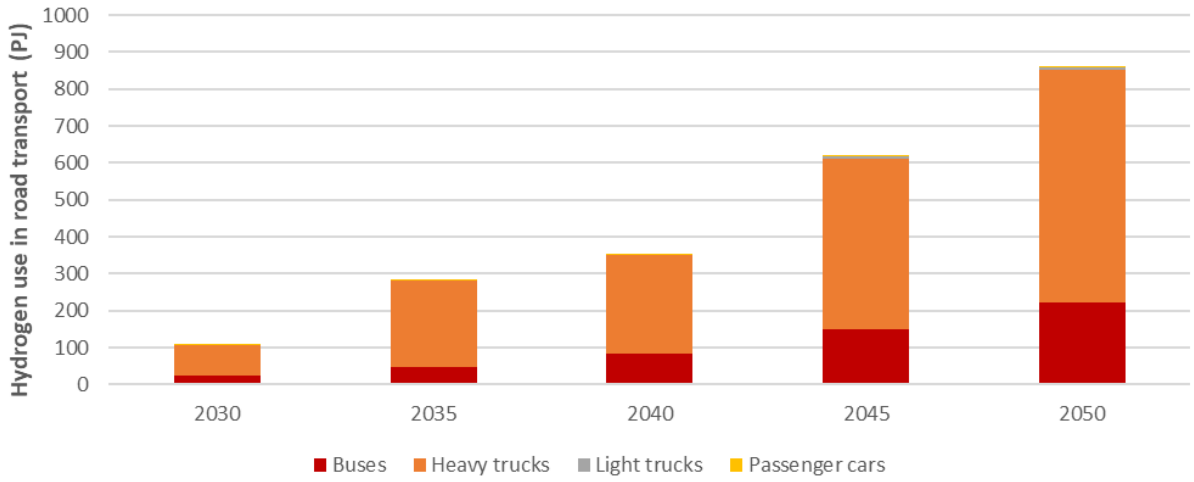

Figure 44. Hydrogen consumption in the road transport sector by mode of transport - EU27 total.

3.1.5 Hydrogen supply

Hydrogen gradually emerges as an important fuel source for industry and transport. The majority of the fuel is supplied via electrolysis, while smaller quantities of hydrogen are imported from non-EU countries (Figure 45). In a sense, electrolysis acts as an energy storage option, given that very little investments in electrical storage are projected in this baseline scenario.

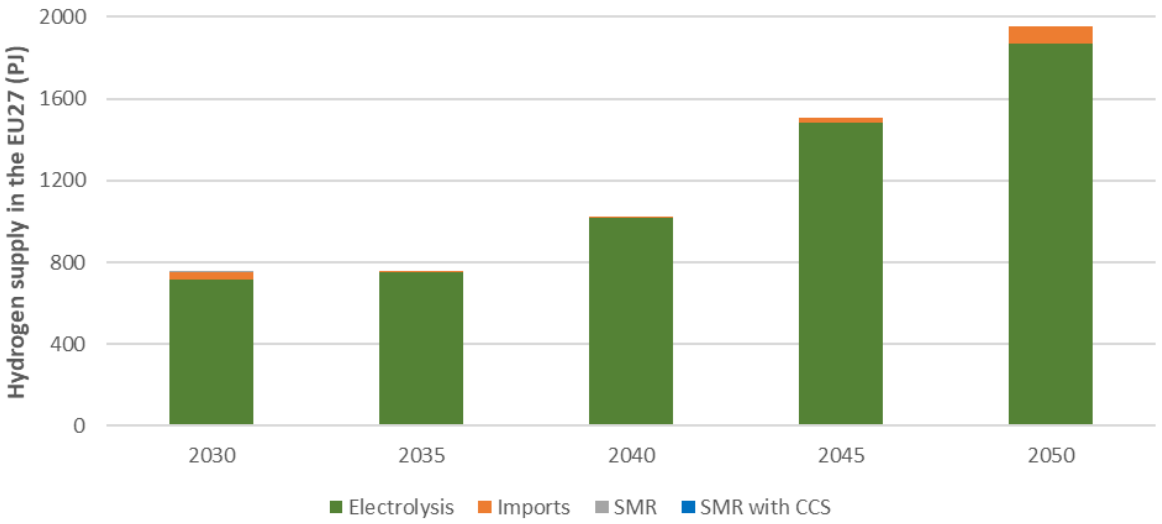

Figure 45. Evolution of hydrogen supply across the EU.

The size of the economy and the energy requirements of the respective national energy system is a key driver for the hydrogen demand projected in the baseline scenario (Figure 46). By 2050, the major consumers of hydrogen in the EU are Germany, Spain, Italy, France, and Sweden. Since hydrogen is primarily supplied via electrolysis, the cost-competitiveness of this fuel relies on the availability of cheap renewable electricity in each country.

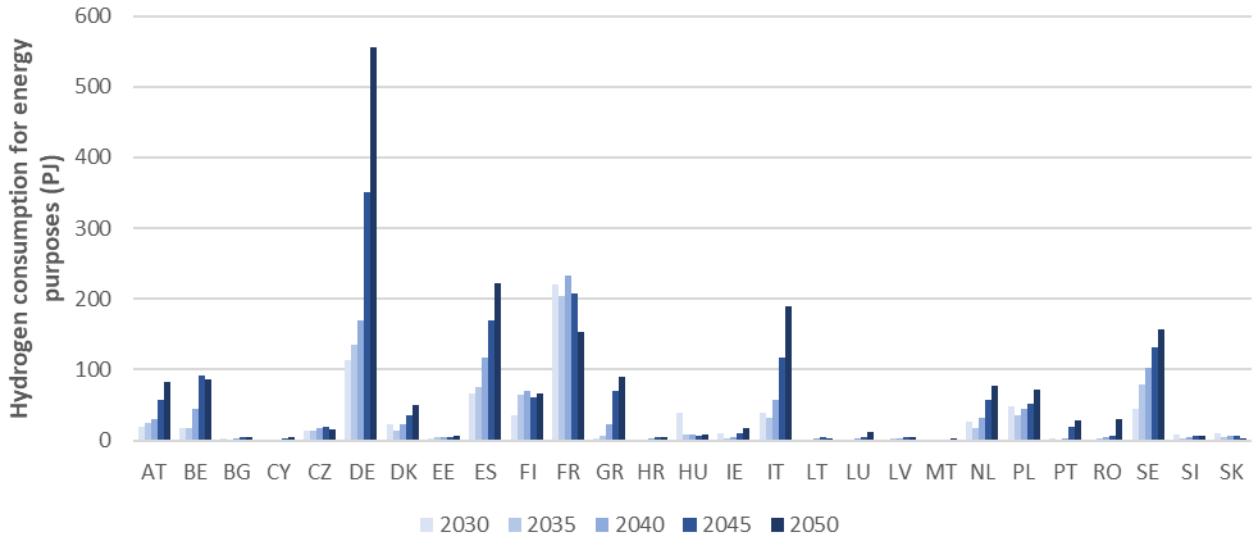

Figure 46. Projected hydrogen consumption for energy purposes in each EU member state.

3.2 Land and Water module

The following subsections summarise scenario results for selected countries and the combined EU-27 across the modelling period.

3.2.1 Crop production and Land Use

The CLEWs-EU model includes the top 9 crops (in terms of area harvested) from each EU country and then combines all the remaining crops into an 'other crop' category to produce a detailed crop profile without greatly increasing data and computational requirements. Triticale is re-classified rye due to conflated definitions across FAOSTAT and Eurostat databases and the similarities between the two crops. In total, 41 different crops are

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modelled across EU countries. The model divides crop production into four possible technology types: 'High Input Irrigated', 'High Input Rainfed, 'Low Input Irrigated', and 'Low Input Rainfed'.

3.2.1.1 Wheat

Wheat is the most widely grown crop in the EU in terms of area harvested (33% of EU cropland). That said, total EU wheat production is projected to decline by 6.5% from 2021 (138.2 million tonnes) to 2050 (129.3 units million tonnes) - note that demand is an exogenous input to the model. This decreasing projection is due to expectations that animal feed demand will decrease (Wheat decline would be more pronounced but for a expected and continuing strong export market) (European Commission, 2025b).

In the baseline scenario, the model 'solves' this demand by favouring intensive irrigated production (high capital/energy/water) or extensive low-input rainfed systems over low-input irrigated or high-input rainfed systems (Figure 48). The production of wheat from high-input irrigated systems increases multi-fold, from 7.2 to 35.3 million tonnes, within the modelling period. This is the emerging technology pathway in the baseline scenario. The historically dominant system, high input rainfed, declines in share by 53%. Low input rainfed production notably increases from 27.2 to 45.2 million tonnes, primarily due to its lower cost.

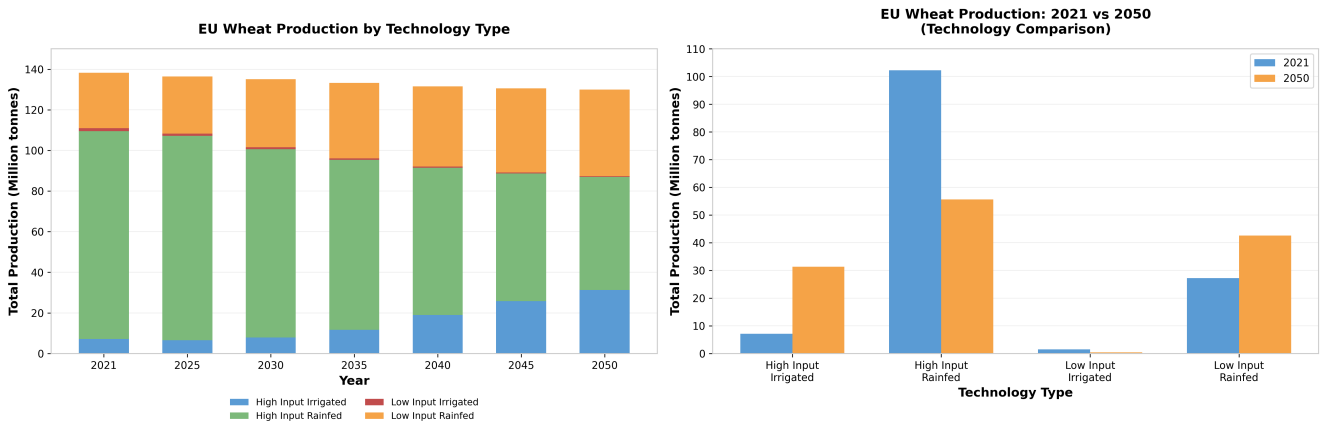

Figure 47. Wheat Production by land use type. Left (2021-2050), Right (Snapshots for 2021 and 2050).

3.2.1.2 Barley

Barley is the second most widely grown crop in the EU in terms of area harvested, accounting for approximately 12% of all EU crop land (FAOSTAT). Figure 48 shows that the baseline scenario favours intensive irrigated production (high capital/energy/water).

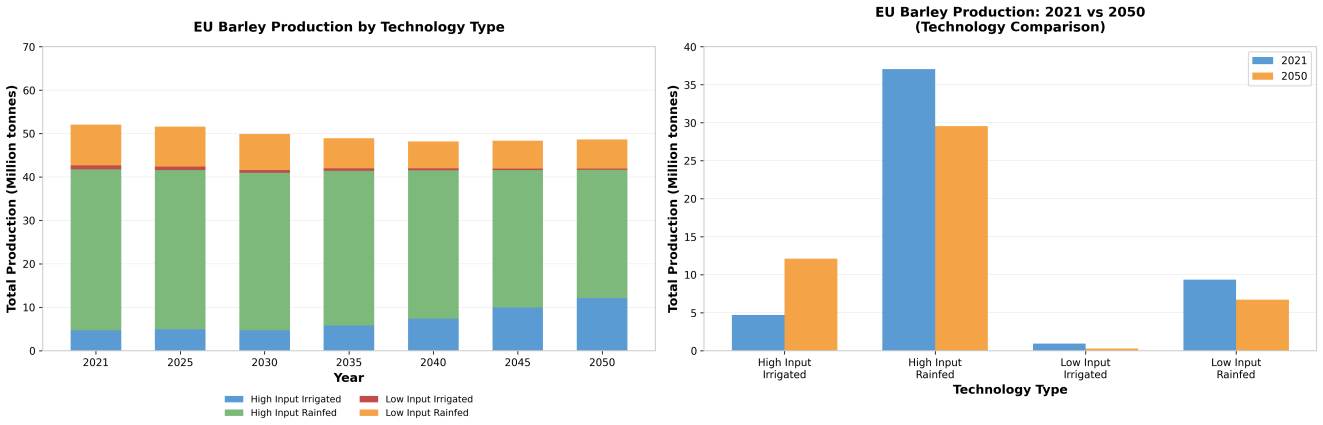

Figure 48. Barley production by land use type. Left (2021-2050), Right (Snapshots for 2021 and 2050).

Total EU barley production is projected to decrease from 2021 (52.0 million tonnes) to 2050 (48.9 million tonnes), a trend similar to that of wheat. By 2050, high-input irrigated land is expected to increase its production from 4.7 to 13.6 million tonnes, outpacing the growth in intensive wheat farming, with production in all the other lower-input systems falling to facilitate this shift. The same analysis has been conducted for each EU country and their corresponding top 9 crops.

3.2.1.3 Germany crop production

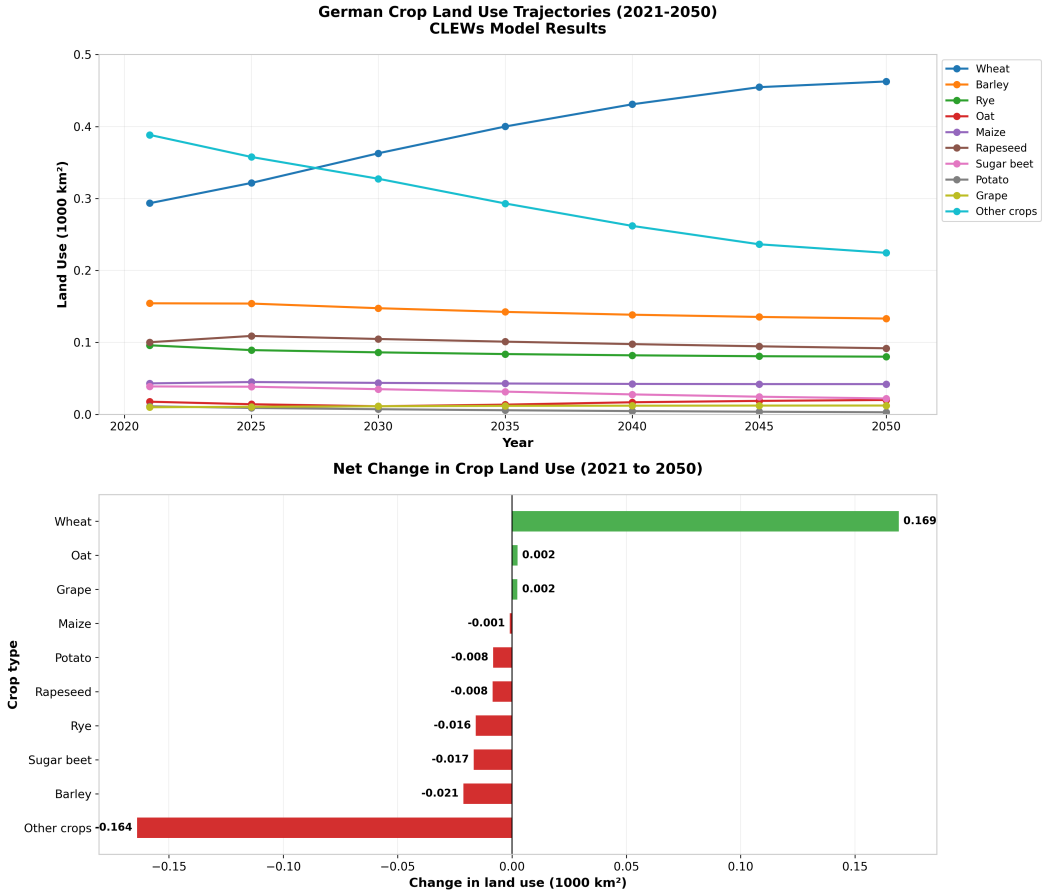

Figure 49. Land use change for crop production (by crop type).

Figure 49 and Figure 50 present the land area by crop type and land use (input levels and water supply) type in

Germany. Despite a decline in demand for wheat, land dedicated to wheat production expands as croplands are converted to less productive, low input rainfed land, to reduce diesel consumption (fuel costs). The figure also highlights the land use. The reverse is true for 'other crops', which is less fuel-intensive, hence the model decision to invert their land type trajectories (note, however, that other crops is a less detailed category, an agglomeration of a variety of crops with different fuel needs). The figure also highlights the land cover change across the major crops; production intensifies for all crops except for wheat, oats and grapes, whilst demands for most crops also reduce over time (European Commission, 2025b).

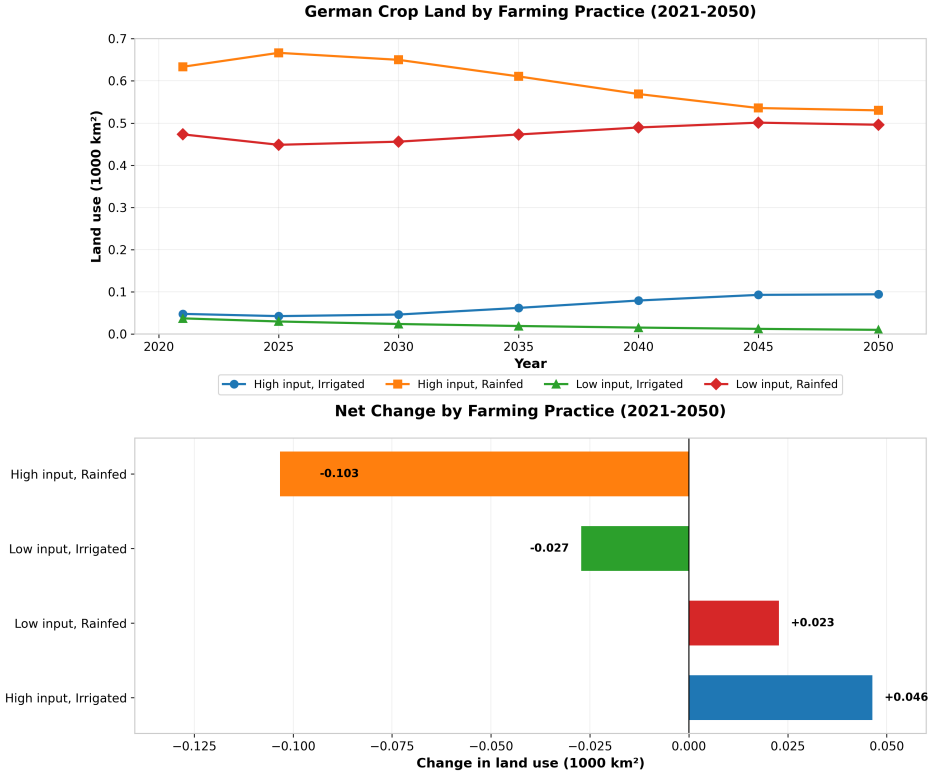

Figure 50. Land use change for crop production in Germany (by Land use type).

Similar metrics can be generated for each EU member state to explore the dynamics between crop production and energy consumption.

3.2.2 Other Land Use

Alongside crops, the model represents seven other land categories: Built-up land (or artificial land), Grassland, Shrubland, Forests (woodland), Bare Land, Water Bodies, and Wetlands. Outside the calibration year (2021), the model also optimises the share of each type of land use within constraints. However, absolute changes in land use are small as projected crop demands are relatively stable over time, leaving little space for other land uses to expand or contract out to 2055 in the baseline scenario (Figure 51). That said, intensification of crop production does free up some land, which is converted primarily to forests due to their low costs. Note also that grassland area and built-up land area increases steadily as livestock demand and urbanisation both increase over the model period.

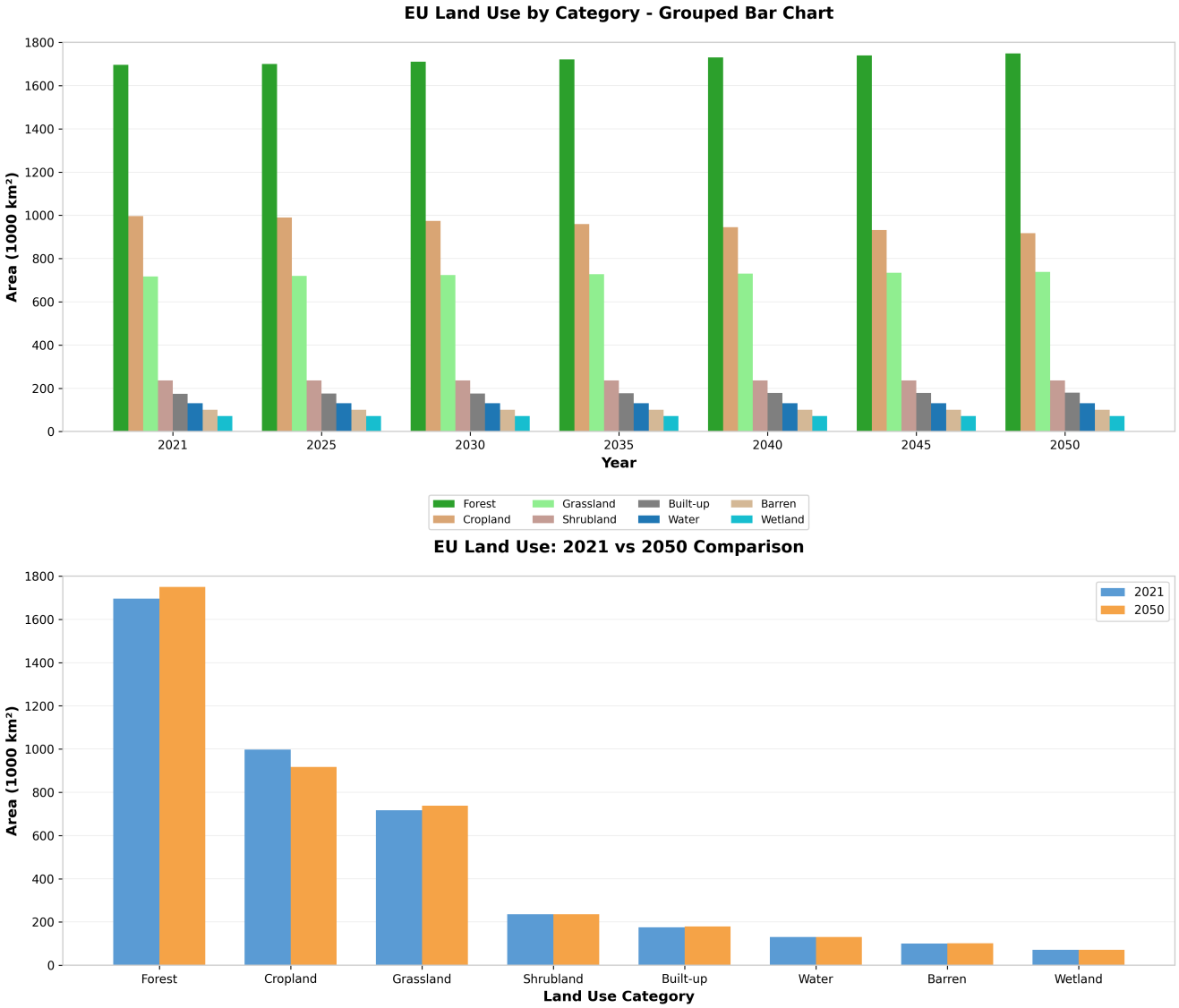

Figure 51. Land-Use Change across the modelling period.

Detailed results are available for each of the 27 EU countries. However, an EU-wide picture can be obtained by looking into Germany. Germany's land use is projected to undergo gradual but notable shifts over the coming decades (Figure 52), as cropland area declines by approximately 100,000km^2 by 2050. Forests, which are already the largest land cover in the country, expand almost commensurately. Grasslands and built-up areas also expand onto land previously allocated to crops. Germany's decline in cropland area has been less substantial compared to the EU average, but it otherwise mirrors EU-wide trends quite closely.

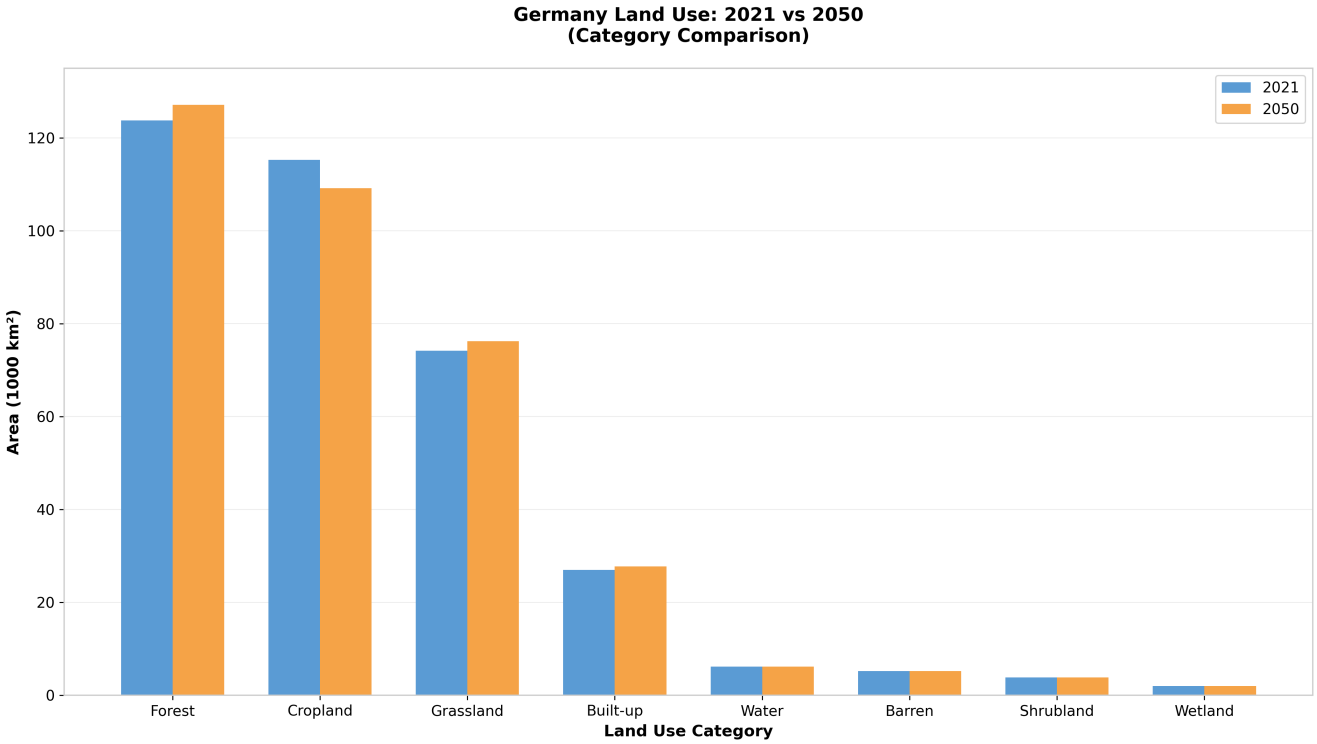

Figure 52. Germany Land-Use Change.

3.2.3 Water Use

The following analysis presents water withdrawals by sector and source for the EU-27 as a whole and several representative countries under the baseline scenario. Indeed, a critical feature of the CLEWs framework is the bidirectional relationship between the land and water modules. Figure 53 presents the change in overall water withdrawals in the baseline scenario in the EU-27 between 2021 and 2050. Note that industrial and commercial (clustered as other sectors) and public water withdrawals are exogenous demands, whereas the power sector and agriculture are endogenous. The volume and share of water consumed in the power sector both decline, as output from fossil fuel power stations is reduced, and so too is the water required for cooling. However, it must be noted that the rate of decrease in water required for cooling is not drastic, as biomass power use increases and requires water-based cooling as well. Conversely, an increase in water withdrawals from agriculture reflects a growing share of irrigated land, despite demand for most crops falling. Note that agricultural water demand in this model represents only irrigation water withdrawals—rainfed agriculture, which comprises over 90% of EU cropland, requires no withdrawn irrigated water and therefore generates no agricultural water demand in the model. This explains why agriculture accounts for only 2.5% of total EU water withdrawals, despite its substantial land footprint (see figure 54).

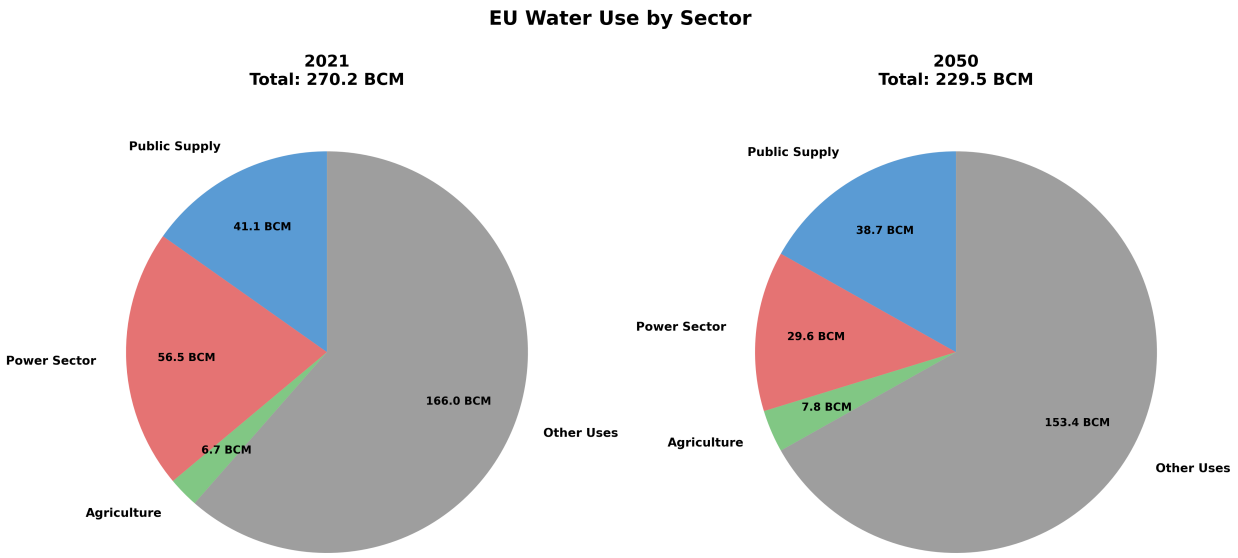

Figure 53. Water Withdrawal in the EU-27 by sector in 2021(left) and 2050 (right).

These trends hold for some countries but not others, as is shown in Figure 54 and Figure 55. When the land module optimises crop choices and farming practices (high/low input, irrigated/rainfed), these decisions directly determine agricultural water withdrawal requirements. For instance, Spain's shift away from irrigation (73% reduction in irrigated area by 2050) manifests as reduced agricultural water demand (figure 56), whilst Germany's intensification of irrigation (32% increase) increases water withdrawals (figure 55). This nexus ensures that water scarcity and abstraction costs influence land-use decisions, and conversely, that agricultural intensification strategies have explicit water resource implications.

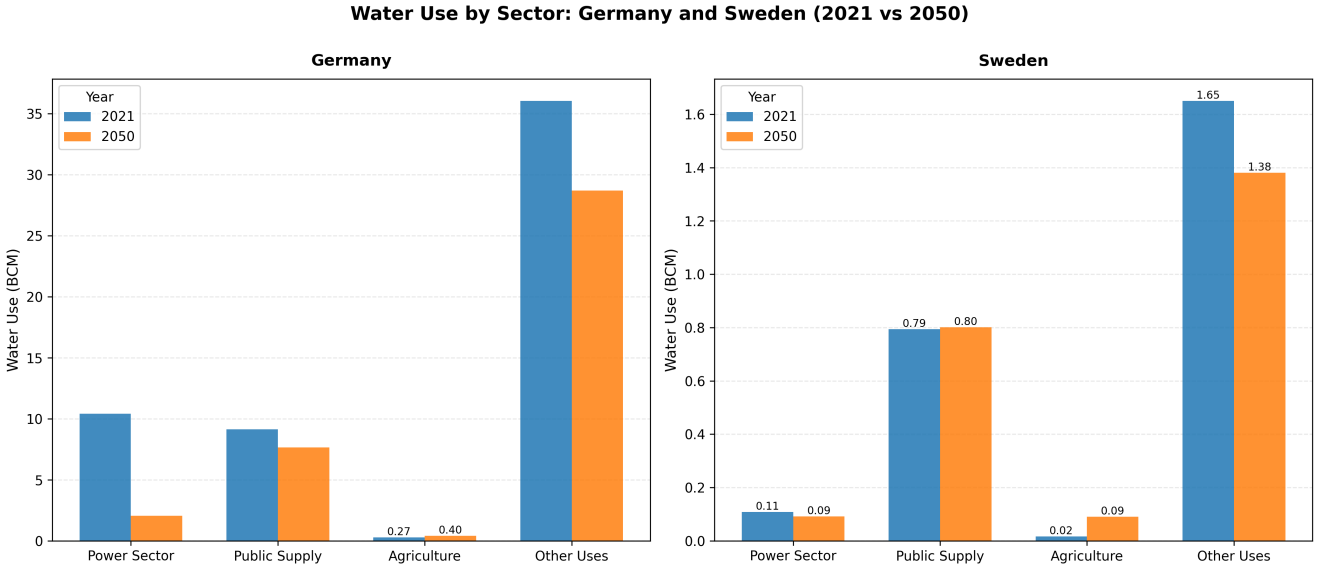

Figure 54. Water withdrawal by sector in Germany (left) and Sweden (right).

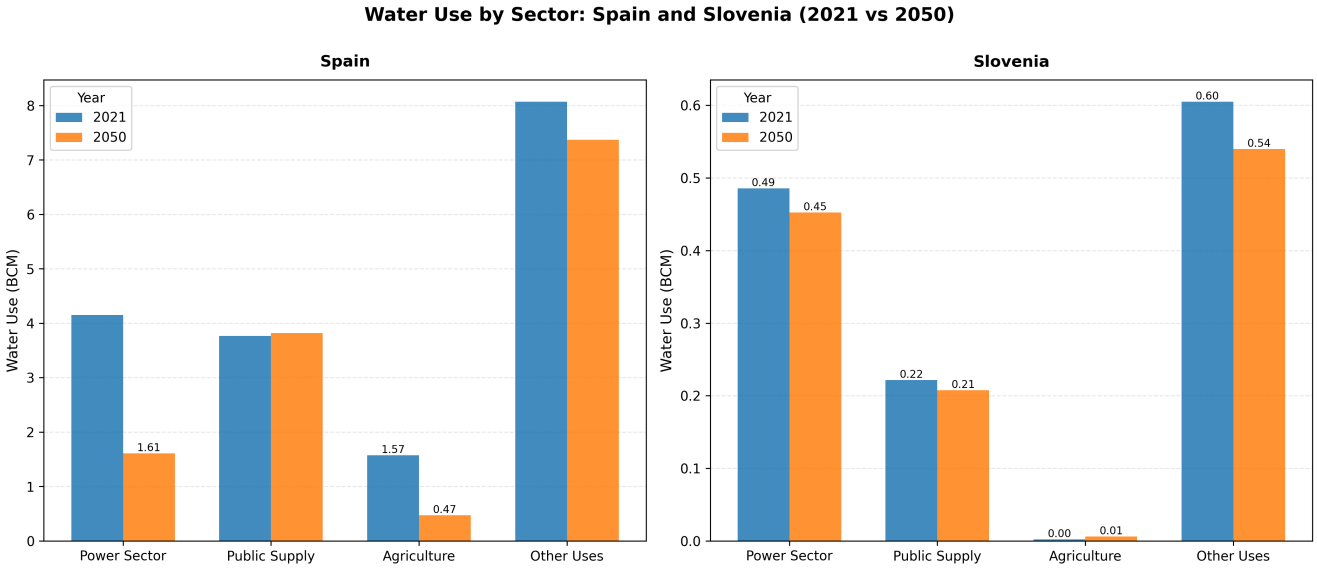

Figure 55. Water withdrawal by sector in Spain (left) and Slovenia (right).

Figure 56 presents a snapshot of the expected changes in water withdrawal demand between 2021 and 2050. 15 of the 27 countries are expected to observe reduced water withdrawals at the end of the modelling period.

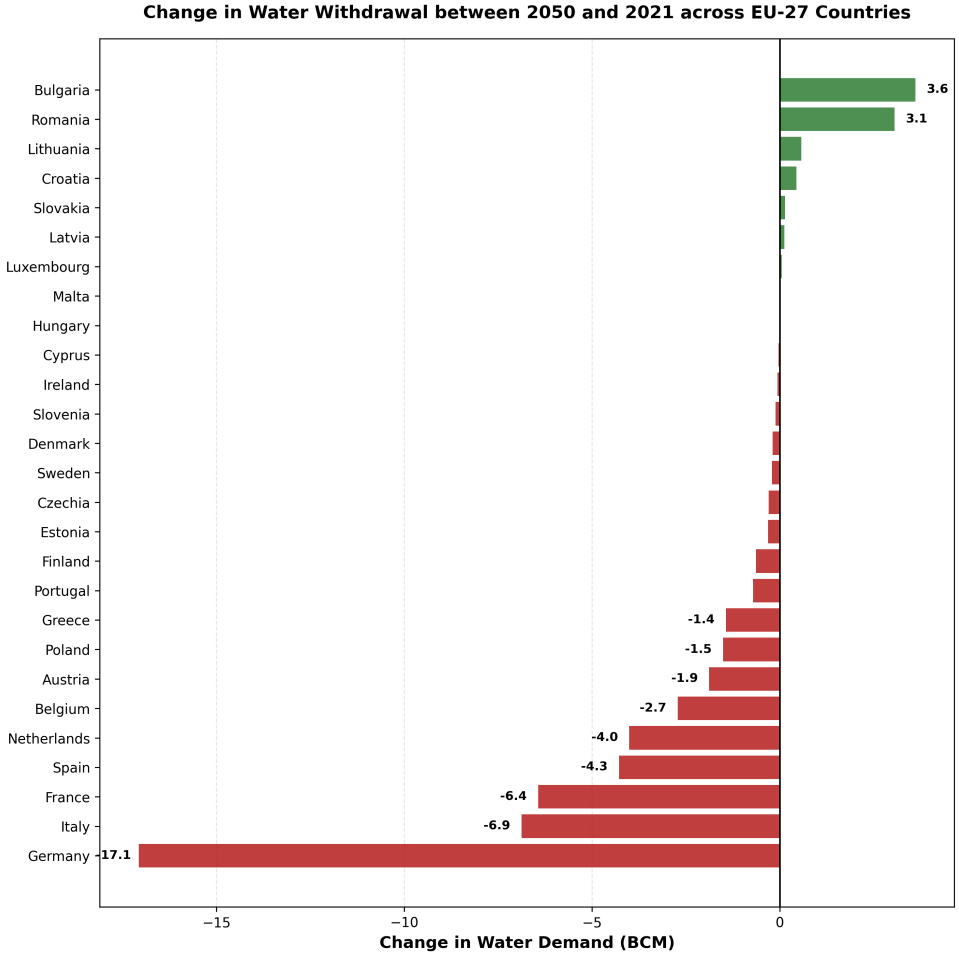

Figure 56. Change in water withdrawal between 2021 and 2050 across the EU-27 countries. Positive figures reveal higher water withdrawals, negative lower.

3.3 Cross-sectoral linkages

3.3.1 Energy-Water Nexus

The CLEWs framework models the energy-water nexus as a multidirectional relationship involving three critical perspectives: thermal power generation requires water for cooling, water supply systems consume electricity for pumping and treatment, and the energy intensity of water infrastructure varies with geographic and technological factors. This section analyses these flows across EU-27 member states through three complementary metrics that together illuminate the full complexity of resource interdependencies. The data presented are for the base year (2021) as opposed to the baseline projections for 2050 shown elsewhere.

Figure 57 illustrates the significant variation in energy intensity of water supply infrastructure across EU member states, ranging from below 2 PJ per BCM in countries such as Croatia and Estonia to over 15 PJ per BCM in Cyprus. This difference reflects contrasting geography, infrastructure age, and water treatment requirements. Cyprus and Denmark exhibit the highest energy intensities, despite having modest total water demands, due to the extensive use of desalination and complex distribution networks. In contrast, Germany and France have much lower energy intensities, which, combined with the region's highest water demands, result in higher water consumption.

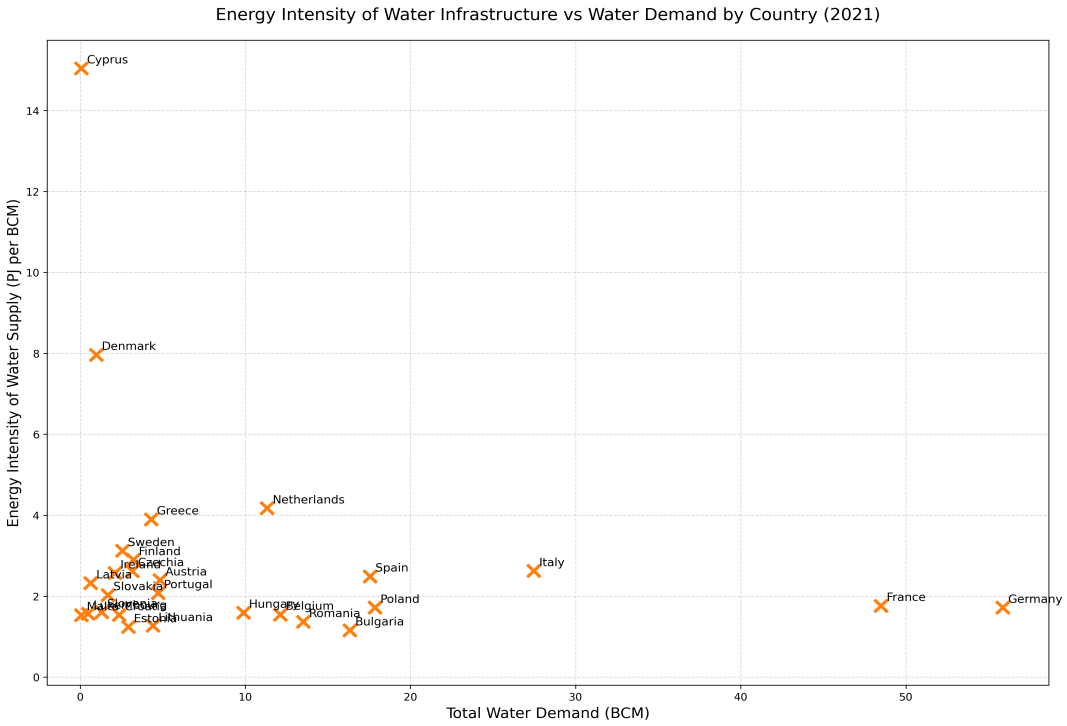

Figure 57. Energy Intensity of Water Infrastructure vs Water Demand by Country (2021).

In Figure 58 water withdrawal intensity of thermal power generation is presented. It reveals critical vulnerabilities in the energy-water nexus. Estonia and Hungary exhibit the high-water withdrawal rates per unit of electricity, likely due to the use of once-through cooling systems in older power plants. In contrast, France and Germany, which operate the largest thermal fleets, maintain relatively low withdrawal intensities due to widespread adoption of closed-cycle cooling systems.

These analyses reveal significant heterogeneity in energy-water interdependencies across the EU, presenting both challenges and opportunities. High-intensity water systems in Cyprus and Denmark require targeted efficiency investments, while the water demands of thermal generation in Estonia and Hungary present opportunities to

reduce water consumption by improving cooling technologies. Notably, large-scale systems like Germany and France demonstrate that efficiency across both dimensions is achievable even at high demand levels, offering valuable models for other member states.

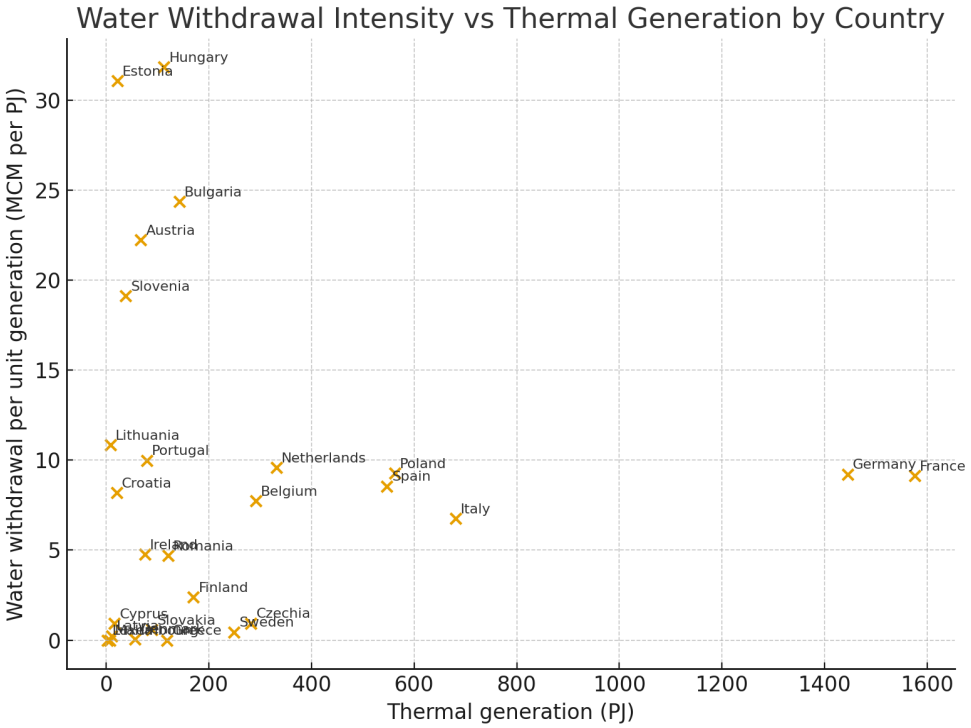

Figure 58. Water Withdrawal Intensity vs Thermal Generation by Country (2021).

3.3.2 Energy-Land Nexus

Interlinkages between the energy and land sectors are explored in this section by comparing energy consumption in the EU Agriculture and Forestry sector between 2021 and 2050 (Figure 59). Overall, there is a moderate decrease in energy consumption from ~1,427 PJ (2021) to ~1,271 PJ (2050) across all EU countries for land use activities.

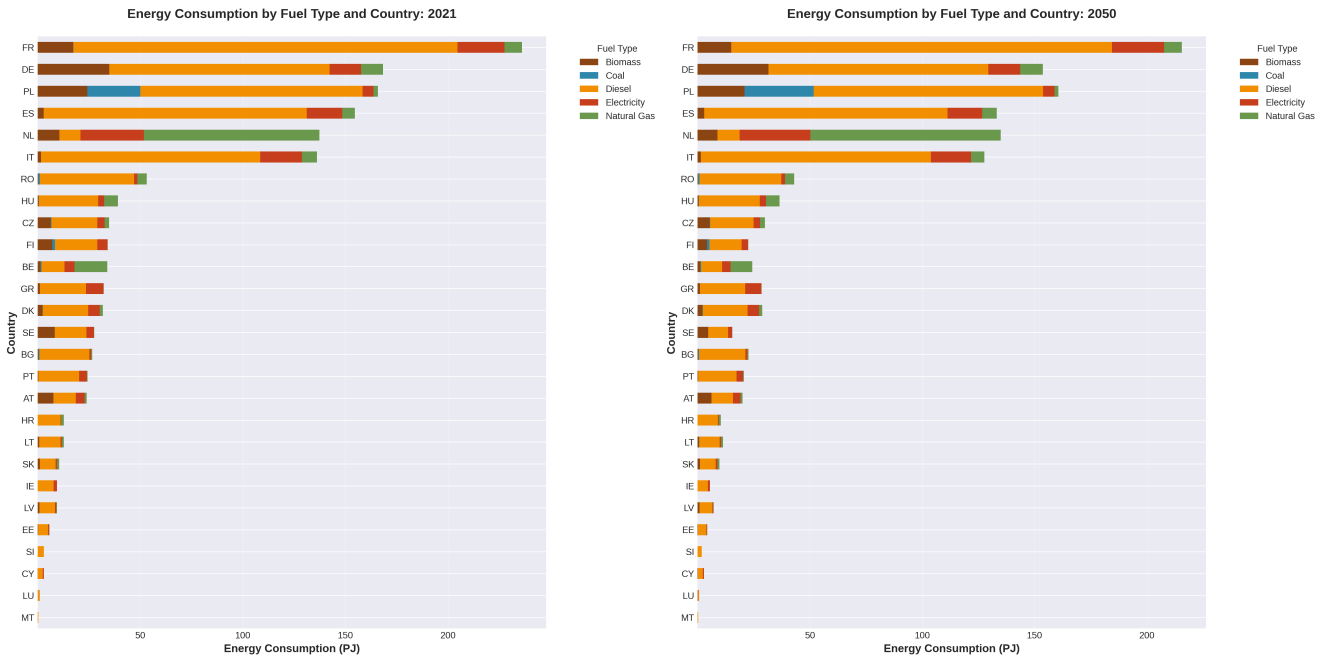

Figure 59. Energy consumption by fuel type and country in the agriculture and forestry sectors. Left (2021) and Right (2050).

Across countries in 2021, France had the highest energy use in agriculture, while smaller member states had minimal energy consumption in crop land. Diesel is the dominant fuel in almost all countries, although gas is prevalent in the Netherlands and coal in Poland. By 2050, energy inputs are expected to decline for nearly all countries, suggesting that agricultural intensification (see Section 3.2.1) appears to be reducing. Coal retains a small share but is expected to persist, especially in Poland.

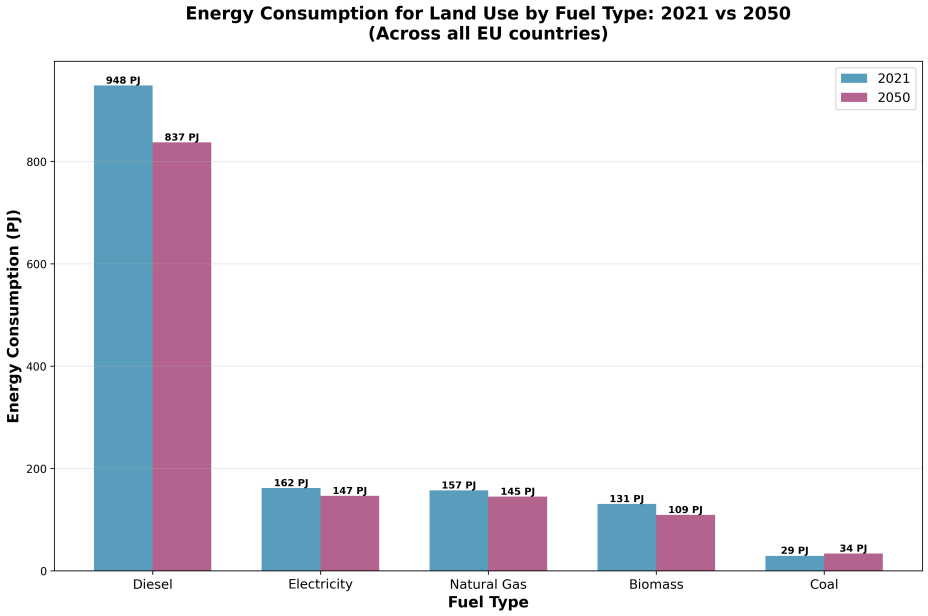

Figure 60. Total energy consumption in the agriculture and forestry sector by fuel type.

Figure 59. Energy consumption by fuel type and country in the agriculture and forestry sectors. Left (2021) and Right (2050Figure 60 demonstrates that, aggregated across the EU, diesel use is expected to drop from 948 PJ in 2021 to 837 PJ in 2050, electricity from 162 PJ to 147 PJ, and natural gas from 157 PJ to 145 PJ. Biomass use reduces from 131 PJ to 109 PJ. Coal is the only fuel that is expected to be consumed more, from 29 PJ to 34 PJ, predominantly in Poland. In summary, a diesel dependency persists despite energy efficiency improvements.

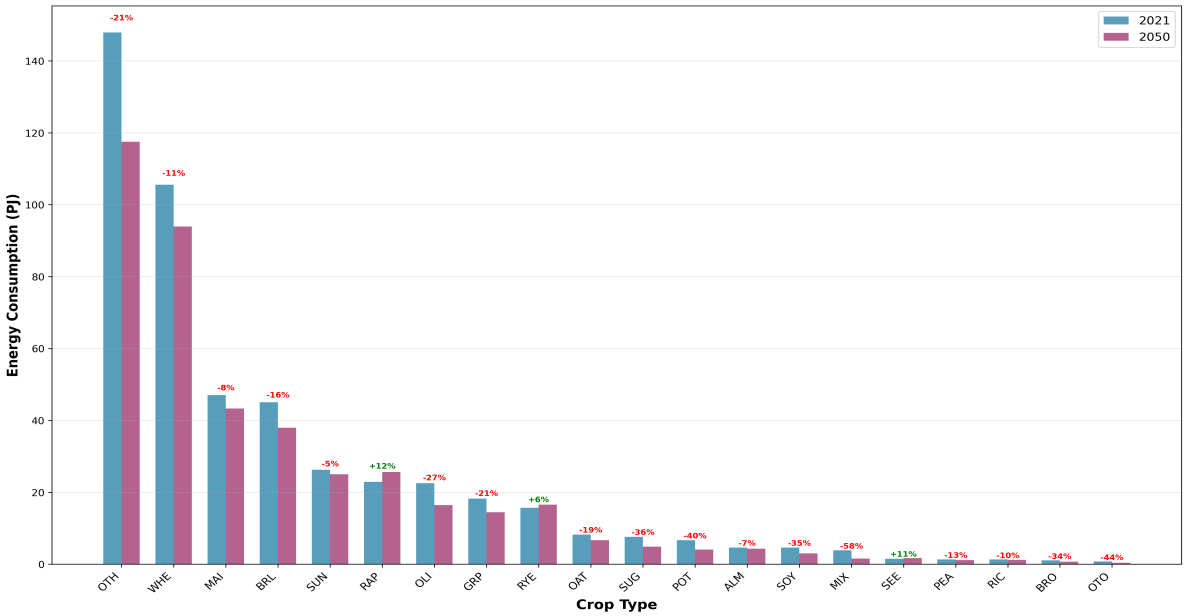

Figure 61. Energy consumption by crop type across the EU-27 countries.

At the crop-level (Figure 61), wheat, maize and barley were the largest users of energy in 2021, and energy consumption for each of these declined by 2050 (-11%, -8% and -16%, respectively). Most crops show reductions, with notable declines for potatoes (-40%), sugar crops (-36%), and soy (-35%). Increases are limited to rapeseed (+12%) and rye (+6%).

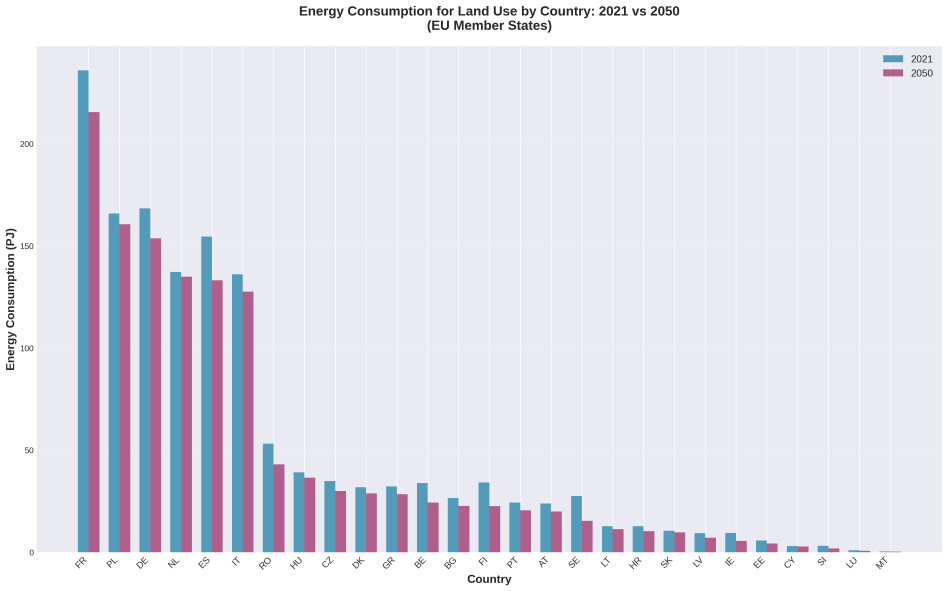

Figure 62. Energy consumption by country in the agriculture and forestry sector.

By country, every EU member state is projected to exhibit lower energy consumption in agriculture and forestry in 2050 compared to 2021 (Figure 62). France remains the highest consumer, with Poland and Germany next. Spain shows a sizeable reduction, and several mid-tier countries (e.g., Italy, Netherlands) also decline.

Diesel consumption trends for selected countries from 2021 to 2050 is presented in Figure 63. In all six countries, it is expected to reduce. France remains the highest, but its level steadily declines. Spain decreases slightly higher than 120 PJ toward ~108 PJ, while Italy and Poland converge near ~100 PJ by 2050. Sweden and Ireland start at a

lower level and continue with gradual reductions.

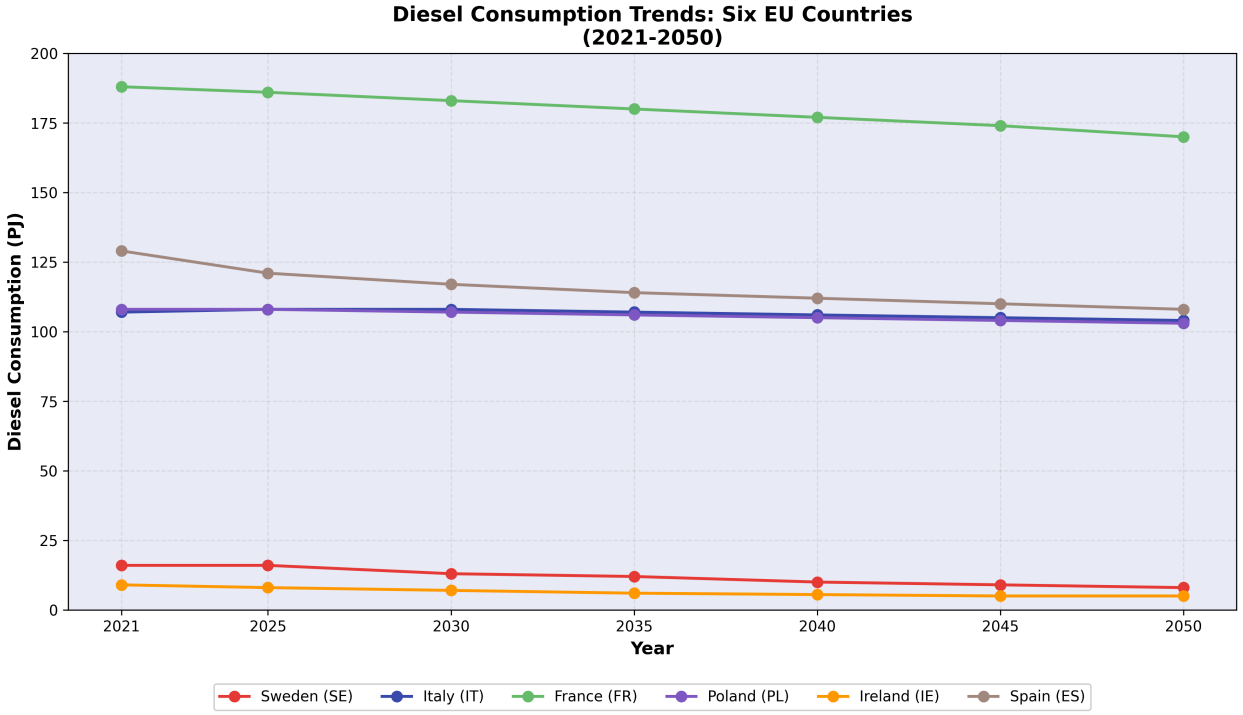

Figure 63. Diesel Consumption in selected countries in the AFOLU sectors.

3.4 Greenhouse gas emissions

The baseline scenario of CLEWs-EU leads to a substantial reduction in carbon dioxide (CO_2) emissions in the energy system, despite the lack of an emissions constraint (i.e., decarbonisation target) (Figure 64). The CO_2 emissions reduce across most sectors, with the exception of aviation and shipping, which increase by 69% and 15% by 2050 compared to their 2021 levels, respectively; the large increase in aviation emissions can be attributed to the low airline activity in 2021 due to COVID-19. The adopted assumptions on fuel prices, ETS prices and technoeconomic characteristics drive the observed CO_2 emissions decrease. The electricity and heat generation sector reaches net-negative CO_2 emissions by 2050 due to the deployment of biomass-fired generation with CCS, while the buildings sector almost completely decarbonises due to its projected large-scale electrification (driven by heat pumps) and energy efficiency improvements. Additionally, CO_2 emissions in land transport (i.e., road and rail) are projected to decrease by 69% from 2021 to 2050, while industrial emissions reduce by 75% over the same timeframe.

The CO_2 emissions estimation in CLEWs-EU is incomplete, as not all sectors are represented. Specifically, in industry, only emissions from fuel combustion are accounted for, while industrial process emissions are not captured. Furthermore, emissions from oil and gas extraction, petroleum refining, coal mining, manufacture of solid fuels, and other energy industries, and fugitive emissions throughout fuel supply chains are not captured. Finally, waste management emissions are not modelled.

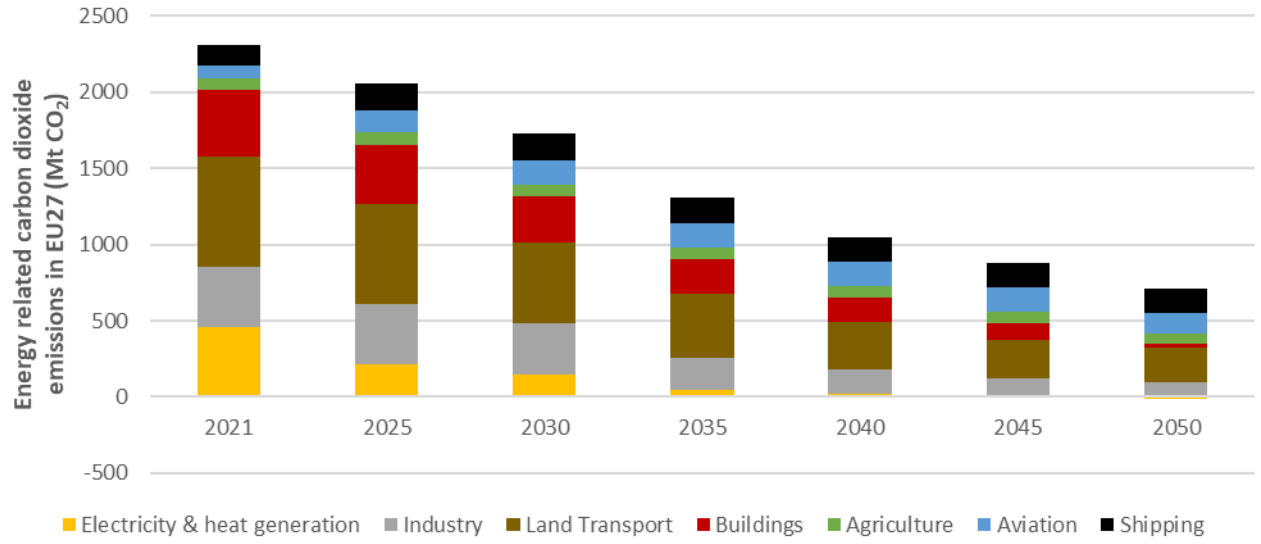

Figure 64. Energy-related carbon dioxide emission projections in the EU27.

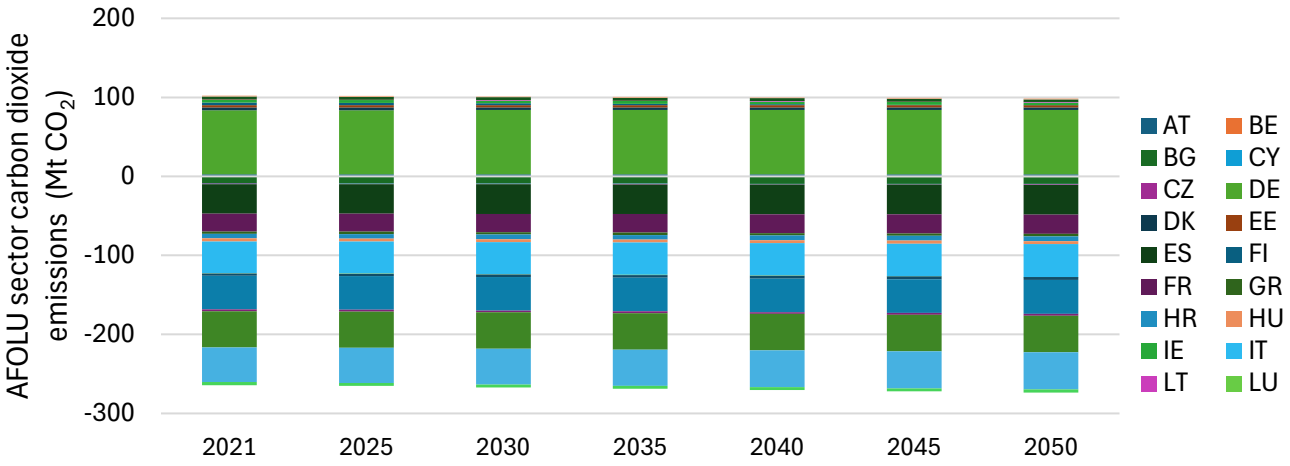

Figure 65. AFOLU sector carbon dioxide emission by country.

The carbon dioxide emissions from the agriculture, forestry, and land use sector in different countries are presented in Figure 65. We can notice that the net emissions are negative, driven by the sequestration of CO_2 in the forests across many countries. Between 2021 and 2050, net CO_2 emissions are expected to decrease from approximately -160 to -175 Mt, primarily due to the increase in forest and grassland cover across many countries. It is also important to highlight here that some countries (like Germany and the Netherlands) have exhibited a net increase in CO_2 emissions as their forests have become net emitters with climate change being a significant contributor to this (*Ergebnisse Der Vierten Bundeswaldinventur*, 2024). Figure 66 presents the methane emissions in the agriculture and livestock sectors. This is primarily the emissions from enteric fermentation and manure management. It is expected that there will be a ~ 11% decrease in methane emissions between 2021 and 2050 in this sector. A reduction in the total number of live cattle and other livestock (excluding poultry) in the EU-27 countries, along with a decrease in the total area under crop cover, is expected to contribute to this decline.

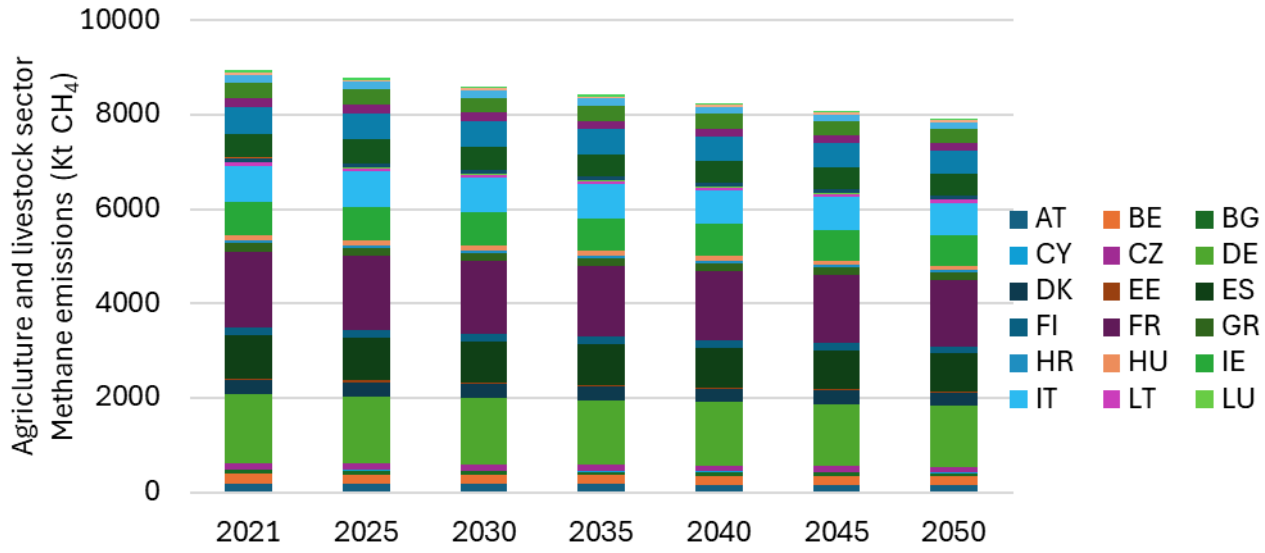

Figure 66. Agriculture and livestock sector methane emissions by country.

4 Future developments

4.1 Limitations and potential improvements in the CLEWs-EU model

Some weaknesses can be identified following the development of the final version CLEWs-EU model. The following bullet points provide an overview of the main items, which the team can aim to address either within the DIAMOND project's lifetime or beyond:

a) The disaggregated CLEWs-EU model is computationally intensive. The underlying **OSeMOSYS code** could be **amended** to reduce the computational effort, which could allow for additional detail to be added to the model, if deemed necessary.

b) Development of a **visualisation** tool for the disaggregated CLEWs-EU version. An equivalent tool for the aggregated version of the model has already been developed by ICCS, which could form the starting point for visualising results from the more detailed version of the model as well.

c) Final small adjustments to the structure or inputs of the model will be made as needed to accommodate **links with external modules** (i.e., climate, finance and behavioural aspects) or during application of the model for the **scenario exploration** phase of the DIAMOND project.

d) The available **model documentation** will continuously be improved to provide more detail on the structure of the individual sector, the adopted input data and assumptions, as well as detailed guidelines on the use of the model. These improvements will be guided by potential feedback to be received by the broader OSeMOSYS and CLEWs communities.

The subsections below provide further detail on potential improvements of the disaggregated CLEWs-EU model in each of the two main modules.

4.1.1 Energy module

The following weaknesses have been identified in the energy module.

- Dependence of the base year definition on the JRC-IDEES 2021 database has in certain cases limited the level of detail included in the model. For instance, in the road transport sector no differentiation between gasoline and gasoline-hybrid vehicles is given in the database; only plug-in hybrid vehicles are separately mentioned. To address this, data from Eurostat have also been used. However, in other cases, such as for industrial energy demand, no differentiation between biomass and waste is provided. Even though national energy balances provide more detailed information on the final energy demand by fuel type and sector, the equivalent information regarding useful energy demand was not readily available, so the team kept the aggregated category "biomass and waste".
- The results of the baseline scenario do not show considerable investments in electricity storage, with the exception of Cyprus, which currently operates an isolated grid system. This may be due to the low temporal resolution within each year, which potentially does not adequately capture peaks in demand and variable renewable energy generation. The team has tested the model with a considerably lower capital cost to see if the technologies appear in the solution, and indeed they do so. As such, the adopted cost assumptions may be too high or, since we have not forced the model to fully decarbonise, the storage requirements are deemed to be low. At the same time, it is possible that the rise in the production of hydrogen through electrolysis has contributed to the lower need for storage investments.

- The non-energy GHG emissions of industrial processes (e.g., calcination of limestone in the cement industry) are not captured by the adopted structure of the CLEWs-EU model. Since the required level of detail is difficult to implement, we do not attempt to make projections that would be highly uncertain.
- As the CLEWs-EU model is developed in the OSeMOSYS modelling framework, it relies on exogenous demand projections. This means that future demand for energy services (e.g., mobility, space cooling/heating, useful heat in industry etc.) has to be provided either by another model or be estimated by the CLEWs-EU modelling team based on a set of assumptions. It is difficult to endogenise demand projections in the model without thorough changes in the underlying OSeMOSYS code, but this can be considered at a later stage.

4.1.2 Land and Water module

We have identified the following limitations in the land and water module, which point to opportunities to strengthen the module and increase the accuracy of its outputs.

- Land use costs need to be improved to represent a country-specific outlook. In some cases, having crop-specific costs (possible in some countries) helps in improving the marginal cost at which a crop can be produced.
- We have deliberately excluded the import and export of crops to simplify the computation load. However, the model has provisions to easily include this setup. This will require detailed data on how the different crops are converted into their final products and exported. For example, grapes are produced in a country that exports both the primary crop (grapes) and wine, which is a product of grapes.
- The model has been calibrated to account for energy inputs to the agriculture and forestry sector, but the factors have not been evenly distributed across the land cover types. This is because the JRC energy balance also provides the numbers in a consolidated manner per country.
- The share of sources of water supply is the same as in the base year. The model could be improved to provide flexibility for including other splits in the supply shares.
- The livestock demand projections could be improved. Currently, we incorporate projections from the EU agricultural outlook, which are uniform across all countries.
- We do not account for animal feed production and its associated water and energy inputs in this model.
- We include crop-specific fertiliser application rates by country. However, there is not enough clarity on how much of these fertilisers are imported (from within and outside the EU-27 countries).
- The share of agricultural land under irrigation is available on a country level, and very little data exists on crop-specific numbers. Though the model has the provision to implement these modalities, the data inputs will need improvement.
- The model has the provision to implement the changes in crop yields for different climate scenarios. However, the data pipeline needs to be streamlined for implementation.
- The hydrological component in CLEWS-EU does not have water routing, like in a hydrological model. This is an area that will need significant rethinking of modelling methodology. However, when done, it will facilitate the analysis of climate-induced variations in water availability.

4.2 Integration of CLEWs-EU with external modules

Other than the conventional representation of the CLEWs components in CLEWs-EU, it is envisioned that the model can incorporate aspects that would otherwise be outside the typical scope of a CLEWs model. Specifically, integration is planned with three different external modules, in DIAMOND, as detailed below.

The aspect of a changing climate and how this affects the various components of the CLEWs-model will be explored. As a starting point, soft-links with the DIAMOND climate modelling and pattern scaling suite (CICERO) will be established to examine the effect of various climate scenarios on critical aspects of the food-energy-water nexus, such as water availability and land productivity. Crop yield is affected by water availability, moisture, and temperature conditions and is a key area to focus on as a first step.

Furthermore, in order to be able to incorporate finance aspects into CLEWs-EU, the OSeMOSYS code can easily be adjusted to adopt technology-specific discount rates. This will allow different discount rates to be assumed for the various technologies, sectors, and countries. The relevant assumptions from the EU Reference Scenario 2020 can be used, as it utilises variable discount rates across sectors of the economy. However, no differentiation is made across EU member states, and this is an area that could be explored.

Finally, representation of behavioural aspects will be pursued. The CLEWs-EU model is 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. The relevant datasets are being prepared by UNIBAS for a set of representative countries and this information will be absorbed into CLEWs-EU. Specifically, the envisioned integration has a focus on the transport sector and the adoption of electric vehicles.

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