iDesignRES

Integrated Design of the Components of the Energy System to Plan the Uptake of Renewable Energy Sources: An Open Source Toolbox

Modularity Design and models standardization

Companion report to Deliverable 2.1

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EXECUTIVE SUMMARY

The iDesignRES project applies energy system and component models to connect the Pan-European energy system perspective with a regionalized and highly technical resolved component modeling. We hence distinguish in the modelling three different layers. The three-layer energy system modeling framework provides a structured approach to optimizing, planning, and operationalizing the energy transition at multiple scales. By integrating models with varying spatial and temporal resolutions, the framework ensures coherence across national, regional, and operational decision-making processes. Task 2.1 "Modularity design and models standardization" ensures the frictionless interaction between the different layers and respective energy system models prepared within Work Package 2.

Layer 1: Pan-European Optimization (NUTS0 Level) The first layer focuses on long-term energy system optimization at the national level (NUTS0). It builds on the GENeSYS-MOD framework, an open-source energy system model designed for decarbonization scenario analysis across power, heating, transport, and industry sectors. GENeSYS-MOD optimizes investments in renewable energy, infrastructure, and sector coupling technologies, ensuring efficient allocation of resources across European countries, including Turkey. The model achieves computational feasibility through a time-series reduction method, enabling high-resolution scenario analyses while maintaining practical runtimes. This layer provides crucial insights into policy-driven investment strategies and energy trade within Europe.

Layer 2a: Multi-Carrier Geolocation Planning (NUTS2 Level) The second layer refines spatial planning by integrating multi-carrier energy flows (electricity, hydrogen, heat, and fuels) at a regional level (NUTS2). It enhances capacity expansion planning by considering optimal infrastructure placement, sectoral interactions, and spatial constraints. The multi-carrier geolocation planning model leverages insights from layer 1 using the modelling results of the NUTS0 analysis, feeding power system investment decisions into the multi-carrier geolocation planning model to determine investment priorities for regional energy hubs, interconnections, and industrial clusters. This layer enables policymakers to assess the feasibility and impact of energy infrastructure investments within sub-national contexts, ensuring alignment with broader energy transition goals.

Layer 2b: Multi-Carrier Operational Model (NUTS2 Level) focuses on the operational feasibility of the planned energy system at the regional level, improving upon the planning insights from layer 2a. The JRC-EU-TIMES model is adapted for high-resolution temporal simulations, incorporating hourly dispatch modeling to evaluate system flexibility, storage requirements, energy grid infrastructures such as electricity and gas, and integration of variable renewable energy sources. This model ensures that planned investments meet reliability criteria and energy security objectives under varying demand and weather conditions. JRC-EU-TIMES operational model performs stress test at the level of the whole energy system, assessing the energy system adequacy of supplying energy to demand sectors. This multi-scale approach of stress-tests can inform the multi-carrier geolocation model in revising the infrastructure expansion planning.

Layer 3: Multi-physics Component modeling The third layer consists of the detailed multi-physics component models that stress-test specific elements of the energy system, e.g. modeling the behaviour of certain industries in different geographic regions in more detail (e.g. hydrogen production) or increasing the technical and regional resolution (e.g. operation of heat pumps).

Model Coupling and Harmonization A critical feature of the three-layer framework is the integration and standardization of input and output parameters across models. Shared input parameters, such as costs, efficiencies, emission factors, and demand profiles, ensure comparability and reliability. All the models follow the Reference Energy System Methodology ensuring the consistent tracking of input and output

energy fuels and their transformation. The IAMC data format is used by the energy system models to harmonize datasets, facilitating seamless model interactions and scenario consistency. The iDesignRES project ensures that each model layer feeds into the next, maintaining data integrity and policy relevance. Therefore, we developed automated conversion scripts to provide input and output data in the common IAMC format for the models.

Scenario Development and Validation The framework incorporates the four EU EnVis-2060 scenarios developed in iDesignRES and its companion Horizon2020 project Man0euvre, representing different decarbonization pathways based on geopolitical, technological, and societal uncertainties. These scenarios guide model parametrization and enable robust stress-testing of system resilience under extreme conditions, such as 'Dunkelflaute' events. To validate the results of the scenarios calculated by the models within the three-layer approach, two models are further developed, namely EnergyPLAN for simulating hourly energy flows within the modelled energy system and AnyMOD.jl to increase robustness of the Pan-European investment decisions (see also Table below).

Preparation of Upcoming Tasks Task 2.1 ensures internal consistency and modular compatibility among models operating at different spatial and temporal scales. These preparations directly support the development of the multi-carrier geolocation and operational models in Task 2.4, the use of long-term scenario inputs in Task 2.3, and the model validation efforts in Task 2.5 using EnergyPLAN and AnyMOD.jl. Moreover, the outputs of Task 2.1 provide the harmonized backbone for WP3 demonstrator cases, enabling consistent integration between energy system and component models and ensuring robustness under stress-testing scenarios.

Overview of models applied and developed in iDesignRES

Model name	Model type	Purpose	Output
GENeSYS-MOD (Layer 1)	Large-scale, open source, linear, techno-economic, bottom-up energy system model	Optimizing investments decisions for the Pan-European energy system	Optimal generation, storage, and transmission capacities by region and time period
Multi-carrier geolocation planning model (Layer 2a)	Energy system model	Determine the optimal geolocation and size of energy infrastructure on NUTS2 level consistent with GENeSYS-MOD investment results	Spatially resolved infrastructure layout including energy hubs and pipelines
JRC-EU-TIMES Operational Model (Layer 2b)	Energy system model	Simulating and stress testing of the optimized energy system on NUTS2 level based on modeling results from Multi-carrier geolocation planning model	Detailed operational profiles of technologies, energy flows, and system resilience indicators
EnergyPLAN (Validation)	Energy system simulation tool	Validation of the energy system resulting from the modelling within the three-layer approach by simulating hourly energy flows across various sectors e.g. district heating	Hourly energy balances, sector coupling dynamics, system feasibility under real-world conditions
AnyMOD.jl/ EuSYS-MOD (Validation)	Large-scale, open source, linear, techno-economic, bottom-up energy system model	Validation of investment decisions of the Pan-European energy system developed in layer 1	Cross-model consistency checks and robust optimal investment pathways
Multi-physics component models (Layer 3)	Sector and technology specific models	Higher technical and geographical resolution of e.g. building, hydrogen, transportation or industry sector for validation and stress testing of modeling results	Technology-specific performance data, detailed energy demand/supply profiles
Pomatwo (Layer 3)	Electricity market dispatch simulation model	Modeling the generation and storage dispatch in the electricity sector and line flows on grid infrastructure (DC load flow)	Hourly dispatch schedules, electricity prices, line loading, congestion patterns
GGM (Layer 3)	Cost-minimizing Mixed Integer Linear Programming Global Gas Model	Computes gas trade and infrastructure investments up to NUTS2 level	Gas flows, infrastructure expansion, trade routes, and supply security assessments
Plan4RES (Layer 3)	Power system investment model	Optimizes power investment decisions on NUTS2 level	Optimal investment strategies in generation and grid, based on techno-economic constraints

1. Introduction to Task 2.1

This is the companion report for the task 2.1 of the iDesignRES project. Task 2.1 establishes standardization and modularization of the models of the iDesignRES three-layer concept. Each of the three layers is equivalent to a certain technological, spatial and timely resolution of the energy system and hence, the different scopes of the layer shed light into different aspects of our energy system. The layers range from a Pan-European large-scale, long-term energy system up to NUTS2, hourly sectoral or even technology-specific multi-physics component models.

Each of the models optimizes or simulates complementing parts of the European energy system, hence the challenge for iDesignRES task 2.1, was to ensure consistency between these layers and respective models. By following common definitions, standards, procedures and shared data sets, we guarantee that regardless of the scope of each of the models, they all look at the same energy system. The present report is a summary and description of this work.

At the core of iDesignRES project, there are three main energy system models in the project, namely GENeSYS-MOD (Pan-European layer), the multi-carrier energy geolocation model and EU JRC-TIMES (NUTS2 geolocation and simulation layer), together constituting the upper two layers. Hence, we established a rigorous data exchange protocol, ensuring, among other things that the three models use the same variable definitions, input data, data types, units, harmonized their sectoral resolution. A description of each of the energy system models can be found in section 2, emphasizing their role and contribution in the layer approach, their basic functionalities as well as their interaction with the two energy system models from layer 1 and 2. Focus of task 2.1 is the interface between the models, the multi-energy carrier geolocation planning tool and JRC-EU-TIMES model itself are still under development and will be finished in task 2.4. In section 3, we describe the concept of the data exchange, the scripts we use to automate the data handling between the models and the common data platform – the iDesignRES scenario explorer app, an expansion of the existing Integrated Assessment Model Consortium (IAMC) scenario explorer landscape.[1]

Apart from the connection of the three main energy system models, one of iDesignRES main contribution and novelty are the multiphysics component models developed in WP1 that form the third layer. Due to the high technical detail of these models, building on the existing IAMC definitions is not efficient for harmonizing the data between the different component models. Hence, the standardization of common input-output definitions for these models follows its own route, which is described in section 3.5.

Part of task 2.1 was also the extension of the EnergyPLAN and AnyMOD.jl model so they can be used to validate the results of the three-layer approach. In order to incorporate the necessary technologies relevant to the multi-energy carrier geolocation planning tool and EU JRC-TIMES, EnergyPLAN and AnyMOD.jl are further developed with these models. EnergyPLAN is a simulation tool that receives the investment decisions of the three-layer approach and simulates the energy system operation. A description of the recent EnergyPLAN additions to provide validation and match the other models follows in section 4. AnyMOD.jl is an open-source energy system model for investments and dispatch calculations capable of representing high technical and spatial resolution and hence, capable of validating the investment decisions within the three-layer approach and providing robustness to the results.

[1] Commonly used data formatting and exchange convention for integrated assessment models, that can be adjusted to serve the needs for energy system models. Follow this link for more information: https://docs.ece.iiasa.ac.at/iamc.html

The key deliverables for task 2.1 described in this companion report are:

- The definition of the scope of each of the energy system models and their interaction (see section 2)
- Defining and providing shared input parameters to ensure consistency of input data across the models. This results from the parametrization of the iDesignRES EU Energy Vision (EnVis) 2060 scenarios (see section 2.1)
- Ensuring standardization and modularization of the three energy system models by following the IAMC data format (see section 3.3).
- A growing list of variables to extend the existing IAMC common definitions. This ensures the consistency of variable naming and units across the models and facilitates a streamlined addition of these variables to the iDesignRES internal common definitions (see section 3.3).
- A representation of the data exchange protocol for which we provide two python scripts, one for writing the scenario input data readable for all the models in IAMC format as well one for writing model output in IAMC format (see section 3.4).
- A shared list of variables to extend the existing IAMC common definitions. This ensures the consistency of variable naming and units across the models and facilitates a streamlined addition of these variables to the iDesignRES internal common definitions (see section 3.3).
- Description of the standardization and modularization of the multi-physics component models (see section 3.5)
- Providing the open code for the model extensions of EnergyPLAN and AnyMOD.jl (see section 4)

2. The iDesignRES layered modelling approach of the energy system

Different kinds of mathematical models can answer different questions related to energy systems. These models can vary in the core methodology and also scope. While a system wide optimization model calculates the system long-term development to meet renewable policy targets at a national scale, a dispatch model examines the operational implication of the same system at finer temporal (e.g., hour, minute) and spatial resolution (e.g., transmission nodes). There are other models that simulate the operation of a specific technology (e.g., gas pipelines, heat pumps etc.) which are usually called Multiphysics models.

In the iDesignRES project, multiple independent models are being developed/ applied to answer different questions (see Table "Overview of models applied and developed in iDesignRES" above). As the scope and rationale of the models are different, we develop a concept of modeling layers (Figure 1). Each layer hosts different models and has a unique scope. The modeling layers can be used to answer specific kinds of questions related to the energy system. However, models within the layers can interact with each other for any potential improvements and feedback for consistency and robustness.

The overall modeling framework is constituted of three interconnected layers. To maintain consistency, the coarse model (upper level) provides boundary conditions/ data to the finer model (lower level). Layer 1 accommodates the GENeSYS-MOD model, operating at NUTS0 resolution providing a consistent pan-European outlook of the future energy system. This layer passes information like country- specific installed capacity to layer 2, which operates at the NUTS2 level. This layer hosts the Multi-Carrier Geolocation Model, which optimizes the future investment (i.e., quantifies capacity) into various energy supply technologies by taking into consideration the associated infrastructure requirements (electricity grid, H2 pipeline etc.). In layer 2, the JRC-EU-TIMES model operational model validates the Multi-Carrier Geolocation Model by also operating at NUTS2 level, but at a higher temporal resolution to provide an operational outlook of the system configuration calculated by the Multi-Carrier Geolocation Model. Layer 2, via the JRC-EU-TIMES model interacts with the Multiphysics models developed in the WP1 for stress testing technology/infrastructure (via the Multi-Physics models) and energy system configurations (via the JRC-EU-TIMES model) and receives feedback for correcting the results from the Multi-carrier Geolocation Model. Layer 3 primarily hosts the Multiphysics component models which are used to perform component level stress tests. In this section layer 1 and layer 2 with associated models are discussed. Multiphysics models belonging to layer 3 are discussed in the following section (see section 3.5).

Having three modeling layers allows us to answer questions related to system development at different spatial and temporal scales, which caters to the needs of various stakeholders. Developing the models independently and linking them through the layers also ensures model reliability without unnecessarily increasing the computational complexity of a single model. In the following subsections, we describe in detail the three layers, the corresponding models, their interactions, and key outputs.

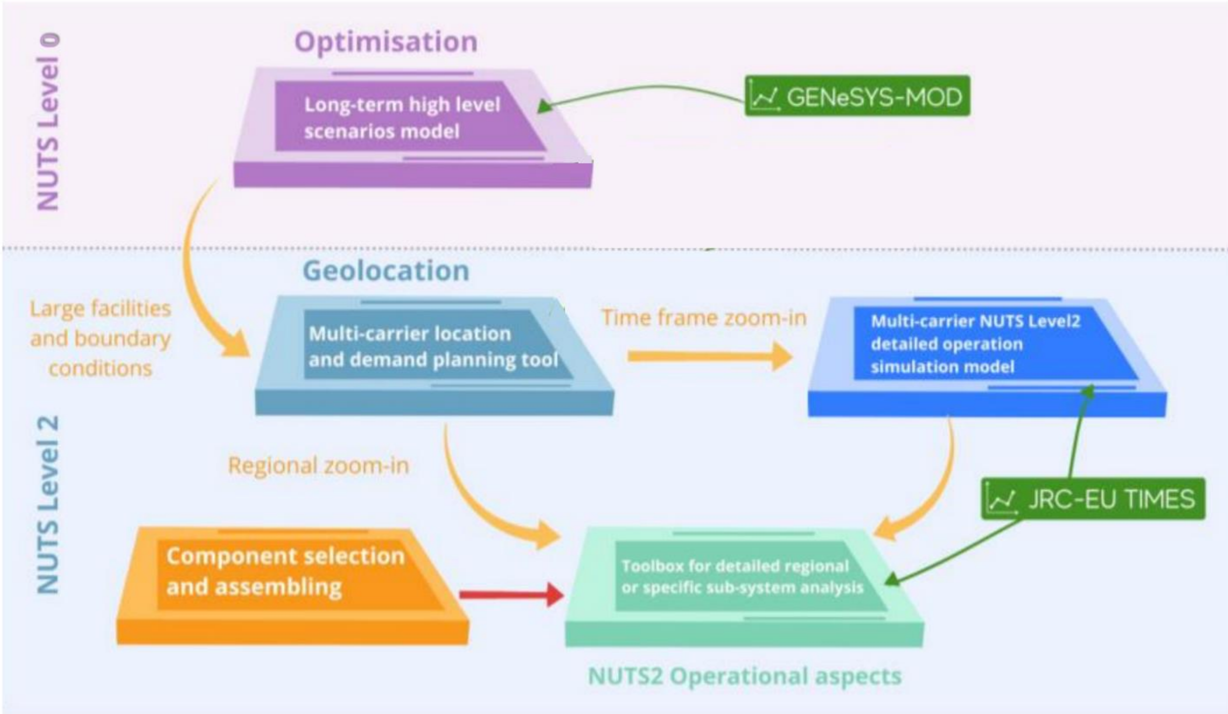

Figure 1: The iDesignRES three-layer approach. The multi-layered modelling framework for energy system planning spans across different spatial scales, from national-level (NUTS 0) optimization with GENeSYS-MOD to regional-level (NUTS 2) geolocation, component selection, and detailed simulations using tools like the multi-carrier location planning model, JRC-EU TIMES and the multi-physics component models.

2.1 Pan-European layer – NUTS0 Level optimisation

In a first step (the **pan-European layer**), we perform a **NUTS0 Level optimization** of the energy system and hence provide **long-term decarbonization scenarios** (see section 0). A long-term high level (NUTS0 Level) scenario model is developed by further building on the **opensource energy system model GENeSYS-MOD**. The goal of the first layers is a **European-wide consistent** and **optimal energy system**. The optimization with GENeSYS-MOD results in scenario-based long term decarbonization pathways for each European country, ensuring efficient investment decisions in the **power, heating (building and industry), and transportation sector** as well as **sector coupling technologies** such as Power-2-Gas.

GENeSYS-MOD

GENeSYS-MOD is a comprehensive modeling framework developed for evaluating **long-term energy transition scenarios**, with a strong emphasis on **decarbonization and inter-sectoral linkages**. The model considers the sectors heating (four industry heat levels and buildings, decentral and district heating), power, transportation (freight and passenger), as well as sector coupling technologies such as Power-2-Heat or Power-2-Gas (see Figure 2).

The tool builds upon the Open-Source Energy Modelling System (OSeMOSYS) and significantly extends its capabilities by offering **numerous modular functionalities**. These functionalities include the **flexible activation or deactivation** of specific modules based on user needs, enabling customizable analyses ranging from **high-level overviews** to **detailed regional assessments**. Typical applications of GENeSYS-MOD encompass exploring **future energy generation** and **demand pathways**, analyzing asset stranding risks, addressing challenges in decarbonizing sectors resistant to transition, and assessing socio-economic implications.

For iDesignRES layer 1 modeling, the model will have a regional resolution on a country level, modeling the **European countries including Turkey** as individual nodes and the energy trade between the countries as well as their energy imports from global energy markets. The model can have up to an hourly temporal resolution. However, for European-wide model runs, the model will use a time series reduction script to select certain key hours and decrease the model size and runtime. The model is openly accessible, accompanied by comprehensive documentation, and distributed under an open-source license. The model is **available in GAMS** as well as in the open programming language **Julia**, significantly lowering entry barriers for other users. GENeSYS-MOD is extensively utilized in research contexts, notably by the Technical University of Berlin (TUB), and supports various European Union-funded projects. Other notable users include SINTEF, NTNU, and Statkraft, underscoring the model's broad applicability and utility in diverse institutional contexts.

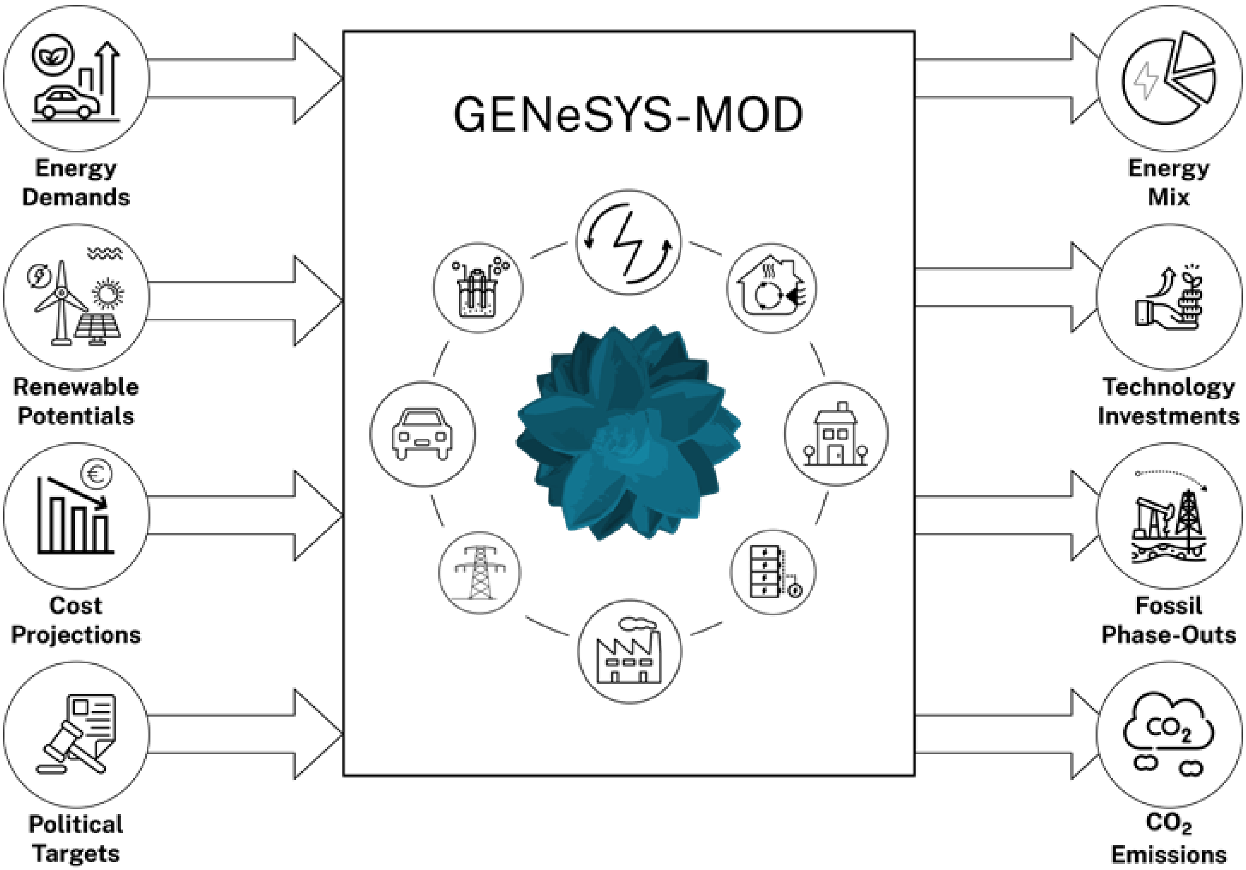

Figure 2: Input-Output structure of GENeSYS-MOD. Key inputs such as energy demands, renewable potentials, cost projections, and political targets feed into the model, which generates outputs including the future energy mix, technology investments, fossil fuel phase-outs, and CO_2 emissions.

Long-term decarbonization pathways with investment decisions

We developed qualitative narratives for the four **EU EnVis-2060 scenarios**, each characterized by distinct attributes and features. These scenarios were developed through an extensive, collaborative scenario-building process involving numerous researchers, experts, and stakeholders associated with iDesignRES and another European project, i.e. Man0EUvRE[2]. While building upon methodologies established by previous EU projects such as SetNAV and Open ENTRANCE,[3] the current storylines significantly broaden and deepen their analytical scope. A comprehensive description of the scenario generation process, accompanied by a detailed literature review and preliminary quantitative results, is provided in a **forthcoming publication**.[4] Figure 3 illustrates how the scenarios are positioned within a **three-dimensional scenario framework** (i.e. social dynamics, innovation and geopolitical instability), and Figure 4 identifies the **key uncertainties** and **driving factors** shaping each scenario.

[2] https://man0euvre.eu/

[3] P. Crespo del Granado, H. Auer, S. Backe, P. Pisciella, and K. Hainsch, 'Storylines for low carbon futures of the European energy system', NTNU, TU Wien, TU Berlin, Trondheim, Norway, Deliverable 7.1 for the H2020 project openENTRANCE, 2019. [Online]. Available: https://openentrance.eu/wp-content/uploads/openENTRANCE-D7.1for-web-1009201.pdf
P. Crespo del Granado, 'SET-Nav – Comparative assessment and analysis of pathways', NTNU, Trondheim, Norway, Comprehensive report, 2019. [Online]. Available: http://www.set-nav.eu/content/pages/library
H. Auer et al., 'Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5 ∘C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE', E Elektrotechnik Informationstechnik, vol. 137, no. 7, pp. 346–358, Nov. 2020, doi: 10.1007/s00502-020-00832-7. K. Hainsch et al., 'Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal?', Energy, vol. 239, p. 122067, Jan. 2022, doi: 10.1016/j.energy.2021.122067.

[4] M. Barani et al. (forthcoming) European Energy Vision 2060: Charting Diverse Pathways for Europe's Energy Transition https://arxiv.org/pdf/2501.12993

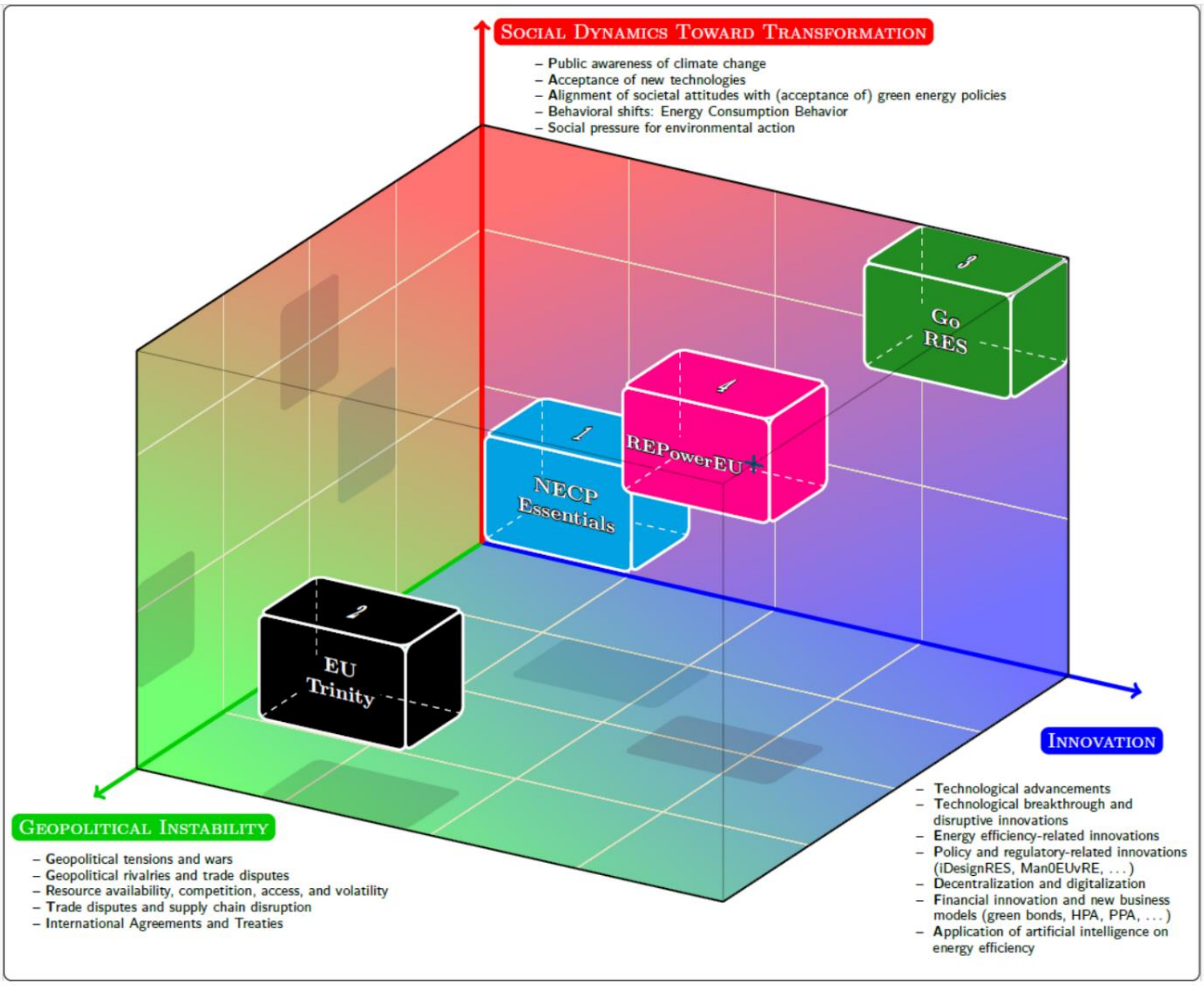

Figure 3: Three-dimensional representation of the scenario space of EU-EnVis-2060. EU Trinity, NECP Essentials, REPowerEU+, and Go RES—along axes of **geopolitical instability**, **social dynamics toward transformation**, and **innovation**. Each axis captures key uncertainties influencing the energy transition, including geopolitical tensions, public support for green policies, and technological progress.

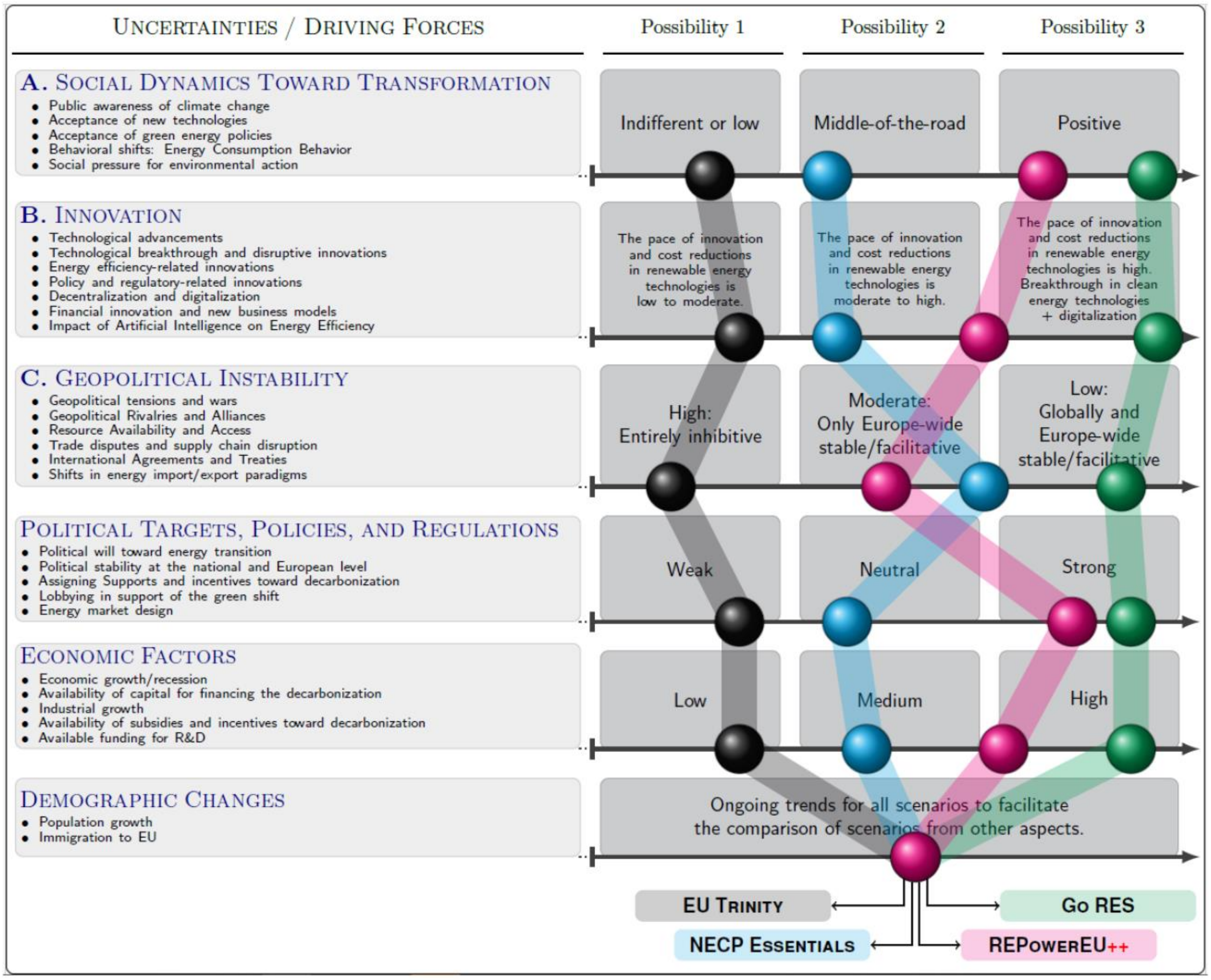

Figure 4: Uncertainties / driving forces of the four EU-EnVis-2060 scenarios. EU Trinity, NECP Essentials, REPowerEU+, and Go RES—are shaped by six categories of uncertainties or driving forces, including social dynamics, innovation, geopolitical instability, and policy ambition. Each scenario follows a unique pathway through varying levels of each driver, illustrating how different combinations of societal, political, and technological conditions result in distinct energy futures.

The **EU Trinity** scenario envisions internal divisions among EU member states amidst global geopolitical instability, impacting the achievement of EU climate targets. The lack of consensus leads to fragmented energy policies, hindering coordinated efforts toward sustainability.

The **REPowerEU++** focuses on steps toward a self-sufficient and independent European energy system by 2050 and emphasizes reducing reliance on external energy sources. It explores the acceleration of renewable energy deployment, enhancement of energy efficiency, and development of domestic energy resources to achieve energy independence.

The **Go RES** scenario examines the feasibility of achieving carbon neutrality earlier than 2050 under favorable conditions. It considers rapid technological advancements, strong societal support for renewable energy, and robust policy measures that facilitate an expedited transition to a renewable-based energy system.

The **NECP Essentials** scenario extends current National Energy and Climate Plans (NECPs) until 2060, this scenario assesses their effectiveness in realizing climate neutrality. It evaluates the outcomes of existing policies and measures, projecting their long-term impacts on the energy system and climate objectives. These scenarios provide a comprehensive framework for understanding potential futures of Europe's energy landscape, aiding policymakers and stakeholders in navigating the complexities of the energy transition.

The scenarios have been parametrized and the new data has been implemented into GENeSYS-MOD. The full data set will be openly available at the GENeSYS-MOD GitHub repository.[5] First GENeSYS-MOD modeling results with the EU EnVis-2060 scenarios have already been presented to the consortium partners and at international conferences, yielding fruitful feedback that is constantly incorporated.

The key input parameter for the models of the three layers listed in Table 1 are crucial for energy system modeling because they collectively define the fundamental economic, technical, environmental, and operational characteristics of energy systems. Sharing consistent parameter values across the different models ensures comparability, reliability, and coherence of results, facilitating robust scenario analyses and informed policy decision-making. Uniform parameters such as costs, efficiencies, emission factors, potentials, and demands underpin accurate assessments of future energy transitions, enabling stakeholders and policymakers to better understand interdependencies, optimize infrastructure investments, and evaluate climate targets within a consistent analytical framework.

Table 1: Shared input parameter across the energy system models of the three layers

Category	Input Parameters
Cost	Capex (overnight), Fixed, Variable (O&M), Fuels
Emissions	Emission factors for fuels, Emission limits, Exogenous emissions
Discount Rate	Discount rate for technologies
Efficiencies	Efficiencies for technologies
Timeseries	RES supply, Demand
Availability Factors	Availability factors
Potentials	RES, Resources, Carbon storages
Operational Lifetime	Operational lifetime
Grid Capacities	Grid/Transmission capacities
Installed Capacities	Initially installed capacities in the base year
Service Demand	Transport (Freight, Passenger), Heat (Industry, Commercial and Residential), Electricity, Feedstock (Hydrogen)
Storages	Energy to power ratio energy storages, Charging and discharging efficiencies

During the iDesignRES project, these input parameters may be refined based on the results from WP1. WP1 examines sectors in detail and will yield high quality data that can improve the modeling results of the energy system models GENeSYS-MOD, Multi-carrier geolocation planning model and JRC-EU-TIMES operational model. The integration of these data will take place during WP3, when the test cases are implemented.

[5] https://github.com/GENeSYS-MOD/GENeSYS_MOD.data/tree/main/Data

Link to the Multi-carrier geolocation planning model

GENeSYS-MOD can generate a wide range of output parameters. The planned output[6] for iDesignRES layer 1 will consist of the parameters in Table 2. The installed power capacities will be the boundary conditions for the modeling for the multi-carrier geolocation planning model (layer 2) (see Figure 1). These values will be considered as input parameters for the multi-carrier geolocation planning model. The other output parameters such as energy demand will be used to compare the model results of the models and check coherence of the results. As the scope of each model is different, the boundary conditions set by GENeSYS-MOD will act as a way to communicate high-level information to the layer 2 models regarding elements and decisions which are not heavily impacted by the more granular regional or temporal resolution. Therefore, the boundary condition will provide a starting point for the more detailed capacity planning and operation performed in the layer 2 models.

Table 2: Output parameters of GENeSYS-MOD the Pan-European layer

Category	Output Parameters
Installed capacities (Boundary condition)	Power, Heat, Storages, Electrolysis, Trade capacities (Power, H2, fossil energy)
Energy demand	Primary, Secondary, Final Energy demand (Power, heat, transportation, fuels (e.g. H2)
Emissions	Emissions by technology or sector
Levelized costs	For power sector
Trade	Power trade between the countries

2.2 Multi-carrier geolocation planning modelling tool at NUTS2 level

Scope of the model

The multi-carrier geolocation model, currently developed in the task 2.4, will explore the integration of the energy system's demand and supply sectors while modelling new energy carriers and their associated infrastructure. The model will be used to allocate the large investment decisions of layer 1 across each country on high spatial resolution. Understanding this sectoral integration is crucial as it can advance the energy transition towards a sustainable, climate-neutral, and resilient energy system and economy. This model aims to provide valuable insights that can support informed policy-making and strategic decision-making related to capacity and infrastructure planning. Additionally, it can provide insights regarding how to optimize energy use across various sectors and different energy carriers while considering overarching targets, such as GHG emission targets for the energy system, as well as overall constraints, such as feedstock limitations for bioenergy products and the varying potential of energy carriers across European countries.

The concept of sector coupling has a central role in a future energy system that is fully decarbonized and uses renewable energy sources across the various sectors. For example, surplus renewable electricity generated during hours with peak RES-based generation can be used for hydrogen production. Electricity and e-fuels are the energy carriers used for decarbonizing energy demand sectors; therefore, to ensure

[6] Output file of GENeSYS-MOD for iDesignRES can be found here: https://zenodo.org/records/14959447

that the future energy system achieves overall efficiency, it has to consider and decide on an optimal planning strategy across the different sectors in parallel.

Model description

The multi-carrier geolocation planning model, which is currently developed within Work Package 2 in Task 2.4, is an energy system model that will determine the optimal investments and location on NUTS2 level of multiple energy carriers, such as electricity, heat, hydrogen, and other e-fuels, considering their interactions through multi-carrier grids for electricity, hydrogen, gas and heat. The spatial resolution of the model will be European-wide at a NUTS2 level and the optimization will cover the period from 2025 to 2060, using a 5-year time step. The model will incorporate the capabilities and techniques of the PRIMES model and use the modeled boundary conditions from the long-term projections at a national level (NUTS0) from GENESYS-MOD complemented by PRIMES.

The main purpose of this tool is to analyze the energy infrastructure requirements and optimize geo-location investment planning at the NUTS2 level. This analysis is based on a detailed simulation of demand patterns by sector and end-use, which is provided by the multi-physics assembly tool, along with annual energy demand projections from GENeSYS-MOD. Additionally, it considers capital-intensive investments from GENeSYS-MOD, such as coal, nuclear, large hydro-power plants, and pumped storage plants. It is important to note that investments in these technologies are not heavily impacted by geolocation cost optimization. Instead, they involve specific decisions made for particular sites based on a list of pre-existing candidate options. The investment in these power generation and storage technologies will vary, of course, depending on the different narratives that explore potential future pathways, as outlined in the EU EnVis-2060 scenarios discussed earlier, and this will be taken as a boundary condition in the multi-carrier geolocation planning model. However, for example the decision on whether to invest in a centralized electrolyser vs. dispersed electrolysers that are closer to the variable renewable potential within the NUTS2 regions is what the model will determine.

The model will use modelling techniques that are part of the PRIMES modelling system, inheriting many of its concepts, while the new model developed in the context of this project will have an expanded regional resolution of the model compared to the existing PRIMES version.

Developing a framework with a pan-European model with high spatial and temporal resolution is a demanding task in terms of computational complexity. Therefore, several tests will be conducted until reaching the final list of sectoral resolution for the multi-carrier geolocation investment planning model. However, as it has been agreed, a minimum level of detail related to sectoral representation and the energy carriers can be shown in the table below.

Table 3: Breakdown of energy sectors and energy carriers based on the IAMC format

Energy demand Sectors	Energy supply sectors	Energy carriers
Industry	Electricity	Electricity
Residential	Heat	Gas|Fossil
Commercial	Hydrogen|Electricity	Biomass
Transportation	Gas|Electricity	Coal
Carbon Management	Liquids|Electricity	Geothermal
		Hydrogen|Electricity
		Nuclear
		Oil
		Solar
		Wind
		Gas|Electricity
		Liquids|Electricity
		Heat

The multi-carrier geolocation model will be a long-term capacity expansion model, determining the optimal size and location of the investment in electricity, heat, hydrogen, gas, and other e-fuels. To determine the optimal investment decision, one must consider how the infrastructure operates and how demand evolves in parallel for all energy carriers to capture the effects of sectoral coupling. Therefore, the model will simulate the parallel operation of the grids and other infrastructure (e.g. storage options) and the cross-border trade of energy carriers across the different NUTS2 regions. In this way, the model will determine the optimal allocation of investment across the regions, considering any bottlenecks that might exist due to weak linkage of different areas. As the decision to invest in infrastructure is usually a capital-intensive action, the model will have foresight over a long period so that the investment planning is optimal for the overall modelling period. Due to the large size of the model, the concept of rolling horizon will be applied, which is one of the techniques also used in the PRIMES model, to keep the computational time at a reasonable level.

In terms of intra-annual resolution, capturing the variability and uncertainty of the generation patterns of variable renewables is crucial for the model. Therefore, the model will maintain an intra-annual resolution, comprising of hourly data for representative days throughout the year. To ensure that capacity planning meets the adequacy and reliability criteria for the energy system, the selected weeks will also feature days or weeks of extreme events. For instance, in several countries in Europe—particularly in Northern and Central-Western Europe—there are periods when solar irradiation is very low, wind activity is minimal, and temperatures drop, a phenomenon called 'Dunkelflaute.' During these times, the availability of variable renewable sources (RES), such as wind and solar photovoltaic (PV) systems, decreases significantly while electricity demand rises due to higher heating needs. In such scenarios, a RES-dominated system should have backup capacity—a combination of storage and conventional energy sources—to ensure the adequacy of electricity supply. Therefore, the selection of the representative days, which is done via appropriate clustering algorithms, will also include extreme events. The elements mentioned above will be validated using the detailed operational JRC-EU-TIMES model across various use cases. However, it is crucial to ensure that the results from the capacity expansion model consider the operation of the energy system, as this will provide a solid foundation for validation by the JRC-EU-TIMES operational model.

An important aspect of the multi-carrier geolocation planning model, which has been inherited by the PRIMES model, is its focus on incorporating various types of policy targets. Additionally, it includes measures designed to facilitate the achievement of these targets. While most of these targets are set at the country level—such as greenhouse gas (GHG) emission targets, overall and sectoral renewable energy source (RES) shares, and renewable fuel of non-biological origin (RFNBO) targets—it is crucial to ensure their fulfilment and to account for their interaction with detailed NUTS2 projections. For instance, the additionality principle for green hydrogen production requires a geographic and temporal correlation between renewable-based electricity generation and the production of RFNBOs, which is an aspect that the multi-carrier geolocation planning model will include. Moreover, the model will include many types of policy instruments that influence the operation and expansion of the energy system, such as price measures, standards and different types of incentives for either the energy carrier production or specific technologies.

Links with the JRC-EU-TIMES and the multi-physics component models

The multi-carrier geolocation planning model will use as inputs the boundary conditions from the layer 1, as these are presented in Section 3.1.4. These will be projections of the energy system at a country level (NUTS0) and more specifically this will include installed capacities, as well as the projections of energy demand by sector. Also, the model has the possibility to include any annual bounds on energy generation, CO2 emission, trades etc., to align with the results of the layer 1 model. Additionally, the model will align in terms of the input data, which will be inherited from the layer 1 models. The output of the model will be the capacity planning schedule for energy technologies and energy infrastructure, which will be used in the JRC-EU-TIMES model, together with the sectoral demands, as explained in Section 3.3.2. The JRC-EU-TIMES model will use this input to provide details on the operational aspects and validation of the energy system configuration suggested by the multi-carrier geolocation planning model.

2.3 Multi-carrier operational model at NUTS2 Level

The aim of layer 2 is also the development of a NUTS2-level operational model for the two case study regions. While the multi-carrier geolocation planning model focuses on capacity and infrastructure planning at the NUTS2-level, the primary objective of this model is to assess the operational aspect of the derived energy system configuration.

Scope and boundaries of JRC-EU-TIMES NUTS2 level Operational model

The JRC-EU-TIMES model[7] is a whole energy system model of the EU27 and the neighboring countries covering all the energy supply and demand sectors such as electricity, energy conversion, building, industries, transport. Figure 5 illustrates the sectoral coverage of the JRC-EU-TIMES model which operates at NUTS1 level with twelve annual time slices. Being also a multi-sectoral and multi-carrier energy system model, it captures the interdependencies between the different energy sectors and regions (trade between countries).

[7] European Commission: The JRC European TIMES Energy System Model https://data.jrc.ec.europa.eu/collection/id-00287

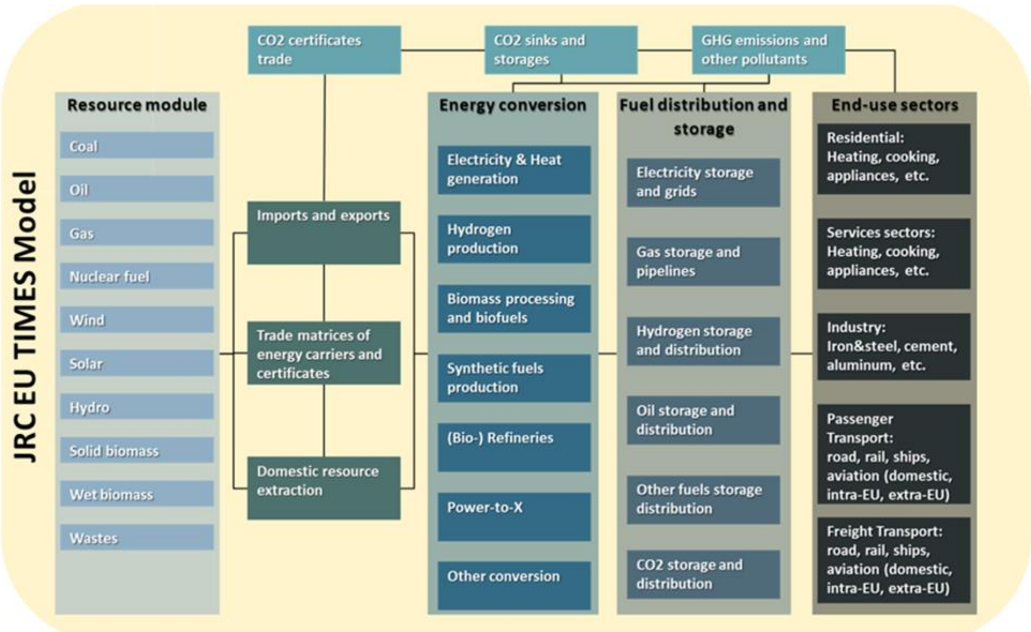

Figure 5: Overview of the JRC-EU TIMES on sectoral coverage of energy system. JRC-EU-TIMES Model covers the entire energy system from resource extraction to end-use sectors. It includes modules for energy conversion, fuel distribution and storage, and emissions, linking various energy carriers, technologies, and sectors through imports, trade matrices, and CO_2-related processes.

The multi-sectoral NUTS2 level operational model will be developed by enhancing the temporal and spatial resolution of JRC-EU-TIMES model. Consequently, the model will feature a high intra-annual time resolution, with at least hourly granularity for each season, using representative days or weeks. The selection of the typical operating hours of the model (or timeslices) will be based on clustering or mixed-integer optimization algorithms[8] ensuring that a) they are relevant for all the carriers considered in the model; b) timeslices corresponding to extreme events are also included. To this end, an asymmetric timeslice approach can be considered, as it is not always suitable to have a uniform timeslice structure for all the energy carriers or end-use service demands. This will allow more flexibility in analyzing the operational aspects of the energy system configuration suggested by the geolocation planning model (which also operates at high resolution) and constitute the JRC-EU-TIMES for tailored-made to the different energy carriers, sectors or system components stress-tests. The exact time resolution will depend on computational complexity, data quality. The model will be used to analyze the operation of the energy system ensuring the supply and demand balance and to check capacity adequacy, system flexibility, role of energy storage technologies to manage variability etc.

In addition, the modeling framework of JRC-EU-TIMES will represent in detail the electricity transmission grids (DC Power Flow approximation), and gaseous fuels and emissions grids (via Weymouth equations). The detailed modeling of these critical infrastructures will depend on the available data from the case studies. An important feature of the framework is the ability to go beyond the energy markets as it also represents ancillary services and reserve markets. These types of markets are particularly important for the integration of large shares of renewable energy, and the assessment of the participation of different technologies will enhance the insights that the operational model can provide to the multi-carrier geolocation model. The extent to which the participation of technologies in reserve markets covers parts

[8] IEA-ETSAP Timeslice selection tool: https://iea-etsap.org/projects/Timeslicetool%20V1.zip

of their investment costs can be used by the geolocation planning model as a guide for improving investment decisions.

A particular emphasis of the operational JRC-EU-TIMES model in iDesignRES will be placed on energy supply and demand flexibility. The TIMES framework already supports endogenous load shifts, possibly associated with inconvenience costs (capturing behavioral aspects if relevant data are provided by the case studies), that can help reduce the pressure to the energy supply. Overall, the model can provide insights into the level of the required flexibility arising from the energy supply configuration suggested by the multi-carrier geolocation planning model, including not only behavioral measures but also technical measures such as storage investments or investments in other small assets that can provide flexibility to the system.

Though the JRC-EU-TIMES model structure serves as the basis for the operational model development, it will be further adapted to the scope of multi-carrier geolocation planning model and Multiphysics models. In this regard the enhanced JRC-EU-TIMES operational model will be suitable for performing stress tests on the whole energy system. Via test-bed cases criticality indicators will be assessed and measures to mitigate the systemic failures will be evaluated. In those areas of the energy system where the JRC-EU-TIMES fails to find a suitable solution to avoid a failure, the model will feedback this to the geolocation planning model for corrective action at the investment decisions.

In this regard, robust energy transition pathways at the NUTS2 level can be defined by combining the multi-carrier geolocation planning model and the operational JRC-EU-TIMES model.

Since the primary purpose of this model is to assess the operational conditions and perform stress-tests for the stability and adequacy of the whole energy system, almost all technological representation from the multi-carrier geolocation planning model will be incorporated on both the supply and demand sides. For the demand sectors the model can consider either energy service demand or final energy demand from the multi-carrier geolocation planning model. In the first approach, demand-side technologies are included (e.g., boiler for residential heat) to calculate the energy needed to meet the energy service demand. In the second approach, only final energy demand and demand patterns are modeled excluding demand-side technologies. Depending on the scope of modeling the demand sector, attempts will be made to include key technologies in industry and transport sector (based on the inputs from WP1).

Links to multi-carrier geolocation planning model

For the case study regions, the JRC-EU-TIMES operational model takes the system configuration for a certain year and scenario from the multi-carrier geolocation planning model. Therefore, the scope of the model i.e., sectoral coverage, technologies, commodities will be aligned as much as possible to ensure data consistency. A mapping of potential data exchanges between the two models has been identified and is outlined in the accompanying Excel sheet. Figure 6 outlines the links of JRC-EU-TIMES operational model to multi-carrier geolocation and the Multiphysics model.

The multi-carrier geolocation planning model supplies installed capacity of energy supply and demand technologies for each NUTS2 region. The capacity of trade processes (electricity grid, H2, GAS pipelines etc.) between the NUTS2 regions are also supplied. Final energy demands/ energy service demands for various demand sectors including the demand profiles will also be provided by the geolocation model to the JRC-EU-TIMES operational model. In addition, the operational model has the option of considering any annual bounds on energy generation, CO_2 emission, trades etc., to align with the results of the coarse higher-level models. This gatekeeping approach helps to manage data quality, minimizing excessive divergence from the high-level model and reducing the risk of feedback loops from lower-level models influencing upper-level results. Depending on the scope of modeling the demand sectors, various demand side technologies will also be included based on the input from component models in WP1 (e.g., industry sector from DU).

Both models additionally need techno-economic attributes such as efficiencies, variable operational costs, fuel price etc., which will be common. Hourly profiles of renewable resources (solar, wind, hydro) and the demand patterns (e.g., space heating in buildings, industrial operation schedule) will also be harmonized for both the models.

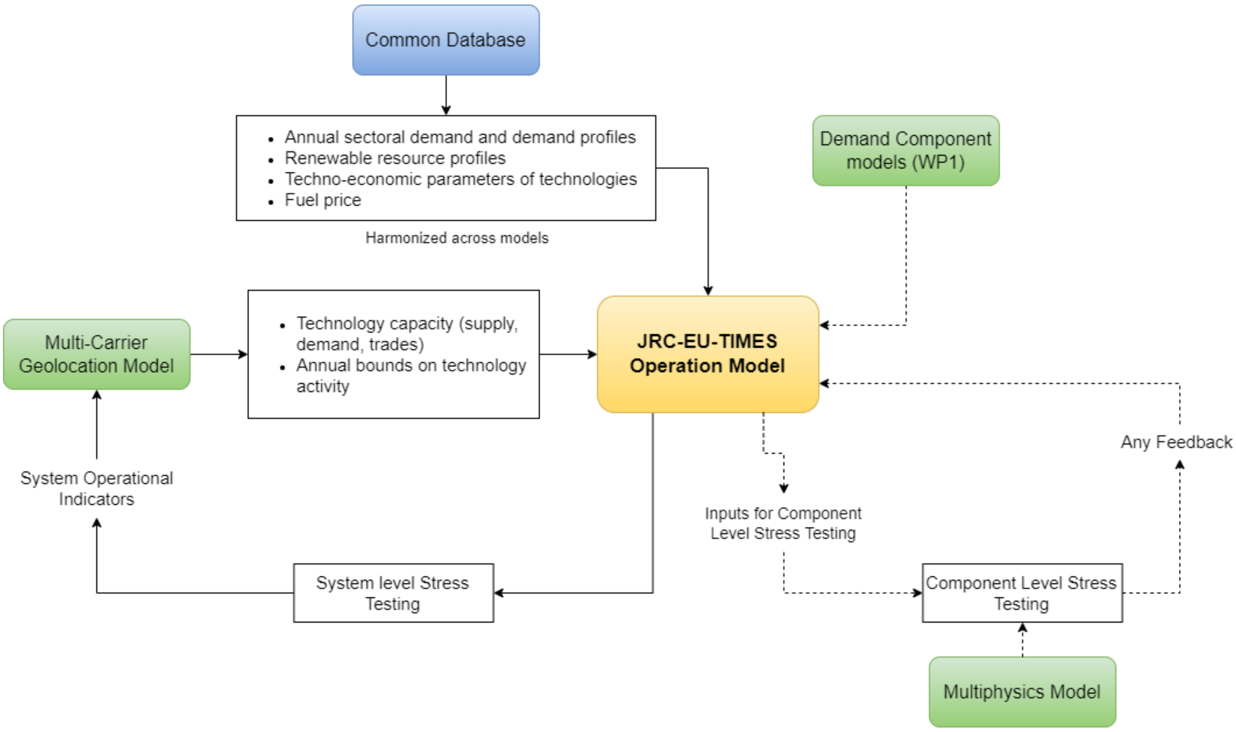

Figure 6: Link and data flow between JRC-EU-TIMES operational, multi-carrier geolocation planning model, and Multiphysics model

Even if both the models are aligned on the installed capacity and annual bounds on energy generation, there may be some critical modeling parameters, assumptions, or boundary conditions, which when not considered in the operational model, may lead to inherent inconsistency. While effort will be made to minimize this case, it cannot be avoided due to the complexity of the frameworks. However, these inconsistencies should not be considered as a flaw of the iDesignRES frameworks as they provide insights that cannot be captured by one model or the other. To this end, a careful assessment of the derived inconsistencies will be performed, which either will lead to their acceptance and justification or will trigger additional harmonization efforts.

Links to Multiphysics models

As an output, the JRC-EU-TIMES operational model provides an aggregated configuration of the energy system, including final energy demand, emissions, fuel consumption and cost, and operational costs.

Although this model provides detailed representations of demand and supply, the NUTS2-level framework still represents an aggregate of multiple real-world energy systems—for example, groups of cement industries or buildings. Similarly, many of the technologies included in both the geolocation planning model and the JRC-EU-TIMES operational model are represented without many technical details or without accounting for non-linear effects in their behavior. Therefore, more detailed analysis with the Multiphysics models is required. The results from the JRC-EU-TIMES model can be further analyzed using the Multiphysics models to assess their real-world implementation and operation —for example, evaluating the operation of a wood pellet boiler or heat pumps in a single-family home. Figure 6 outlines the links of JRC-EU-TIMES operational model to multi-carrier geolocation planning model and the Multiphysics model. An important task shown in the figure is the performance of stress tests by the Multiphysics models. In contrast to the JRC-EU-TIMES model that stresses the whole energy system but by having a rather aggregated representation of energy supply and demand technologies or infrastructures, the Multiphysics models enter deep technical details of individual technologies, sectors and infrastructures. Based on the outcome of the analysis performed with the Multiphysics models, any information that needs to be incorporated back into the JRC-EU-TIMES operational model, will be considered to make its results more realistic and consistent with the outcomes from the Multiphysics models. For example, this can include e.g. envelopes of industrial processes, industrial processes pathways, envelopes of heating and renovation options, various technical constraints of key technologies assessed in WP1, mobility patterns, modes selection profiles and demand profiles.

3. Modularization and Standardization

3.1 Reference Energy System methodology – the common guideline for all models in iDesignRES

The **Reference Energy System (RES)** is a foundational conceptual framework well established in energy system modeling to represent the structure, processes, and flows of energy from primary resources to final energy demand across different sectors.[9] It enables the disaggregation of the energy system into a network of *technologies (processes)* and *commodities (energy carriers)*, facilitating transparent accounting of conversions, emissions, and energy balances. Typically, the RES is structured into four layers: (i) **primary energy sources** (e.g., coal, gas, renewables), (ii) **conversion technologies** (e.g., power plants, electrolysers), (iii) **energy carriers** (e.g., electricity, hydrogen), and (iv) **end-use demands** (e.g., industry, transport, buildings).

The application of the RES framework across different models in iDesignRES enables a harmonized and modular representation of the energy system. **GENeSYS-MOD**, based on the OSeMOSYS platform, applies the RES in a more schematic form, using technology chains defined by process input-output relations, linked through commodities within an optimization structure. The model adheres to the RES by representing energy transformation technologies and final demand processes across sectors, and by incorporating constraints such as capacity expansion, emissions, and resource limits in a temporally disaggregated framework.

The **Multi-energy carrier geolocation planning model** adopts an advanced RES-based architecture with explicit representation of techno-economic processes across sectors. The model structures its modules—such as power generation, transport, industry, and buildings—within a bottom-up, partial equilibrium framework consistent with the RES. The model couples these modules through interlinked energy carriers and price feedbacks, making the RES essential for coherent system-wide interaction.

JRC-EU-TIMES, based on the TIMES framework, provides a classic implementation of the RES (see **Figure 5**). The model defines energy system configurations as a network of technologies with associated input-output relationships, mapped over multiple time slices and regions. The RES serves as the central modeling logic for integrating energy demand, supply, conversion, trade, and emissions within an optimization setting.

EnergyPLAN, while differing in structure as a simulation-based model rather than an optimization model, also applies an implicit RES. The model is built around predefined sectoral and technology blocks, simulating hourly operation of the energy system based on specified configurations. The RES is reflected in the internal accounting of energy flows and conversion processes across power, heat, transport, and storage technologies.

In **AnyMOD.jl**, the RES is realized through a directed graph structure in which technologies are modeled as transformation nodes, and commodities as edges connecting processes across time and space. This modular design allows for flexible definition of technologies, carriers, and regions, while maintaining clear physical and economic linkages—an abstraction that aligns well with the RES concept.

The consistent application of the RES across these models offers substantial benefits for **modularization, standardization**, and **inter-model coupling**. It enables a clear definition of technological and sectoral boundaries, promotes interoperability through shared commodity definitions and process structures, and

[9] M. Beller (1976): Reference energy system methodology. https://www.osti.gov/biblio/7191575

facilitates the design of automated data exchange protocols (see section 3.4). In the iDesignRES project, the alignment of models via a common RES architecture—combined with harmonized variable naming (IAMC format), standardized input-output tables, and shared data definitions—supports a modular workflow wherein each model can serve a specific analytical layer while contributing to an integrated system perspective.

3.2 Requirements for modularization and standardization in iDesignRES

Within the iDesignRES project and, more specifically, in Work Package 2, a variety of models and tools is being developed; therefore, to ensure the quality of their design, modularization and standardization extending the RES methodology are essential. The application of modularization and standardization facilitates better collaboration among diverse teams and enables the seamless integration of different models. The models and tools must adhere to common protocols regarding information exchange, data storage, and openness, thereby fostering an environment where users can easily access and share information. An aligned formalism for the specification of the system is crucial, and the features of these formalisms include:

- **Uniform data naming**: Adopting the same data names is vital to guaranteeing the soft-linking and interaction between the models. This consistency is particularly important for elements such as resources, conversion facilities, storage options, and equipment, enabling a more coherent integration of the various models.
- **Consistent units of measurement**: Establishing the same units for capacities, energy flows, emissions, and economic figures (such as costs and prices) is critically important. This consistency not only eases the modelling process but also improves the accuracy of data interpretation and analysis across different tools and models.
- **Aligned sectoral and technological representation**: To ensure effective results exchange between models, an aligned representation across sectors and technologies is necessary. This standardization promotes a more comprehensive understanding of how different sectors interact and depend on one another, ultimately leading to better-informed decisions.
- **Compatibility in Regional Resolution**: Each model utilizes varying levels of Nomenclature of Territorial Units for Statistics (NUTS) regional resolution, which can lead to discrepancies in analysis outcomes. Harmonizing these resolutions is essential to facilitate accurate comparisons and integrations of results across different geographic areas.
- **Defined Model boundaries and conditions**: Clearly defining the boundaries of each model and determining the boundary conditions is paramount for ensuring their effective linking, as described in the three-layer energy system modelling approach. This definition helps delineate what is included in the model scope and the assumptions and conditions that drive model performance, thus enhancing the validity of the outcomes.

3.3 Achieving modularization and standardization for the three existing energy system models

Standardization ensures that energy system model outputs are comparable, interpretable, and seamlessly integrated into broader energy transition analyses with e.g. the multi-physics component models. Using the same data structure and variable naming (see section 3.3) improves standardization. Additionally, exchanging data via file types that are independent of the programming language of each model allows for a standardized exchange but also modular assembly of the models as the connections between the models is not restricted by the programming interfaces. The **Integrated Assessment**

Modeling Consortium (IAMC) format[10] provides a widely accepted data structure that enables harmonized reporting and scenario comparison across various models. We use this as starting point for the naming of the modeling input and output variables which are passed on between the models using .csv-files.

The IAMC Data Format and its Role in Standardization

The IAMC format is a structured data format designed to facilitate the transparent and systematic exchange of **model results, scenarios, and assumptions** across energy and climate research communities. It is used by various research projects and brought together in the IAMC **Scenario Explorer**[11] (see Figure 7), are registered and harmonized. The IAMC format follows a tabular structure where variables are organized by **region, scenario, year, and unit**, ensuring a consistent representation of data. The official IAMC documentation and data repository provide **common definitions**, **methodological guidelines**, and **data-sharing protocols**. These resources serve as a foundation for aligning different energy models, ensuring they follow the same **variable naming conventions** and **data structures**.

[10] IIASA – Standardized naming convention https://docs.ece.iiasa.ac.at/standards.html

[11] Scenario Databases by the IAMC https://www.iamconsortium.org/resources/databases/

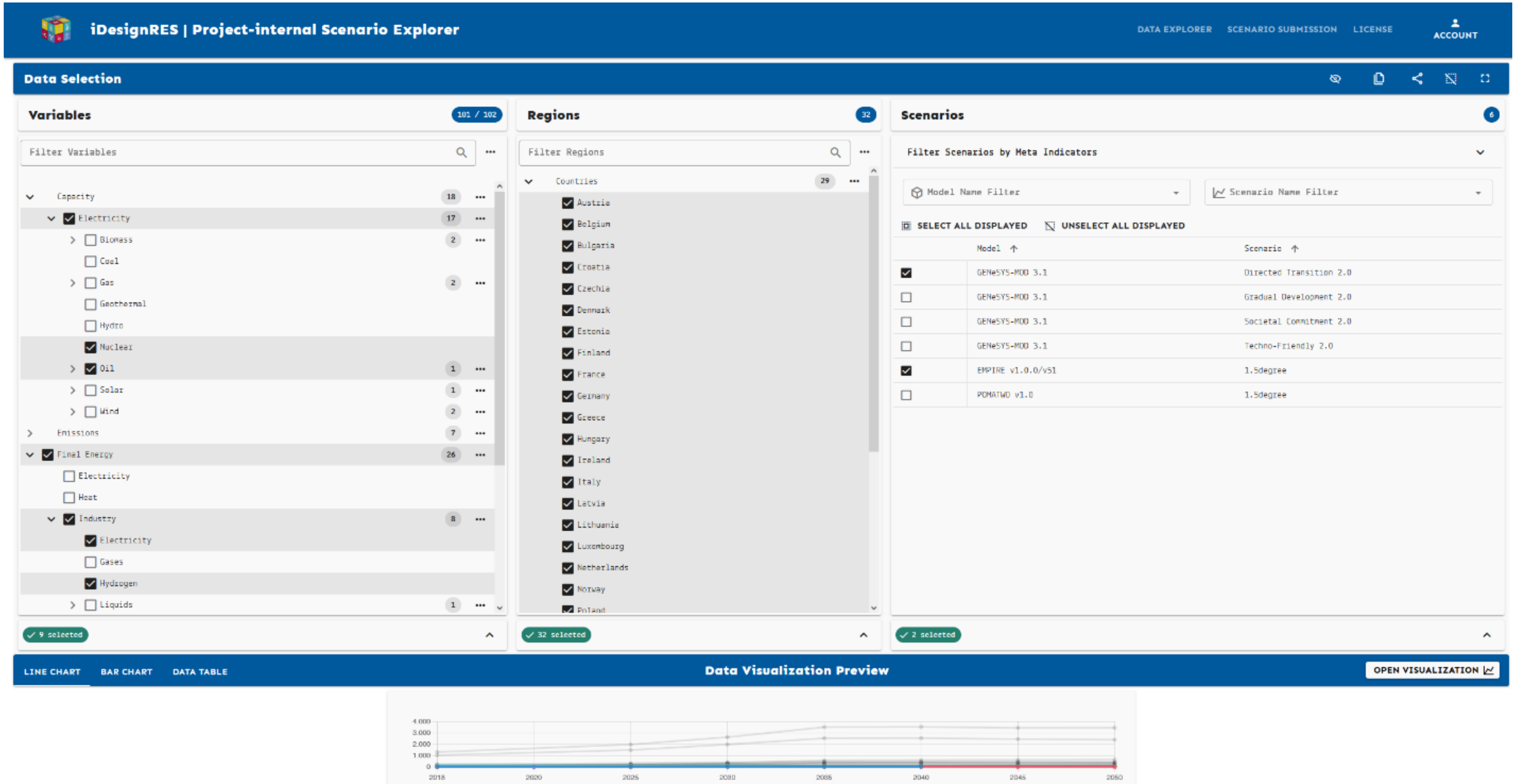

Figure 7: Snapshot of the iDesignRES scenario explorer app representing modeling results in IAMC format for different models, scenario, technologies and countries. Below, the results are displayed over the selected period.

By adopting the IAMC format for all models, **GENeSYS-MOD, JRC-TIMES, and Multi-carrier geolocation planning model** can ensure that their results are **cross-comparable** and can be seamlessly integrated into IAMC-based tools such as the **Scenario Explorer**.[12] Standardized data formats also facilitate external collaborations, allowing policymakers and researchers to use model outputs without extensive reformatting.

Developing a Shared IAMC Common-Definitions Template for iDesignRES

A key step toward standardization is the use of the **IAMC common-definitions template**,[13] where each model explicitly defines its **input and output variables**. This template acts as a **shared reference document** that aligns the parameter lists across models. Currently, this approach is limited to the three **energy system models** (GENeSYS-MOD, the multi-carrier geolocation model and JRC-Times), but future iterations can include **other models as well**. These input and output variables of each model are collected in the **iDesignRES common-definitions excel file**.[14]

Each model must indicate its **input and output parameters** using IAMC's standardized **nomenclature and variable definitions**. The common-definitions template will help prevent discrepancies in data labeling and ensure that all models contribute to a **harmonized dataset**. This approach requires coordination, as **missing variables** need to be identified, added, and named consistently. Variables that are currently missing are collected in the sheet **"variable_new"**. They are added via **pull requests** to the **iDesignRES workflow** on GitHub which extends the IAMC common-definitions. Since the IAMC format focusses mainly on integrated assessment models, certain variables such as specific power plant types or energy infrastructure needs to be added to meet the **higher technological resolution** of energy system models. The ongoing coordination with the **IIASA** team through **pull requests** will ensure that updates to IAMC's definitions remain aligned with the latest **research needs, model developments, and scenario-based policy assessments** in iDesignRES but also other international research projects. The modularization and standardization efforts are hence not only limited to this project but benefit all future projects using the IAMC data format.

3.4 The role of a data exchange protocol in iDesignRES

A robust **data exchange protocol** is pivotal for ensuring seamless communication between the various energy models integrated in the **iDesignRES framework**. By adhering to the **standardized and transparent** set of data conventions in the iDesignRES workflow, the protocol allows the models to share crucial input parameters with minimal friction. This standardized exchange protocol (e.g., the use of **.csv-files, uniform units**) ensures that all models—**regardless of the programming language** they are written in—can readily consume and process the data they need.

Moreover, establishing such a protocol guarantees that the correct values and underlying assumptions are passed on as **boundary conditions** to other energy system models, including GENeSYS-MOD, the multi-carrier geolocation model, and JRC-TIMES. In doing so, it preserves the integrity of scenario assessments by maintaining consistency across diverse simulation and optimization tools. The protocol also supports versioning and traceability, allowing users to track which datasets were used for each scenario.

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[12] For the iDesignRES project, we will use the project internal Scenario Explorer – a derivation of the IAMC scenario explorer.

[13] IAMC common definitions template: https://github.com/IAMconsortium/common-definitions

[14] https://zenodo.org/records/15039766

Finally, this approach greatly simplifies the process of preparing outputs for platforms such as the **IAMC Scenario Explorer**. By generating standardized model results, iDesignRES stakeholders can easily upload and compare inputs and outputs across scenarios and research teams. This capacity not only improves collaboration among iDesignRES researchers but also supports quality assurance and fosters a transparent research environment across international projects.

In essence, the data exchange protocol forms the backbone of integration in iDesignRES—enforcing technical **compatibility, improving data accuracy**, and creating a smooth pathway for sharing both **inputs and outputs** among the **three energy system modeling** tools, the **other models in WP1 and WP2** (e.g. Pomatwo, Multi-physics models) and the internal (iDesignRES) and public (IAMC) **scenario explorer**.

Data handling and transfer

A key component of the iDesignRES framework lies in the management and transfer of data among the multiple energy models (GENeSYS-MOD, PRIMES and JRC-TIMES). Each model in the system works with a **predefined list of potential input and output parameters**, ensuring that the necessary information is captured in a structured manner. The shared values are clearly labeled according to their significance and usage in the **iDesignRES common-definitions excel file**. The file will be **continuously updated** throughout the iDesignRES project according to the experiences with the **testcases in WP3**. Other models such as the **multi-physics models** will add their input and output parameters when the test cases start and allow to build fitting connections between the models. The model outputs from each model will be saved in **.csv-files**.
Based on the iDesignRES common-definitions excel file, we created a .csv-file containing the input parameters that all the models will share to guarantee consistency of key parameters for the models.

During **testing phases**, model input and output are uploaded and stored in **Zenodo repositories** to expedite collaboration and limit the number of people involved. After the results are validated, the **final data sets** are uploaded to the **iDesignRES Scenario Explorer**, providing a transparent platform for sharing model outputs and facilitating scenario comparisons. This involves then the testing and approval of the IIASA team, who serves as gatekeeper for the integrity of the variables and values uploaded to the scenario explorer app. The next model in the chain can then pick up exactly the data it requires—through a **tailored script** (see section3.4)—and use it as an input for further analysis.

A specific illustration of this process for GENeSYS-MOD can be seen in . This figure illustrates the **workflow for standardizing and modularizing energy system model outputs** using the IAMC format, with a focus on GENeSYS-MOD and its integration into the **iDesignRES framework**. The workflow starts with **input data stored in the GENeSYS-MOD GitHub repository**, where multiple scenarios (e.g., Scenario 1, Scenario 2, etc.) contain .csv-**files with various energy system parameters**. An **internal GENeSYS-MOD script processes the selected scenario**, converting it into **Excel-based or .csv data files**. These scenario-specific data files are then used as inputs for the **IAMC input conversion script** (see section 3.4), which transforms them into a standardized IAMC-compliant structure resulting in the **shared input parameter file**. The IAMC conversion process ensures that the outputs align with the **iDesignRES common definitions Excel**, which provides a structured list of **input and output parameters** necessary for model harmonization. The converted outputs are stored in IAMC format, including **time series outputs**, enabling comparability across different models. These outputs are then integrated into the **iDesignRES Zenodo repository and scenario app**, ensuring consistency and accessibility across multiple energy system models. The diagram also highlights interactions with **other models**, showing how the IAMC format serves as a **centralized standard** for facilitating cross-model comparisons and ensuring that results from GENeSYS-MOD can be effectively used alongside other modeling frameworks.

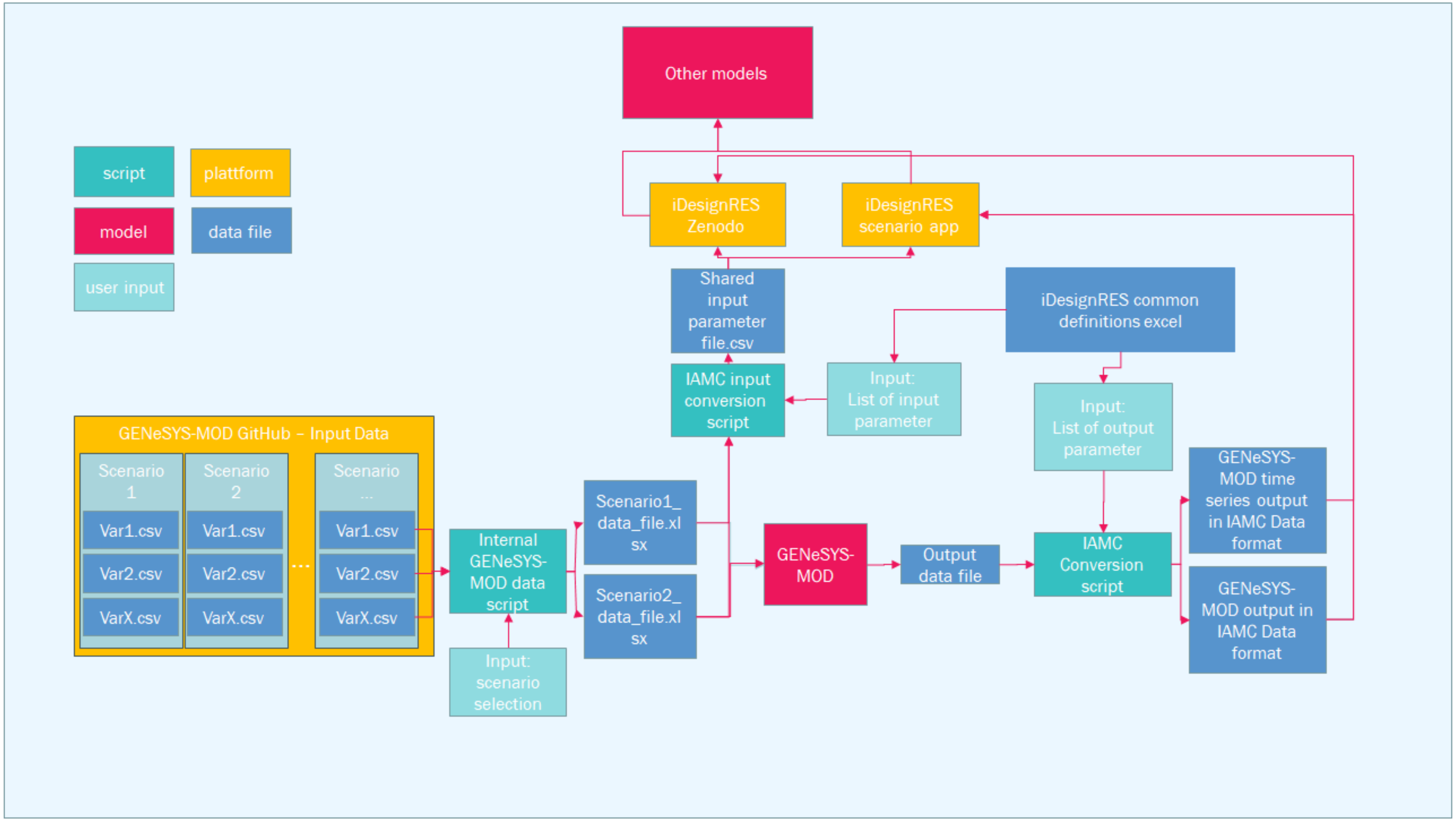

Figure 8: Exemplary data handling from the point of view of GENeSYS-MOD. The data flow and toolchain for running and integrating GENeSYS-MOD scenarios starts from input data stored on GitHub through to model execution and output formatting. It highlights the role of scripts, user inputs, and platforms like Zenodo or iDesignRES scenario app in converting, processing, and aligning scenario data for broader model comparison and integration.

Ultimately, this data handling and transfer procedure—spanning everything from parameter prioritization to storage and retrieval—helps maintain clarity, consistency, and reproducibility across all models in iDesignRES. By relying on standardized processes and repositories, the researchers in iDesignRES and outside can work efficiently and confidently, knowing that inputs and outputs are both accurate and readily accessible.

Data conversion scripts

The IAMC conversion script for the shared input data

The **IAMC_conversion_input.py** script is designed to convert the energy system modeling input data shared by the three energy system models into a standardized format compatible with the Integrated Assessment Modeling Consortium (IAMC) framework. The script processes multiple Excel files containing scenario-based energy data, applies predefined mappings to harmonize terminology, and restructures the data for IAMC-compliant reporting. This ensures consistency across energy modeling studies and facilitates integration with other IAMC datasets.

The script uses three mapping files (`./Mapping/`) that contain mappings for **technology names, fuel types, and regional names**. These mappings are loaded into dictionaries and used throughout the script to ensure uniform naming conventions. The script also defines a list of **regions**—primarily European countries, with additional global categories—to filter and structure the output data appropriately.

The core function, **iamc_conversion()**, iterates over all Excel files in the input directory and processes relevant sheets based on predefined parameter lists. The script focuses on key **energy system parameters**, including:

- **Technology costs and efficiencies:** Capital costs, fixed costs, and variable costs.
- **Emissions and climate constraints:** Annual emission budgets, exogenous emissions, and carbon content of fuels.
- **Energy demand and supply:** Residual capacity, annual energy demand, trade capacities, and storage potential.
- **Operational and policy constraints:** Lifetime of technologies, technology discount rates, and maximum activity limits.

For each processed parameter, the script performs the following transformations:

1. **Filtering and renaming** – Data is filtered based on the list of valid regions, and outdated or inconsistent naming conventions are replaced using the mapping dictionaries.
2. **Reformatting** – The script reshapes tables to an IAMC-compatible structure, ensuring that key dimensions such as **Region, Variable, Unit, and Year** are correctly represented.
3. **Pivoting and aggregation** – The script pivots data into a format where **years become columns**, making it easier for IAMC-based energy system analysis.
4. **Scenario tagging and export** – Each processed dataset is labeled with a **scenario name** (e.g. EU EnVIS-2060 scenarios) derived from the input file and linked to the **GENeSYS-MOD 4.0** model. The final data is exported as a CSV file into the `./Output/` directory.

We uploaded the script in the GENeSYS-MOD tools repository which is available here.

IAMC Conversion Script for GENeSYS-MOD: A Prototype for the Energy System Models

The **IAMC conversion script** is designed as a **prototype** for processing and transforming energy system modeling outputs into a standardized format that aligns with the requirements of the **Integrated Assessment Modeling Consortium (IAMC)**. This script has been specifically developed for **GENeSYS-MOD 4.0**, a model used to analyze energy transitions, but it serves as a **proof of concept** that will later be applied to **JRC-TIMES** and **Multi-carrier geolocation planning model** once those models are finalized. The goal is to establish a streamlined workflow for converting raw scenario data into IAMC-compliant formats, ensuring consistency across energy modeling frameworks.

The script follows a structured process, beginning with **data ingestion** from model output files, which are stored in either **GDX** (GAMS Data Exchange) or .csv-format. These files contain scenario-based projections of various energy system parameters, including **primary energy production, final energy demand, capacity installations, emissions, and costs**. The script reads these files and applies predefined **mapping rules** to standardize technology names, fuel categories, and regional definitions. These mappings are sourced from external .csv-files and nomenclature definitions, ensuring that the processed data aligns with the IAMC framework.

Once the data is loaded, it undergoes a **transformation process** where energy system parameters are filtered, categorized, and restructured. Functions within the script process different types of data, such as capital costs, emissions, storage capacities, and efficiency values. Specific functions handle key transformations, including the conversion of **primary energy sources into IAMC categories**, the calculation of **final energy demand across sectors**, and the aggregation of **regional energy balances**. The script also integrates time-series processing, ensuring that subannual data is correctly formatted for IAMC reporting.

A critical component of the conversion process is **data aggregation**. The script uses **Pyam**, a Python library for scenario analysis, to compile transformed data into IAMC-compatible structures. This step involves the calculation of **regional totals**, ensuring that results can be analyzed at both **national and EU27 levels**. The data is validated against a pre-defined IAMC data structure to ensure compliance with international energy modeling standards.

The final step in the workflow is the **generation of IAMC-compliant output files**. The script exports processed data as structured **.csv-** and **Excel** files, making them readily available for further analysis and visualization. Additionally, a validation and processing workflow ensures that the output adheres to IAMC's formatting requirements, with checks on **regional definitions, variable classifications, and subannual time formatting**.

While the script is currently implemented for **GENeSYS-MOD 4.0**, it is **a prototype that will serve as the foundation for broader applications**. Once the **JRC-TIMES** and **Multi-carrier geolocation planning model** models are finalized, the methodology developed in this proof of concept will be extended to process data from these models as well. Once these models are finalized, the validation tools EnergyPLAN and AnyMOD.jl (see section 3.4) will adapt the technical and sectoral resolution of the three models and adjust the data exchange script from GENeSYS-MOD accordingly.

This approach ensures that all three models will produce IAMC-compliant outputs, facilitating **comparability across different energy system frameworks** and accomplishes the close interface with the project database and visualization tools (iDesignRES scenario app). The most recent version of the IAMC output script is uploaded at the GENeSYS-MOD git hub "TOOLS" repository. The output of model runs with EU EnVIS-2060 scenario data is available on Zenodo.

Model interaction

Figure 9 illustrates how the energy system models and data sources within iDesignRES interact, emphasizing the **flow of shared parameters** and outputs among **various modeling layers**. On the left, the grey panel lists the core **shared input parameters.** These parameters form the foundational data that every model uses to ensure **consistency in scenario analyses**.

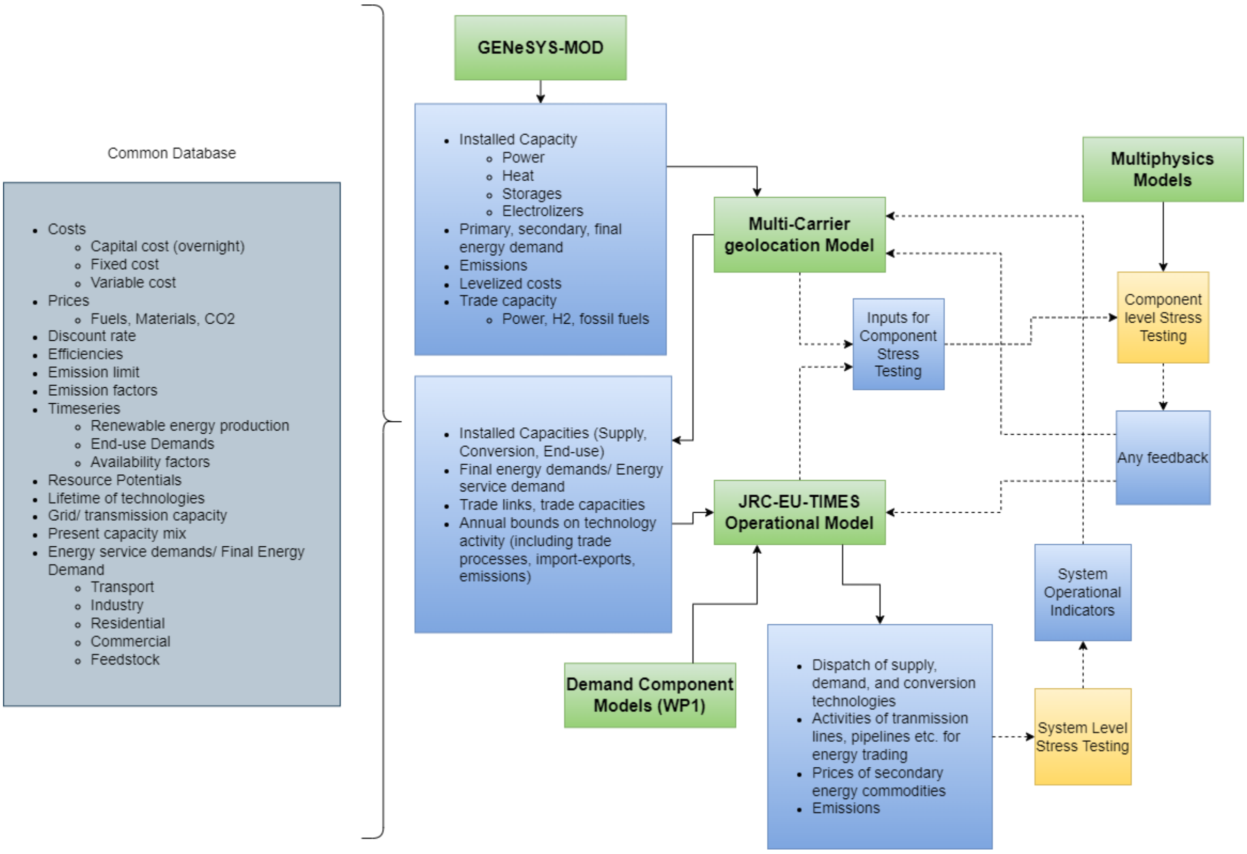

Figure 9: Depiction of the data flow in the three-layer approach. Outline of the interaction between GENeSYS-MOD, JRC-EU-TIMES, geolocation, and multiphysics models, all drawing from a shared common database of energy and economic parameters. The data flows from energy system modeling to component and system-level stress testing, enabling feedback loops and integration of operational insights into broader energy scenario assessments.

In the central green areas, the **three main energy system** models are shown as green squares: GENeSYS-MOD (NUTS0 optimization), the multi-carrier geolocation model (NUTS2 regions), and JRC-EU-TIMES (simulation on NUTS2 level). The WP1 Demand Component Models, highlighted just below JRC-EU-TIMES, produce **more granular inputs** such as energy demands or service demands at the NUTS2 level. GENeSYS-MOD processes the shared input parameters and provides outputs and boundary conditions (i.e. installed power capacities (coal, nuclear, large hydro-power plants, and pumped storage plants) or annual energy demand projections) to the multi-carrier geolocation tool. The multi-carrier geolocation tool further refines these results according to different regions (on NUTS2 level) and passes relevant data—demand profiles, trade capacities, geolocations of installed capacities and emissions—along to JRC-EU-TIMES. JRC-

EU-TIMES then simulates and stress-tests the whole energy system on high temporal and spatial resolution.

On the right, there are feedback loops indicating a **process** in which results from component models GGM, Pomatwo, Plan4RES, and SINTEF´s multi-physics component models – see table in the introduction) can be used to **stress-test and refine the outputs** of the multi-carrier geolocation model and JRC-EU-TIMES operational model. These multi-physics models can incorporate additional constraints or detailed engineering perspectives, feeding any new insights back into the overarching energy system layer. While these multiphysics models perform stress test at the level of individual technologies or infrastructures (e.g., district heating), JRC-EU-TIMES operational model performs stress test at the level of the whole energy system, assessing the energy system adequacy of supplying energy to demand sectors. This multi-scale approach of stress-tests can inform the multi-carrier geolocation model in revising the infrastructure expansion planning. If infeasibilities should arise while stress-testing, adjustments on the higher model levels can be performed, e.g. constraints for flexible peaking capacities or curtailment. The experiences with the test cases in WP3 will bring more clarity.

Finally, the data pipeline structure—shared parameters on the left, energy system models in the center, and iterative feedback from detailed models on the right—demonstrates how iDesignRES orchestrates a harmonized data flow. By passing consistent inputs and outputs between models at different scales (regional, national, cross-sectoral), the framework ensures coherence across all analyses, enabling robust scenario building and refined policy assessment.

3.5 Achieving modularization and standardization for the new multi-physics component models

Input-output definitions for component models

The individual multi-physics component models developed within Work Package 1 have been developed in different programming languages and different frameworks. In addition, due to the requirement of these models, different types of input parameters are required for these models. It is hence necessary to provide unified input-output definitions for these models for the integration of the models with the component assembling tool developed in Task 2.2. We can differentiate these models into three categories (as described in Deliverable D1.2, but with the merging of groups 2 and 4, that is energy consumer models (group 2) and stand-alone component models with detailed operational capabilities (group 4)):

1. system tools for a single energy carrier for detailed analyses of the behaviour of a given energy carrier,
2. component models directly developed within the framework of the assembling tool of Task 2.2[15], and
3. standalone models for energy consumers and detailed operational analysis capabilities which are sampled to provide input for technology descriptions in the assembling tool.

[15] The tool is based on *EnergyModelsX, an open-source energy system optimization framework.* It is available on https://github.com/EnergyModelsX.

Model types 2 and 3 will be directly integrated into the *EnergyModelsX* (*EMX)* framework, and hence, will utilize the same input format as already defined in *EMX*. The following subsections will outline the individual input-output definitions developed within Task 2.1 for the model categories.

System tools

The system tools operate independently of the developed assembling tool of Task 2.2.

Component models developed for EMX

Component models that are directly developed for the framework *EMX* can be incorporated without any adjustments. In this situation, the input-output definitions of the individual component models follow the approach chosen in *EMX*. The individual component models are coupled through the inflow and outflow of a technology (process or distribution and transmission infrastructure) while the internal behaviour in the component model can be modified by the user. In addition, the different component models include default variables as we outlined in the dedicated documentation on GitHub. These variables must be included in the model description.

As the direct integration of these component models requires that the modules are complying with *EMX*, individual functions are developed within Task 1.5 and distributed in Deliverable 1.3 that can be used by future model developers to identify potential bugs within the development phase.

Stand-alone component models that are sampled

Stand-alone models that are sampled for the assembling tool of Task 2.2 require a given format. Within Task 2.2, we developed sampling routines that can be utilized for connecting the assembling tool, written in Julia, with models developed in both Python and C++. These sampling routines require the component model to provide a callable function which has individual keyword arguments for the input. The output from the function is subsequently utilized to provide time profiles for costs and/or capacities. The individual time profiles are utilized within standard *EMX* elements, *e.g.*, the production profile from solar PV and wind farms within a non-dispatchable renewable energy source (NonDisRES) subtype. It is not possible to have a unified approach for models that should be sampled as both the input of the models and the output from the models differ in, *e.g.,* the transport model and the wind power component model. As an example, it is possible to provide the wind power component model with information regarding the latitude, longitude, orientation, turbine height, as well as the start and end time for the sampling of the data through keyword arguments. Differing temporal resolutions in the receding horizon model compared to the component model will be accounted for in the sampling routine.

However, certain input-output definitions hold for all component models that provide a time profile; in this case, the geographical location is the input to the component model and the corresponding time profile is the output.

4. Development of the energy system validation tools EnergyPLAN and AnyMOD.jl

To ensure the robustness and internal consistency of the three-layer modeling framework, **validation** plays a critical role in iDesignRES. Therefore, the models **EnergyPLAN** and **AnyMOD.jl/EuSYS-MOD** are prepared and extended in Task 2.1, specifically to **validate the modeling chain** by independently simulating or re-optimizing system configurations derived from the core models (GENeSYS-MOD, the multi-carrier geolocation planning model, and JRC-EU-TIMES). Validation is essential to assess whether the results produced across layers—particularly investment decisions, installed capacities, and system operation—are both technically feasible and consistent when viewed from different modeling paradigms and methodological approaches. **EnergyPLAN**, as a deterministic simulation tool with detailed hourly resolution, can validate aspects of **system operation**, such as energy balancing, system reliability, and cross-sectoral interactions, based on fixed infrastructure configurations. In contrast, **AnyMOD.jl** is an open-source optimization model with high spatial and temporal resolution, which can be used to re-run selected scenarios under alternative modeling assumptions to test the **robustness of investment pathways**, technology choices, and spatial allocation of infrastructure. Together, these tools allow the iDesignRES framework to cross-check results, identify critical assumptions, and strengthen confidence in the integrated modeling outcomes. The following sections describe the adaptation of each tool for this purpose.

4.1 EnergyPLAN

EnergyPLAN is an energy balance simulation tool for cross-sectoral energy system analyses on national, regional and local scale. EnergyPLAN has been in continuous development since 1999, and have been widely used in research shown be having been used in more than 315 peer-reviewed papers.[16] The main purpose of EnergyPLAN is to assist in the design of energy planning strategies with technical and economic analyses of the consequences of different choices and investments. The purpose of EnergyPLAN is not to provide the basis for prescribing or predicting the future energy system, but rather to form a basis for an informed, transparent and conscious deliberation of potential development pathways for the energy system.

EnergyPLAN simulates hourly energy balances across all energy sectors (electricity, heating, cooling, mobility, and industry) over a leap-year. A principal overview of the technologies included in EnergyPLAN can be seen in Figure 10.

[16] P.A. Østergaard et al. (2022): Review and validation of EnergyPLAN. Renewable and Sustainable Energy Reviews Volume 168 https://doi.org/10.1016/j.rser.2022.112724

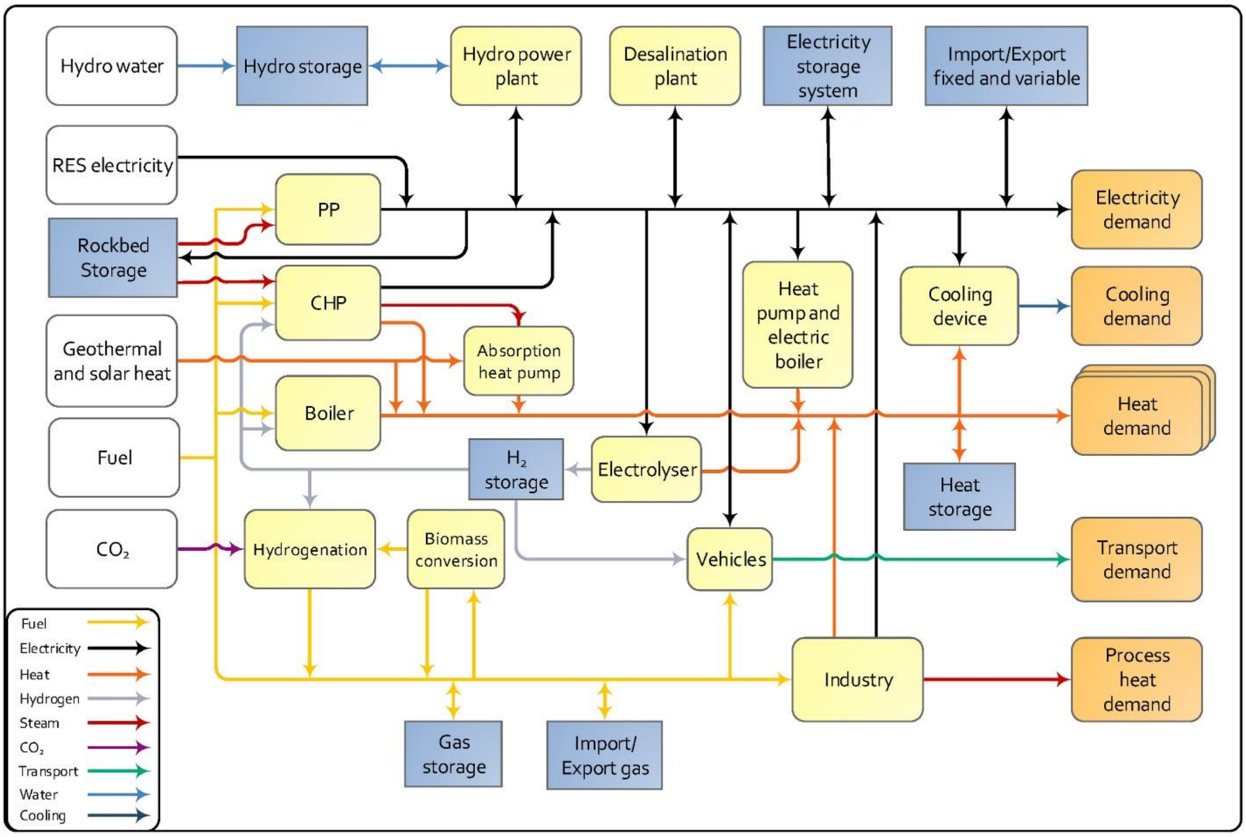

Figure 10: Principal overview of technologies and energy flows in EnergyPLAN following the Reference Energy System (RES) methodology of input fuels, technologies and output fuels[17]

For simulating EnergyPLAN uses what can be referred to as "analytical programming". Rather than establishing a series of balance equations that are solved numerically as in optimization and equilibrium models, EnergyPLAN is based on a series of endogenous priorities within, e.g., power and heat production and pre-defined procedures for simulating the operation of units that are freely dispatchable. The approach is purely deterministic with no stochastic elements.

An overview of the inputs and outputs of EnergyPLAN can be seen in Figure 11.

[17] H. Lund et al. (2021): EnergyPLAN – Advanced analysis of smart energy systems. Smart Energy Volume 1 https://doi.org/10.1016/j.segy.2021.100007

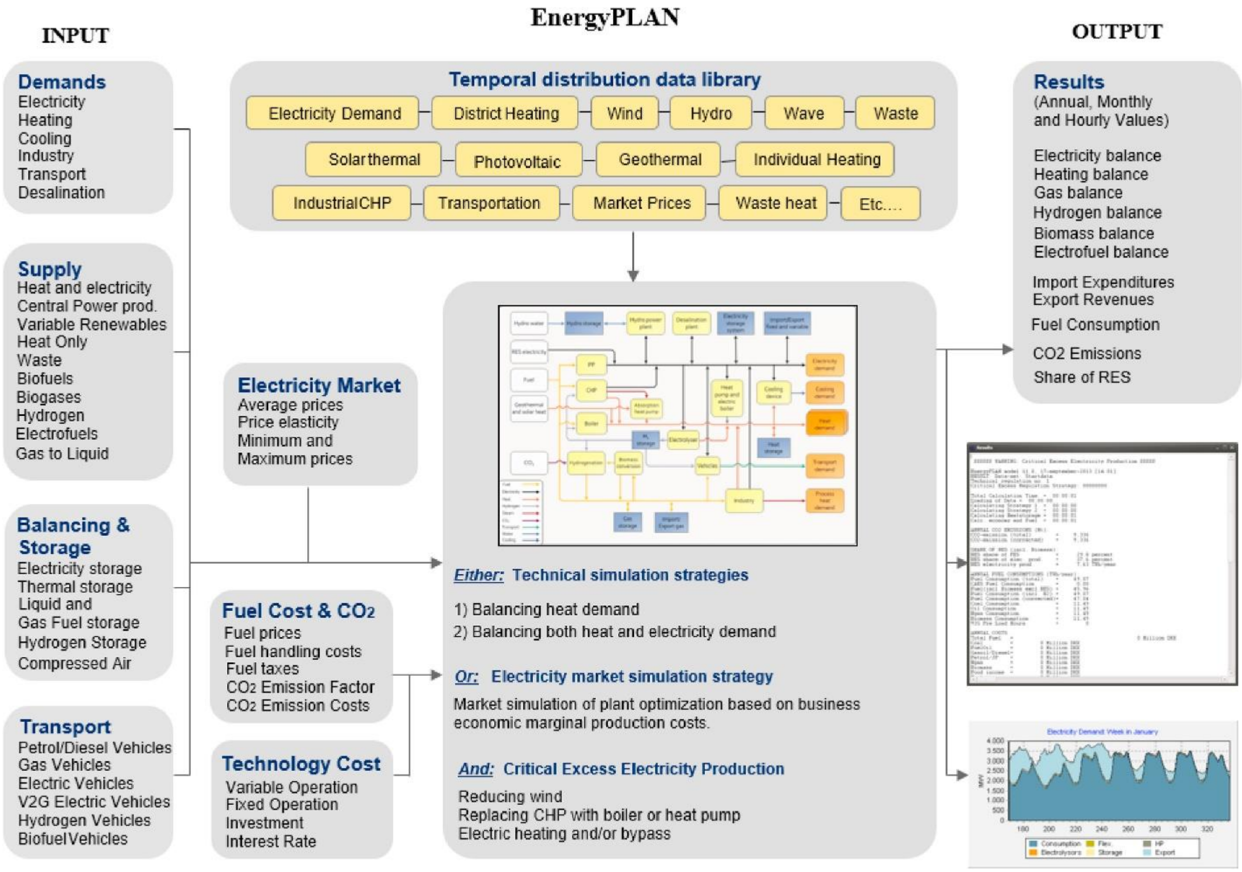

Figure 11: Overview of inputs and outputs of EnergyPLAN[18]

In iDesignRES, EnergyPLAN will be used for validation purposes, and to that extend EnergyPLAN is updated and developed to be able to facilitate that. More specifically, EnergyPLAN is used in the following parts of the project:

- Subtask 2.3.1: Decarbonization scenarios: This activity will be implemented jointly by E3M, TUB, EDF and AAU providing a series of state-of-the-art decarbonization scenarios from their multi-carrier geolocation model, GENeSYS-MOD, Plan4res, and EnergyPLAN models respectively building on existing data and model mechanics.
- Task 2.5: Aalborg University (AAU) to preparing the EnergyPLAN for WP3 through a first quality check of the model based on the task's test cases
- WP3: AAU will implement the EnergyPLAN model to compare and validate the results of the iDesignRES, assessing differences and similarities from both models, hence certify their robustness.

The currently released version of EnergyPLAN is v16.3, and a new version is in development to better allow validation of iDesignRES tools. A major focus is on developing CCUS technologies in EnergyPLAN. The new CCUS module in EnergyPLAN tracks the flow of CO_2 emits from different sources, captured, utilized, and stored. An overview of the changes can be found in Figure 12. The output table is under discussion now, but the idea is to deliver the amount of CO_2 captured from point sources (ideally include both biogenic and non-biogenic), DAC and DOC; the amount of CO_2 to be stored in the permanent CO_2 storage; the electricity consumption of carbon capture and storage.

[18] ibid.

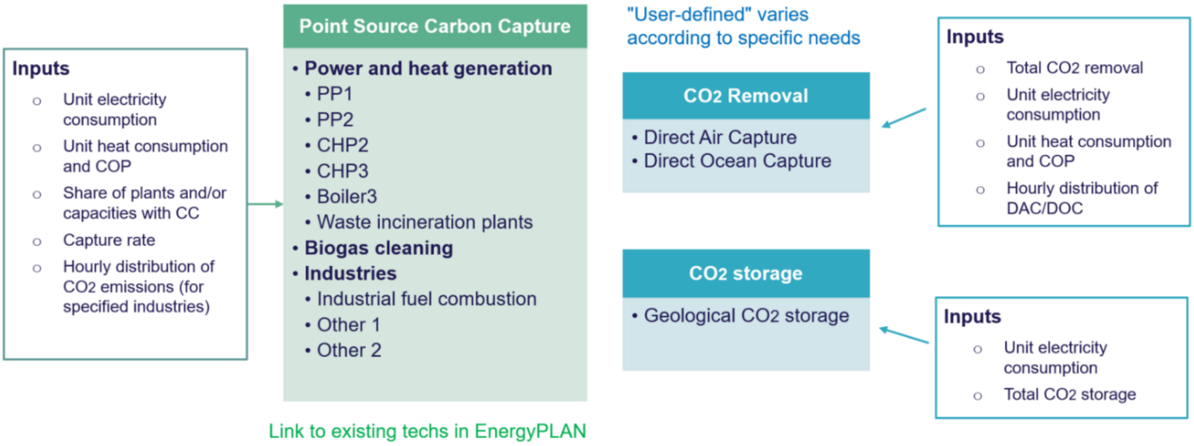

Figure 12: CCUS upgrade to EnergyPLAN

4.2 AnyMOD.jl - open energy system modelling framework

AnyMOD.jl is used in iDesignRES for the validation of investment decisions of energy system modeling results of the three-layer approach. Its technical and spatial flexibility enables the model for validate model results in iDesignRES. AnyMOD.jl[19] is a **Julia-based modeling** framework designed for large-scale energy system models with multi-period capacity expansion developed at TU Berlin by Göke.[20] It is formulated as a linear optimization problem and is particularly well-suited for addressing the complexities of energy systems with high shares of intermittent renewable energy sources and sector coupling. By integrating multiple energy sectors, such as **electricity, heating, transport, and industry**, AnyMOD.jl enables comprehensive analysis of energy transitions and long-term decarbonization strategies.

The framework employs a **graph-based approach** to efficiently represent complex system interdependencies (see **Figure 13**). This allows for a flexible and scalable representation of energy infrastructures and their interactions, as detailed in Göke.[21] AnyMOD.jl optimally determines capacity expansion and operational decisions, considering constraints related to resource availability, grid limitations, and technology-specific characteristics. The software's implementation and technical functionalities are further elaborated in Göke.[22]

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[19] https://github.com/leonardgoeke/AnyMOD.jl?tab=readme-ov-file

[20] L. Göke (2021): "AnyMOD - A graph-based framework for energy system modelling with high levels of renewables and sector integration." Applied Energy Volume 301, 1 November 2021, 117377 https://www.sciencedirect.com/science/article/pii/S0306261921007807?via%3Dihub

[21] ibid.

[22] L. Göke (2021): AnyMOD.jl: A Julia package for creating energy system models. SoftwareX Volume 16, December 2021 https://doi.org/10.1016/j.softx.2021.100871

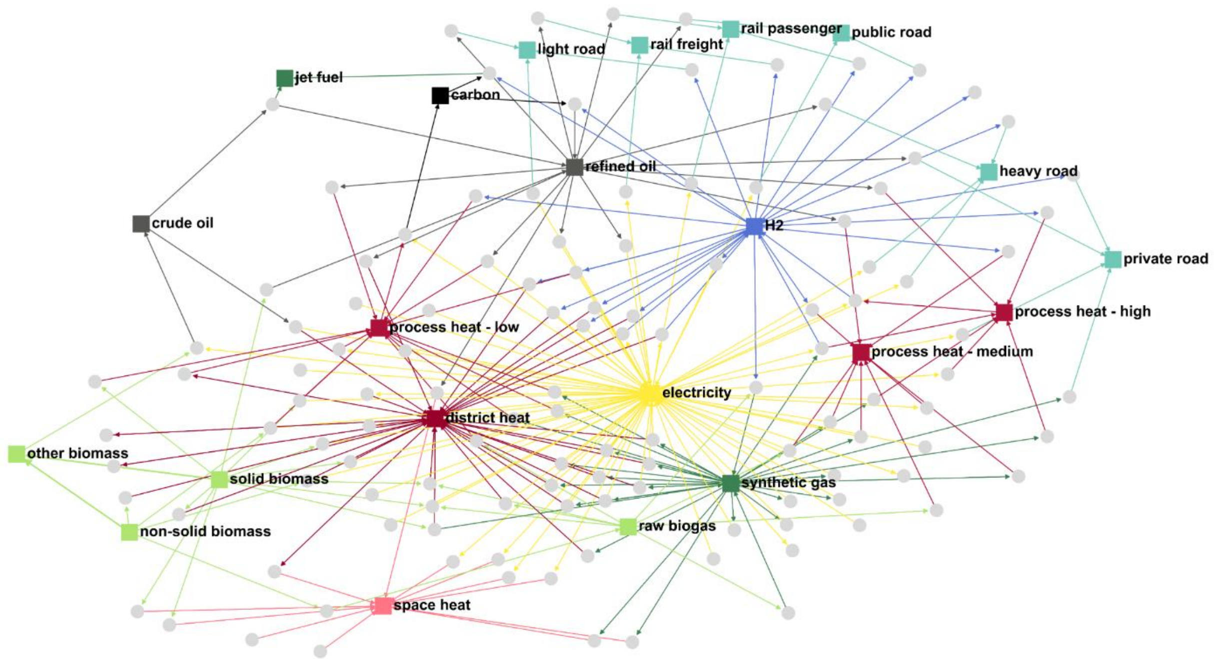

Figure 13: Graph based approach of AnyMOD.jl (Wimmers et al., forthcoming)[23]

AnyMOD.jl has been applied in various studies focusing on renewable energy integration and sector coupling. It has been used to analyze deep **decarbonization pathways**, including increased electrification, hydrogen integration, and demand-side flexibility measures. Due to its computational efficiency and adaptability, the framework supports both national and cross-border energy system analyses, providing essential insights for policymakers, researchers, and industry stakeholders. The modeling framework provides a robust and versatile tool for energy system modeling, facilitating integrated assessments of multi-sector energy transitions. Its capability to handle large-scale optimization problems makes it a valuable asset for long-term planning and policy analysis, supporting the transition towards a sustainable and efficient energy future.

In alignment with the iDesignRES project scope, the AnyMOD.jl framework can be implemented using Europe as the geographical scope. The European application of AnyMOD.jl is called EuSYS-MOD[24], a model specifically developed for analyzing the expansion and operation of energy technologies and transmission infrastructure in the **European energy system**. Built upon the graph-based, highly flexible architecture of AnyMOD.jl, EuSYS-MOD inherits its modular structure and multi-sector capabilities, allowing for integrated modeling of electricity, heat, hydrogen, and transport systems at varying spatial and temporal resolutions. EuSYS-MOD extends AnyMOD.jl by embedding detailed European-specific data and modeling features, including NUTS2-level regional disaggregation, cross-border transmission capacities, renewable energy potentials, and technology-specific investment and operational constraints. The model includes representations of key infrastructure elements—like **power lines, pipelines, and storage systems**. To create EuSYS-MOD from AnyMOD.jl, developers instantiate a new model using the AnyMOD.jl framework and then parameterize it with European datasets, including technology cost data,

[23] https://arxiv.org/pdf/2412.15083

[24] https://github.com/leonardgoeke/EuSysMod/tree/greenfield

demand projections, policy targets, and spatially resolved resource availability. The model structure is customized by defining regions, nodes, and technologies according to the European context, while maintaining compatibility with AnyMOD's core abstractions. The result is a robust, adaptable planning tool capable of exploring a range of scenarios for achieving a climate-neutral European energy system.

Recent developments of **EuSYS-MOD** have significantly expanded its technical scope and applicability, enabling deeper insights into Europe's energy transition. Among the key additions are the integration of **sector-specific modules** for **transport** (e.g., electric vehicles, modal shifts) and **hydrogen infrastructure**, allowing detailed modeling of fuel-switching and demand-side decarbonization strategies. The model is capable of **enhanced spatial granularity** , supports **cross-sectoral flexibility** through energy storage and demand response, and incorporates **robust representations of power, gas, and hydrogen grids**, including trade between regions.

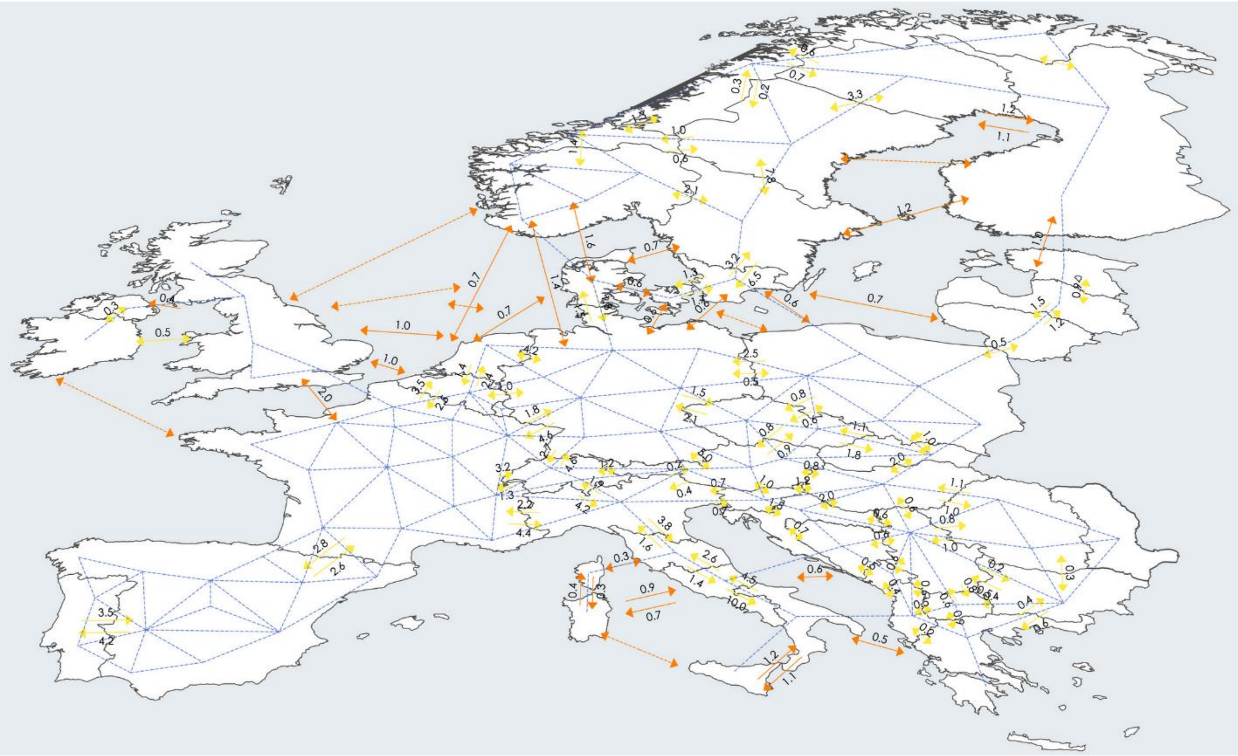

Figure 14: Hydrogen and electricity grid connections in EuSYS-MOD application in Aliasghari et al. (2025)[25]

EuSYS-MOD has been applied in studies examining **the role of nuclear energy** in decarbonization pathways, the **optimal configuration of renewable energy infrastructure** across Europe, and the **strategic value of sector coupling** in achieving climate targets.[26] The model supports multi-scenario comparisons and is increasingly used to **validate regional and national decarbonization strategies** by

25 Aliasghari et al. (2025): The potential of electrified transport for enhancing flexibility in integrated renewable energy systems https://www.sciencedirect.com/science/article/pii/S2352484725001453

26 Wimmers et al. (forthcoming): Assessing the viability of non-light water reactor concepts for electricity and heat generation in decarbonized energy systems https://arxiv.org/pdf/2412.15083, Aliasghari et al. (2025): The potential of electrified transport for enhancing flexibility in integrated renewable energy systems https://www.sciencedirect.com/science/article/pii/S2352484725001453

providing investment roadmaps under techno-economic, spatial, and political constraints. These additions make EuSYS-MOD a key tool in iDesignRES as it is able to validate European scenarios with high technical detail.

5. Conclusion

This report has detailed the extensive efforts undertaken in Task 2.1 of the iDesignRES project to standardize and modularize the three-layer modeling framework designed to analyze Europe's future energy system. At its core, this task tackled the challenge of integrating diverse models—GENeSYS-MOD, the multi-carrier geolocation model, JRC-EU-TIMES, and the newly developed multi-physics component models—each operating at different spatial, temporal, and technological resolutions. By implementing a harmonized data exchange protocol, adopting the IAMC format for model inputs and outputs via automated scripts, and extending shared variable definitions, the task aligned all models toward a consistent representation of the same energy system.

The layered structure ensures a robust balance between breadth and detail: Layer 1 provides long-term strategic planning at the Pan-European level; Layer 2 supports investment and operational decisions at NUTS2 granularity; and layer 3 stress-tests system components with high technical detail. The connections between these layers are more than data exchanges—they form a coherent, modular framework that allows iterative refinement, validation, and scenario comparison. The integration of validation tools such as EnergyPLAN and AnyMOD.jl/EuSYS-MOD further strengthens this framework by testing assumptions and ensuring result robustness across layers.

By developing a shared data infrastructure and automated conversion scripts, Task 2.1 enables seamless model interaction, supports transparency through the iDesignRES scenario explorer, and lays the groundwork for reproducible, collaborative energy system research. This standardization effort not only supports internal coherence within iDesignRES but also aligns with broader international initiatives for harmonized energy modeling by following the IAMC format.

Task 2.1 laid the foundation for cross-model consistency and modular development across the iDesignRES framework. Its standardization of input parameters, variable definitions, and data formats directly feeds into the ongoing development of the pan-European NUTS Level2 multi-carrier energy geolocation planning model and the JRC-EU-TIMES operational model. Furthermore, the upcoming long-term decarbonization scenarios & data (NUTS1 optimization) work builds on the scenario parametrization and boundary conditions provided by GENeSYS-MOD at the NUTS0 level, benefiting from the aligned assumptions and data scripts established in Task 2.1. The extensions and adaptations of EnergyPLAN and AnyMOD.jl developed will later be employed to validate the outcomes of the three-layer approach, helping to assess robustness across spatial and temporal scales. Beyond enabling the layered modelling framework, standardizing and harmonizing modelling aspects across different models will also enable more seamless analysis of the planned demonstrator cases. Its outputs support consistency between energy system models and component models, ensuring that case-specific analyses at the NUTS2 level are aligned with broader system-level results. This alignment is crucial for the stress testing of the models under future uncertainties—such as extreme weather events—and ultimately supports the broader goal of making iDesignRES modeling tools robust, transparent, and transferable for public and private actors.

iDesignRES

Integrated Design of the Components of the Energy System to Plan the Uptake of Renewable Energy Sources: An Open Source Toolbox

More information on iDesignRES project:

https://www.linkedin.com/company/idesignres

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