iDesignRES

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

Deliverable 2.4: NUTS Level 2 optimisation model for system operation and validation

NUTS Level 2 optimisation model for system operation and validation

Deliverable 2.4

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EXECUTIVE SUMMARY

Deliverable D2.4 presents the development of a high spatial and temporal resolution operational energy system model, JRC-EU-TIMES-OP, derived from the well-established European multi-energy-carrier, multi-sectoral energy system model JRC-EU-TIMES framework. Originally designed as a long-term energy system planning model, JRC-EU-TIMES has been substantially restructured in iDesignRES to enable detailed operational assessment and stress-testing of the case-study regions. While the original model focused on long-term transition pathways with investment optimisation and annual or seasonal balancing, the enhanced version now assesses short-term operability, flexibility, network constraints and resilience under stress events. In the iDesignRES project, future energy system configuration and new investments at the NUTS2 regions are designed and quantified by the GeoMEC geolocation multi-carrier planning model[1]. Hence, the JRC-EU-TIMES-OP Model does not design or quantify future system configuration, demands, or technology capacity, but these inputs are taken from the GeoMEC model outputs. It then evaluates the operability of the investment decisions produced by GeoMEC, which are treated as boundary conditions.

Therefore, while deliverable D2.3 documents GeoMEC as the iDesignRES NUTS2 planning layer, optimising long-term capacity expansion and infrastructure siting under regional constraints, this deliverable (D2.4) complements D2.3 by providing the operational layer required to test whether GeoMEC's investment solutions can operate under higher temporal variability and additional operating constraints. In particular, many operational infeasibility issues only emerge when (i) demand and renewable supply are represented at a high temporal resolution, (ii) flexibility constraints (storage dynamics, ramping, minimum stable generation, cross-vector coupling constraints) are enforced, and (iii) infrastructure constraints and contingencies are applied as short-term shocks. The JRC-EU-TIMES-OP model therefore enables iDesignRES to translate "plausible in planning" into "reliable in operation", and to quantify operational performance indicators used in WP3 test cases. In iDesignRES, this separation of roles is intentional: GeoMEC determines where and what to build over the transition horizon, while JRC-EU-TIMES-OP determines how the resulting system operates under normal and stressed conditions. This makes the modelling chain more transparent and avoids embedding operational complexity (and computational burden) in the planning model, where it would reduce tractability.

The restructuring of JRC-EU-TIMES into JRC-EU-TIMES-OP focuses on three main dimensions:

1. Spatial Resolution
The operational JRC-EU-TIMES-OP model adopts the 30-region configuration of the JRC-EU-TIMES planning model and repurposes it as a proxy for NUTS2 representation. This enables multi-regional flows of electricity, hydrogen, and other energy carriers, and forms the basis for further refinement where full NUTS2 detail is available. Although complete NUTS2 energy balances are not yet accessible for all regions, the modelling structure is fully compatible with such disaggregation. Remaining limitations are data-driven rather than methodological; full alignment will be achieved as WP1 and WP3 datasets are finalised for case studies.

2. Temporal Dimension
A flexible, newly developed time-slice structure supports intra-annual temporal detail up to hourly resolution for representative weeks. The framework allows dynamic selection of temporal structure

[1] GeoMEC is a geolocation multi-carrier planning model that simultaneously covers several energy carriers, electricity, heat, hydrogen, gas, CO_2 flows, and e-liquids and identifies the most cost-effective spatial deployment of technologies needed to satisfy projected demand for these carriers.

depending on data availability and research needs. Prototype tests were performed using several granularities – from coarse (12 to 72 time slices) to detail representations of one or three weeks per season at the hourly level (672 and 2016 time slices). Scaling from 12 to 2016 time slices (x168) resulted in a 400-fold increase in matrix size and a 130,000-fold increase in computational time, demonstrating both feasibility and computational implications of high-resolution operation.

3. Operational Features

The model incorporates additional features needed for operational realism, including:

- Detailed electricity dispatch and unit-commitment-like constraints
- Representation of electricity and gas networks (Power Transfer Distribution Factors (PTDF) - based grid modelling with transmission expansion and pipeline physics)
- Ancillary service requirements
- Flexibility provision from storage, demand-side measures and cross-vector technologies (e.g., electrolysers, heat pumps, methanation, etc.)

These enhancements allow the operational model to capture flexibility limits, bottlenecks, curtailment behaviour, and multi-vector interactions that are not visible in long-term planning models.

Model application in iDesignRES

The application of this operational model, depending on the case study, is mentioned in Deliverable D3.1, which sets the research questions, scenario framework, and stress-test requirements. A possible list of stress scenarios has also been developed in Task 2.5 in cooperation with other modelling teams. To use JRC-EU-TIMES-OP as a stress-testing framework, the model will adopt investment decisions from the GeoMEC model, i.e., energy demand and infrastructure are treated as boundary conditions for a given scenario and year. In this context, a soft-linking approach that maps core energy system configurations and technology parameters has also been established. High-resolution demand profiles from the component models (buildings, industry and transport), as well as renewable resource profiles (solar, wind, hydro, ocean), are supplied by WP1 and integrated into the operational timeline. This soft-linking approach ensures that the long-term system design is transparently transferred into the operational domain with harmonised techno-economic data, capacities, fuel balances, and regional definitions. While the high spatial-temporal framework has been shown to be functional, the final decision on temporal details depends heavily on the research question and data availability.

Model linking

A dedicated mapping framework has been developed to align technologies, commodities, parameters and regional structures between GeoMEC and JRC-EU-TIMES-OP. Automated routines read GeoMEC outputs and transform them into TIMES-compatible parameter sets following IAMC conventions. The soft-linking of the models is one-directional, i.e. GeoMEC provides JRC-EU-TIMES-OP with the capacities for generation, storage, infrastructure assets and boundary conditions for activity. A feedback loop can be performed via the dedicated mapping framework; however, it requires user intervention. This enables the automatic construction of operational model instances, ensuring consistency, reproducibility and transparent data exchange across WP2 and WP3.

Validation protocol and stress tests

To validate the operability of GeoMEC-derived energy system configurations, JRC-EU-TIMES-OP computes a set of operational indicators, including unmet demand, renewable curtailment, storage state-of-charge patterns, flexibility utilisation and network constraints. These metrics are used to identify operational inadequacies that are not visible in the planning model. In parallel, Task 2.5 has developed a comprehensive stress-test taxonomy and matrix, grouping shocks into environmental, technical, socio-economic and behavioural categories. JRC-EU-TIMES-OP is responsible for implementing system operational stress tests relevant to the test cases (e.g., low renewable periods, peak-demand events, infrastructure outages, and short-term fuel supply disruptions). These stress tests provide insights into the robustness, resilience and flexibility of the long-term system designs when exposed to extreme or adverse operating conditions. Based on stress-tests outputs, operational insights may need to be fed back into the GeoMEC model to recalculate the system configuration. JRC-EU-TIMES-OP incorporates mechanisms to reduce the number of iterations by including a set of technological options in the model (with a lead time of less than a year) that can mitigate short-term operational inadequacies in the GeoMEC-derived system configuration.

1. Introduction

1.1 iDesignRES Modular Framework

In the iDesignRES project, a multi-layered modelling approach is adopted to address energy system transition-related questions at different spatial, temporal, and system-component levels. The layered approach caters to any specific modelling, data, and research questions related to the needs of the stakeholders corresponding to test case regions. These layers have been described along with a detailed description of the roles of various models in Deliverable D2.1 (Figure 1).

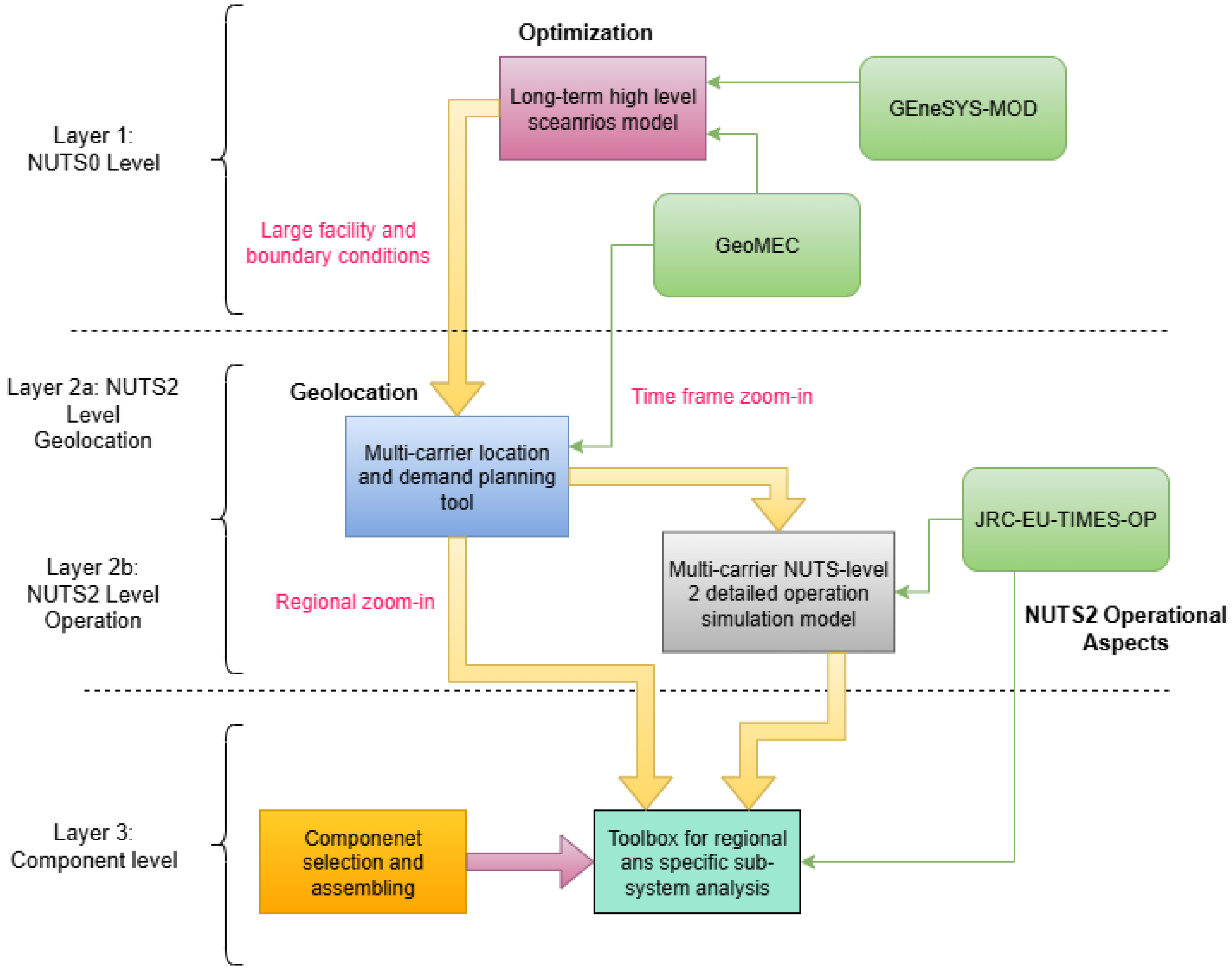

Figure 1: Multi-layer modelling approach in the iDesignRES project (Deliverable D2.1)

The layer 1 hosts models operating at NUTS0 resolution, i.e., GENeSYS-MOD[2] which provides a consistent pan-European outlook of the future energy system development. Information like national installed capacity, energy demands, etc., is then passed onto Layer 2, which hosts models operating at the NUTS2 regional level. In this layer, the Multi-Carrier Geolocation Model (GeoMEC) optimises future investments in various energy supply technologies, and the JRC-EU-TIMES-OP model provides operational insights of

[2] The Global Energy System Model - or GENeSYS-MOD - is an open-source cross-sectoral energy system model aimed at long-term developments of the energy system. https://genesysmod.readthedocs.io/en/latest/index.html

the system for a specific year. The Layer 3 hosts multi-physics component models that stress-test specific elements of the energy system.

1.2 Role of the Operational Model: JRC-EU-TIMES-OP

The system operational model JRC-EU-TIMES-OP is hosted at layer 2 and interacts primarily with the GeoMEC model and possibly with various multi-physics component models. The primary role of JRC-EU-TIMES-OP is to validate GeoMEC's system portfolio designed for a targeted year, with respect to operational feasibility at the NUTS2 level at a high temporal resolution. This is achieved by stress-testing the system configuration of GeoMEC under various extreme operational conditions. To validate the system configuration for operational feasibility, various performance indicators are calculated and checked for acceptability. In case these indicators exceed acceptable thresholds, an iterative feedback loop (initiated by the user of the combined GeoMEC – JRC-EU-TIMES-OP framework) will ensure that GeoMEC can consider operational information during optimisation and redesign system configuration. For the test case regions, in addition to system validation, JRC-EU-TIMES-OP also answers specific research questions and quantifies various system performance indicators identified in Deliverable D3.1. Table 1 outlines the utility and complementarity of GeoMEC and JRC-EU-TIMES-OP model for the iDesignRES project. A link of JRC-EU-TIMES-OP with the Multiphysics component models is identified in the Deliverable D2.1. Currently, the JRC-EU-TIMES-OP model interacts with the component models by considering energy demand profiles generated by the specific models for the industry, building and transport sectors developed in WP1. The JRC-EU-TIMES-OP model has the flexibility to incorporate feedback from various component models on the operational feasibility of any system component. However, the scope and need of this feedback and interactions specific to a test-case research question will be further explored in WP3.

Table 1: Complementarity of GeoMEC and JRC-EU-TIMES-OP

Aspect	GeoMEC (Geolocation planning)	JRC-EU-TIMES-OP (operation)	Why it matters for iDesignRES
Primary decision	Long-term investments & siting	Short-term dispatch/operation (long-lead investments fixed from GeoMEC, short-lead investments can be made by JRC-EU-TIMES-OP	Separates "build" vs "run" questions
Time resolution	Coarse time representation	High temporal granularity (configurable up to hourly for representative weeks)	Captures variability & flexibility limits
Feasibility checked	Planning feasibility	Operational feasibility and adequacy	Reveals hidden bottlenecks
Key outputs	Capacity mix, infrastructure expansion, and regional allocation	Technology operation, Demand-not-served, curtailment, congestion/bottlenecks, storage cycling, scarcity	KPIs required by WP3 stress tests
Stress tests	Transition and planning uncertainty	Short-term shocks and contingencies	Enables resilience assessment

In addition to the JRC-EU-TIMES-OP model, the EnergyPLAN model[3] developed by AAU provides system validation insights for the North Sea case study region (Lund et al., 2021). EnergyPLAN represents the scenarios and technologies from the planning models in iDesignRES, i.e., GeoMEC and GENeSYS-MOD, and generate hourly operation dynamics (over a year) of the sector-coupled energy system covering power, heat, and transport. Being a copper-plate model with technological options specified as groups,

[3] EnergyPLAN is an energy balance simulation tool for cross-sectoral energy system analyses on national, regional and local scale developed by Aalborg University [Frontpage - EnergyPLAN]

EnergyPLAN provides fast sense checking of the system reliability by calculating annual system performance indicators like Critical Excess Electricity Production (CEEP) (Østergaard, 2015). For the North Sea test case the EnergyPLAN model also validates the GeoMEC's system configuration and thus validating JRC-EU-TIMES-OP results.

1.3 Report Structure

Section 2 describes the development of the sector-coupled operational model JRC-EU-TIMES-OP with detailed description of core assumptions, operational constraints, and linkage with GeoMEC. The linkage between JRC-EU-TIMES-OP and the GeoMEC models is further described in Section 3. This is followed by modelling insights and preliminary results from the prototype JRC-EU-TIMES-OP model in Section 4. A strategy for model validation and stress testing is presented in Section 5. Finally, Section 6 summarises the work performed as part of Deliverable D2.4 and identifies future work for further model development, linking, and implementation for the test case regions in WP3.

2. Optimization Model for Energy System Operation

2.1 Purpose and Scope of the Operational Model

The JRC-EU-TIMES-OP model has been developed in iDesignRES to assess the operational feasibility, flexibility and resilience of the energy system configuration produced by the GeoMEC planning model. Whereas GeoMEC operates at a coarse temporal granularity and focuses on long-term investment pathways, JRC-EU-TIMES-OP resolves short-term supply-demand balancing, infrastructure utilisation and flexibility provision at high temporal and adequate spatial granularity. This enables the identification of operational bottlenecks, adequacy challenges, and stress-induced failures that are not observable in long-term planning frameworks.

Within the iDesignRES modelling chain, the operational model serves three strategic purposes:

a. Operational validation of GeoMEC system designs, identifying potential inadequacies in flexibility, network availability, fuel supply or cross-vector coupling
b. Quantification of operational indicators, such as demand not served, curtailment, storage cycling and fuel shortages, which inform the feasibility of the proposed transition pathways for the test cases
c. Implementation of stress testing in WP3, where the model simulates extreme conditions using the stress-test matrix developed in Task 2.5

The JRC-EU-TIMES-OP operational model thus acts as the bridge between long-term planning solutions and real-time operational performance, ensuring that results are technically robust and actionable for the test cases. It brings additional operational features not represented (or only partially represented) in planning model. More specifically, while GeoMEC captures multi-carrier investment decisions and spatial allocation, JRC-EU-TIMES-OP introduces operational constraints that are typically relaxed in planning models due to computational reasons. These include time-coupled storage dynamics, unit-commitment-like constraints, operational reserve/ ancillary service representation (where activated), and explicit long- and short-term infrastructure limitations (e.g., PTDF-based transmission constraints or pipeline flow bounds, subject to data availability). This is essential because GeoMEC solutions can be cost-optimal in planning terms while still producing operational infeasibilities (e.g., scarcity hours, congestion, or insufficient ramping/ firm capacity) once high-resolution balancing is enforced. Table 2 presents a "reader map" that highlights the capabilities of GeoMEC and JRC-EU-TIMES-OP and how the two models can complement each other within their interlinked use as a single, integrated framework.

Table 2: Overview of features comparison (planning vs operational layer) in iDesignRES

Capability	D2.3 GeoMEC (planning)	D2.4 JRC-EU-TIMES-OP (operation)
Endogenous long-term investments	Full representation	Fixed from GeoMEC; only short-lead-time investments are endogenous
Hourly (or representative hour) balancing	Limited/aggregated	Full representation
Storage state-of-charge time coupling	Simplified	Explicit trajectories and cycling indicators
Ramping / minimum stable generation / part-load efficiency losses / commitment-like constraints	Limited / aggregated	Full representation (where activated)
Short-term infrastructure bottlenecks (power, gas, hydrogen, CO_2)	Partial	Full representation; the model also allows for endogenous transmission planning expansion (i.e., modification in the grid topology), if activated
Operational adequacy metrics (demand not served, scarcity hours, etc.)	Not included	Full representation
Operational stress tests (contingencies, extreme profiles, etc.)	Full representation when affecting planning	Full representation when affecting the operation

2.2 Sector-Coupled Operational Representation

While Section 2.1 described the role of the operational model within the iDesignRES modelling chain, this section outlines the system-level motivation for adopting a sector-coupled operational framework. Reliable power system operation is often highlighted in discussions of the challenges associated with large-scale integration of variable renewable energy sources. However, the transition to a decarbonized energy system will need more than large-scale investment in renewable electricity generation. Clean fuels, e.g., hydrogen, e-methane, and advanced biofuels, are expected to play a critical role in multiple sectors such as industry and transport, both as energy carriers and as feedstocks. Production of these fuels will require clean electricity and CO_2 captured from the atmosphere or industrial sites, as well as robust transport and storage infrastructure, such as pipeline networks.

As a result, future energy systems are expected to become increasingly integrated and sector-coupled, with individual energy supply and demand sectors interacting dynamically and energy technologies complementing each other to ensure reliable system-wide operation. In such systems, operational flexibility is provided not only by traditional power plants and storage units but also by cross-vector conversion technologies, such as electrolysers, methanation units, heat pumps, and CHP plants, as well as by demand-side flexibility and storage options across all sectors.

Assessing the ability of highly decarbonised interconnected energy systems to operate reliably is therefore essential for supporting long-term energy transition targets. In iDesignRES, this is achieved by developing a sector-coupled whole-energy-system operational model based on an enhanced version of the JRC-EU-TIMES planning framework, adapted to represent short-term operational behaviour at high temporal resolution. This operational model allows the project to evaluate how cross-sector interactions, clean fuel production pathways, and infrastructure constraints influence overall system adequacy and resilience under both normal and stress-test conditions.

2.3 The JRC-EU-TIMES Model

The JRC-EU-TIMES-OP model is being developed based on the JRC-EU-TIMES planning model and aligning with GeoMEC's system configuration and data. Therefore, a brief description of JRC-EU-TIMES is presented in this subsection, followed by the steps of modelling details of the JRC-EU-TIMES-OP. Section 4 describes various steps taken to create a model instance of JRC-EU-TIMES-OP based on the JRC-EU-TIMES model.

JRC-EU-TIMES is an open-source, multi-region, multi-sectoral, and multi-carrier, dynamic energy system model of 30 European countries (Simoes et al., 2013) (GAGO et al., 2013). It is developed using the TIMES energy system modelling framework (Loulou et al., 2005) developed by IEA-ETSAP. Its goal is to minimise the system cost over the planning horizon by simultaneously making investment (or retirement) and operating decisions to meet energy service demands. In the process of doing that, it considers several constraints related to resource potential, technology deployment, energy policy and targets, etc. The model has a detailed representation of the energy supply, conversion, transmission, distribution, storage, and end-use. Figure 2 illustrates the sectoral coverage of the JRC-EU-TIMES model, which operates at a national level with twelve annual time slices. As a whole-energy-system model, it captures interdependence among the different energy sectors and regions. It also optimizes endogenous trading of energy commodities, e.g., electricity, gas, hydrogen, carbon permits and green certificates, and investment in corresponding infrastructure, e.g., electricity transmission lines or gas and hydrogen pipelines.

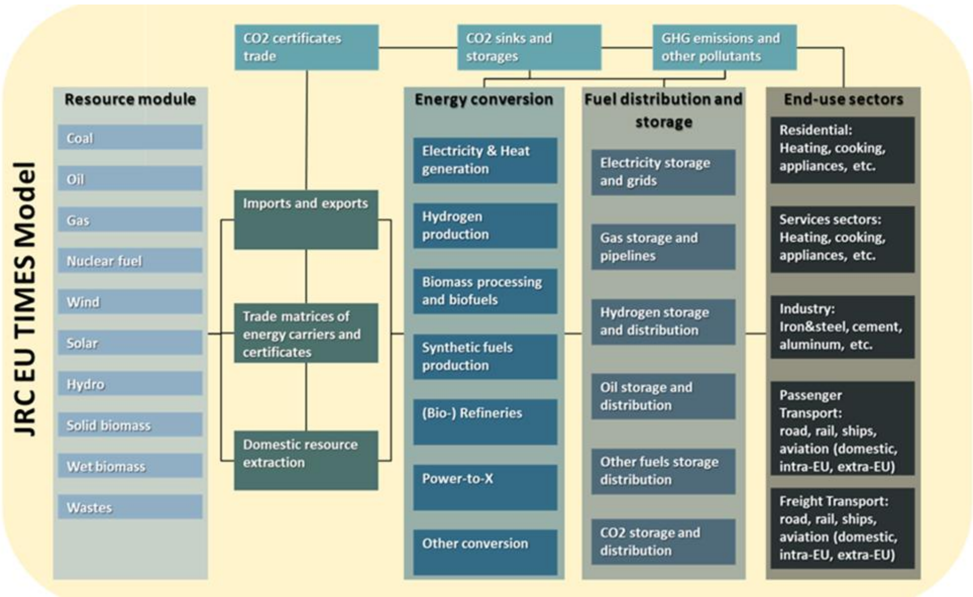

Figure 2: JRC-EU-TIMES energy system model structure

2.4 JRC-EU-TIMES-OP Model

2.4.1 From Planning to Operational Modelling

The JRC-EU-TIMES model is a long-term energy system planning tool designed to optimise investment decisions that meet future energy service demands at least cost. To ensure computational tractability at the European scale, the planning model uses a simplified operational structure, typically relying on twelve time slices per year and treating each country as a single node in a copper plate setting. While appropriate for investment planning, such coarse temporal and spatial assumptions limit the representation of short-term operational constraints, flexibility needs, renewable variability and infrastructure bottlenecks. Hence, driven by the computational complexity of developing an hourly energy systems model with endogenous capacity expansion for the entire Europe, the planning framework underrepresents key operational constraints of technologies and infrastructures at a non-realistic level. Further, these coarse assumptions may lead to an overestimation of the system's ability to integrate variable renewable energy sources, e.g., wind, and to an underestimation of the need for flexible dispatchable resources, such as energy storage.

To realistically assess whether the GeoMEC-designed system can operate reliably under real-time conditions, a more detailed operational model with a realistic representation of various technical constraints of system components is required. It is also necessary that the model has sufficiently detailed temporal and spatial resolution to ensure that the demand and supply are in equilibrium at every point in time.

In iDesignRES, the JRC-EU-TIMES model has therefore been extended and restructured into JRC-EU-TIMES-OP, an operational model designed to:

- Represent system operation at high temporal resolution (from 12 to 2016 time slices per year)
- Reflect NUTS2 spatial granularity for the test-case regions
- Incorporate technology-specific operational constraints
- Capture multi-vector interactions across electricity, gas, hydrogen, heat and fuel networks
- Include additional operational parameters and constraints for infrastructures (e.g., electricity grids, gas pipelines).

Therefore, the objective of JRC-EU-TIMES-OP is no longer long-term capacity optimisation quantifying new investment (or retirements) for long-term system transition, but short-term operational optimisation, ensuring demand-supply balance at high spatial and temporal resolution, reflecting on the system's operational reliability and adequacy at all relevant time periods. The model therefore provides a realistic assessment of system reliability and robustness – both under normal conditions and under the extreme conditions to be analysed in WP3 stress testing.

2.4.2 System Configuration and Data Alignment

In transitioning from the planning to operational domain, the fundamental structures and sectoral inter-dependencies of JRC-EU-TIMES are preserved as much as possible. However, the configuration and energy system structure of JRC-EU-TIMES-OP for a given analysis year are dynamically aligned with the outputs of the NUTS2-level geolocation model GeoMEC. The detailed energy system structure and future technological options in the JRC-EU-TIMES planning model provide the possibility of aggregating or disaggregating certain sectors, processes, and commodity groups to align JRC-EU-TIMES-OP with GeoMEC and even operate beyond GeoMEC's configuration when adequate data is available.

The following elements are imported directly from GeoMEC:

- Installed technology capacities of supply, conversion and storage technologies
- Annual activity levels of technologies and electricity, hydrogen, heat, fuel balances
- Final energy demands by sector and regions
- Regional definitions and NUTS2 geographical boundaries

Common parameters between models (e.g., efficiencies, cost, prices) are also aligned to ensure consistency. In addition, JRC-EU-TIMES-OP incorporates:

- Temporal energy demand profiles
- Resource availability profiles (wind, solar, hydro, etc.) that are aligned between the two models but aggregated for their different temporal definitions
- Network data (electricity transfer capacities, gas/hydrogen pipeline limits) where available
- Stress-test parameters derived from Task 2.5 and Deliverable D3.1

Table 7 summarises the data needed to create an instance of the JRC-EU-TIMES-OP model based on GeoMEC outputs and other data inputs. Various energy system data sets (e.g., supply and demand sector-related technoeconomic parameters, demand profiles) are collated as a part of the data task in WP1 and mapped to JRC-EU-TIMES-OP input parameters. A complete model instance of JRC-EU-TIMES-OP is dynamically created for a specific year through the GeoMEC & JRC-EU-TIMES-OP mapping procedure described in section 3. This enables the operational model to fully reflect the system configuration foreseen in the planning stage.

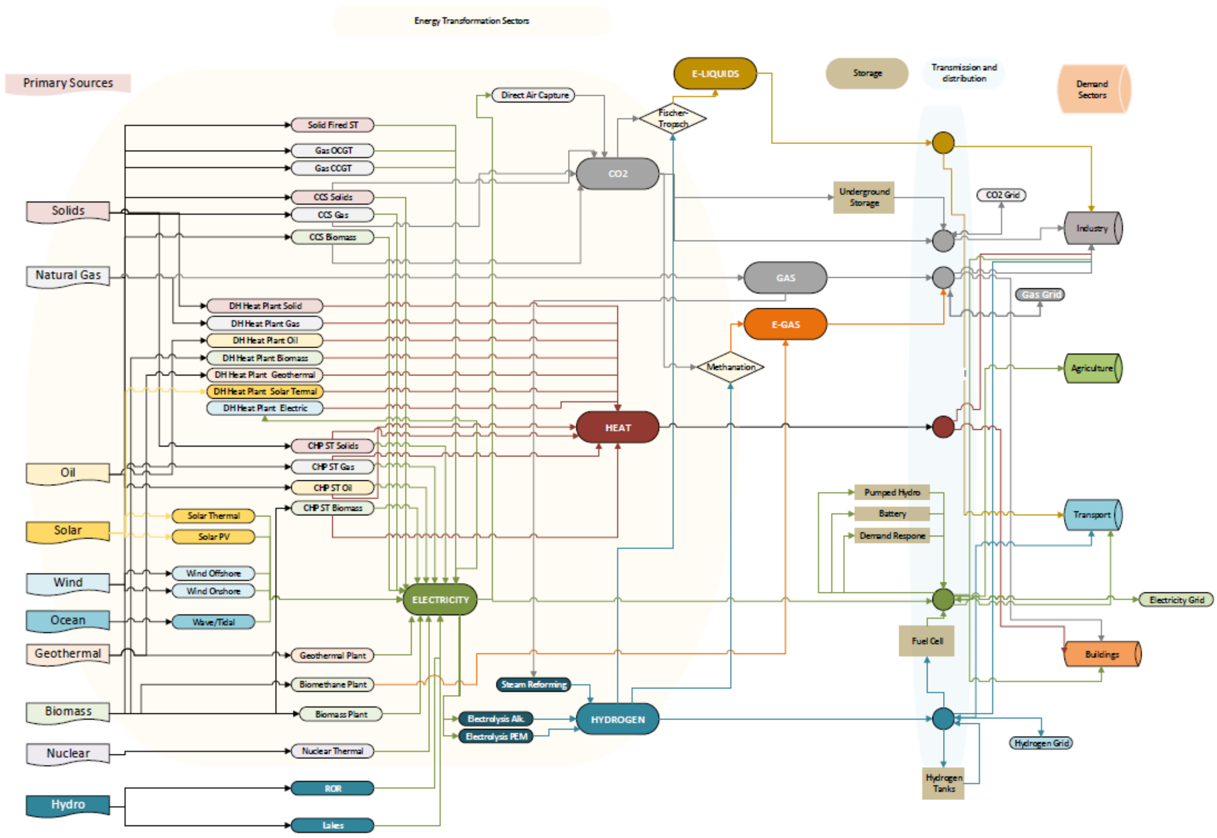

Figure 3: Reference Energy System of the GeoMEC model (source: Deliverable D2.3 of iDesignRES project)

Figure 3 outlines the Reference Energy System (RES) of the GeoMEC model, as described in detail in the Deliverable D2.3 report. GeoMEC considers various types of processes for electricity, heat, and hydrogen generation, including storage options for electricity, hydrogen and CO_2. Captured CO_2 can be utilised to produce e-gas and synthetic fuels via methanation of hydrogen and the Fischer-Tropsch process, respectively. It also has the representation of infrastructure technologies (electricity grid, pipelines, district heating network, etc.) for trading fuel and electricity between NUTS2 regions. GeoMEC works with representative technologies without distinguishing between existing and future options. JRC-EU-TIMES-OP reproduces the RES of GeoMEC for each model instance for a particular year. For this, the mapping of technologies between the models is crucial (described in Section 3). With a detailed database of technologies (existing and future) of the JRC-EU-TIMES model, the JRC-EU-TIMES-OP model can internally map GeoMEC's processes and commodities (in particular, the energy demands) to suitable ones used in the JRC-EU-TIMES framework, to ensure that JRC-EU-TIMES-OP fully represents the RES of GeoMEC. By "inheriting" the RES of GeoMEC via this interface, the JRC-EU-TIMES-OP model optimises the operation of the energy system configuration of GeoMEC, accounting for additional operational constraints at a higher spatial resolution.

2.4.2.1 Technology and commodity coverage in operational model

As stated above, the JRC-EU-TIMES-OP model retains the multi-carrier, multi-sector structure of the JRC-EU-TIMES and is instantiated using the specific technology portfolio and energy balances produced by GeoMEC for the selected year, scenario and case-study region(s). Operational simulations therefore cover the main energy vectors used in iDesignRES stress testing: electricity, gaseous fuels (natural gas, hydrogen, biogases, biomethane, and synthetic methane where relevant), heat (including district heating where represented), CO_2 flows where needed for e-fuel pathways, and relevant liquid fuels, biofuels and synfuels represented through the GeoMEC boundary conditions. On the supply and conversion side, the operational model can dispatch variable renewables (e.g., wind and solar profiles), dispatchable generators (e.g., thermal units and CHP where present in GeoMEC outputs), cross-vector converters (e.g., electrolysers, power-to-heat units, methanation where included), and storage technologies (e.g., batteries, hydro storage, gas/ hydrogen storage where represented) subject to time-coupled operational constraints.

It should be noted that D2.4 documents the operational representation rather than re-listing the full JRC-EU-TIMES database: the exact set of active technologies is dynamically generated from GeoMEC outputs and the mapping tables (Section 3), ensuring that each operational instance remains consistent with the planning solution it validates. Table 3 gives an overview of the technology groups represented in JRC-EU-TIMES-OP, as an illustrative example. These groups are inherited from the full JRC-EU-TIMES model and are activated according to the specific GeoMEC instance applied to each case study. In this regard, the list of technology groups, individual technologies and outputs shown in Table 3 should not be considered to be present in each case study in iDesignRES (as this depends on data availability and energy system representation from GeoMEC in each case study), but demonstrates the capability and logic of the model.

Table 3: Illustrative technology groups represented in JRC-EU-TIMES-OP (activated depending on case study and GeoMEC portfolio)

System component	Typica technology groups (examples)	Operational constraints/outputs produced
Electricity supply	Wind, solar PV, run-of-river/ hydro inflows (if available), thermal/ CHP units (if present), nuclear	Hourly dispatch, curtailment, scarcity, ramping (where activated), part load efficiency losses, minimum online/ offline times, provision of ancillary services, emissions, operating and ramping costs, maintenance schedules and duration
Cross-vector conversion	Electrolysers, methanation/ synfuel steps (where present), heat pumps/ e-boilers, CHP	Coupled balances, electricity-to-fuel/ heat constraints, utilisation, ramping and part-load efficiency (where activated), hourly dispatch
Storage	Batteries, pumped hydro/ hydro reservoirs (where present), hydrogen/ gas storage, thermal storage, CO_2 storage	SOC trajectories, cycling frequency, charging/discharging limits, hourly/ daily/ weekly/ monthly/ seasonal operation and dispatch, provision of ancillary services
Networks/ trade links	Electricity inter-node transfers (transport or PTDF), gas/ hydrogen/ CO2 pipelines (capacity/ flow bounds), truck or ship transport and distribution of fuels, district heating networks	Congestion, bottlenecks, binding constraints, physical limits and constraints, topology constraints, hourly/ weekly/ seasonal dispatch
Demand sectors	Fuel demands in buildings (by age or type of use), industry (by subsector), transport (by mode), Agriculture	Demand not served, peak contributions, load-shape sensitivity

2.4.3 Core Settings: Temporal, Spatial and Sectoral Resolution

A flexible structure has been implemented to allow JRC-EU-TIMES-OP to run at varying levels of temporal and spatial resolution, as well as at different levels of detail for the representation of the energy system sectors. Overall, JRC-EU-TIMES-OP considers a significantly higher temporal resolution than the JRC-EU-

TIMES model. To balance data unavailability and computational complexity, the model runs at varying levels of temporal resolution:

- Coarse resolution: 12 seasons/diurnal time slices that are compatible with planning workflows
- Intermediate resolution: 12 to 672 time slices selected to capture the basics of renewable variability and energy supply and demand imbalances
- High resolution: from 672 to 2016 intra-annual time slices, reflecting 3 consecutive weeks per season at an hourly level

High temporal granularity is essential for representing the variability of renewable energy sources, storage dynamics, ramping constraints and stress events such as cold spells or multi-day "*Dunkelflaute*". The TIMES framework uses cyclic, representative time slices rather than a fully chronological sequence. These slices (e.g., representative days or seasons) approximate demand and supply variability but are not temporally linked. As a result, the end conditions of one representative day do not define the initial conditions of another; each day is self-contained and forms a closed cycle. This structure applies across all time-slice levels (weekly, seasonal) and reflects TIMES' purpose as a long-term energy system planning model, not a fully chronological operational simulation with inter-temporal state continuity. In this regard, EnergyPLAN model which operates at full hourly resolution over a year will validate the results of JRC-EU-TIMES-OP. This validation will be undertaken by energyPLAN for the North Sea test case.

Regarding spatial resolution, JRC-EU-TIMES-OP is at a similar level to GeoMEC's NUTS2 structure for the case-study regions (e.g., the North Sea and Lombardy). However, the JRC-EU-TIMES-OP model is flexible and can aggregate a specific set of regions when needed for computational reasons or due to incomplete data availability, without altering the modelling logic.

Table 4: End-use sector and sub-sectoral details in the JRC-EU-TIMES planning model

<table>
<tr><th>Sector</th><th>Sub-sector</th><th>End-uses</th></tr>
<tr><td rowspan="7">Industry</td><td>Iron and Steel</td><td>Steel</td></tr>
<tr><td>Non-metallic minerals</td><td>Cement production
Lime production
Glass production (hollow, flat)
Other non-metallic minerals production</td></tr>
<tr><td>Chemical</td><td>Ammonia production
Chlorine production
Other production</td></tr>
<tr><td>Non-Ferrous metals</td><td>Aluminium production
Copper production
Other non-ferrous metals production</td></tr>
<tr><td>Pulp and paper</td><td>High-quality paper production
Low-quality paper production</td></tr>
<tr><td>Other industries</td><td>Machine drive
Process heat
Steam</td></tr>
<tr><td>Non-energy use</td><td>Non-energy demand</td></tr>
<tr><td>Agriculture</td><td>Agriculture</td><td>Agriculture, forestry and fishing</td></tr>
<tr><td>Residential</td><td>Apartment buildings
Detached houses
Semi-detached houses</td><td>Space heating, cooling
Water heating
Cooking
Lighting
Refrigeration and freezing
Dishwashing
Clothes washing, drying
Other electrical applications</td></tr>
<tr><td>Commercial</td><td>Hospitals
Hotels and restaurants
Sports and recreation facilities
large and small shops
Offices (Offices, Schools, Universities, Museums, etc.)
Streetlights</td><td>Space heating, cooling
Water heating
Cooking
Refrigeration and freezing
Lighting
Ventilation
ICT & multimedia
Other electrical applications</td></tr>
<tr><td rowspan="4">Transport</td><td>Road transport</td><td>Passenger: cars, motorcycles, mopeds, buses (urban and long-distance)
Freight: light duty trucks, heavy duty trucks</td></tr>
<tr><td>Rail transport</td><td>Passenger: Conventional trains, high speed trains, metro, trams
Freight: Rail freight</td></tr>
<tr><td>Navigation</td><td>Inland
Coastal</td></tr>
<tr><td>Aviation</td><td>Domestic
International</td></tr>
</table>

Unlike the original JRC-EU-TIMES planning model, which uses energy service demands, JRC-EU-TIMES-OP directly models fuel demands aligned with GeoMEC's structure. By aligning with GeoMEC, JRC-EU-TIMES-OP follows a similar sectoral/ sub-sectoral breakdown of the GeoMEC model for end-use demands. However, the JRC-EU-TIMES-OP model is flexible and supports finer sub-sector disaggregation (e.g., non-metallic minerals into cement, lime, glass, etc.) when sector-specific demand profiles or flexibility behaviours are required. This disaggregation for certain demand sectors goes beyond GeoMEC's consideration and requires suitable data to incorporate sub-sector-specific energy demand profiles, demand response, etc., depending on the analysis requirements (Table 4).

2.4.4 Technical Specifications and Model Features

JRC-EU-TIMES-OP retains the mathematical foundation of the TIMES framework while activating additional constraints to represent detailed operational behaviour. Key equation groups of TIMES include:

- Energy balance equations for all commodities at each time slice and region
- Technology activity constraints, linking inputs and outputs via efficiency coefficients or emissions factors
- Storage balance equations, representing state-of-charge, charging/ discharging efficiencies and reservoir inflows
- Renewable resource availability via time-slice specific availability factors
- Curtailment equations and variables allowing renewable reduction when network or flexibility resources are insufficient
- Import/ export constraints reflecting electricity and gas/ hydrogen interconnection limits
- Adequacy and reserve constraints, which can be activated for stress tests

The objective function minimises operating costs, including fuel costs, variable O&M costs, import expenditures or export revenues, and penalty terms for unserved demand or flexibility shortages. Short-lead-time investments, e.g., batteries or demand-side-management measures, can be endogenously deployed to mitigate GEOMEC-derived infeasibilities. The investment expenditures for these assets are also accounted for in the model's objective function.

In the TIMES framework, various modelling extensions, implemented as an elaborated set of equations, can be activated on request to represent integrated energy system operation in more detail. Some of the modelling extensions relevant for the iDesignRES project, which are present in the JRC-EU-TIMES-OP model, are as follows and are further elaborated in Table 5.

- Unit Commitment and Dispatch
- Electricity and Gas Grid modelling
- Ancillary Service Markets
- Residual load curves

Some of these operational constraints (e.g., unit commitment and ancillary services) are also considered by GeoMEC. However, due to limited temporal resolution, the constraints are represented in the planning model in a mainly stylised manner. Additionally, JRC-EU-TIMES-OP represents the operation of the energy infrastructures (transmission lines, gas, H_2, CO_2 pipelines) considering various physical properties. Gas flow in pipelines can be represented considering pressure drops between nodes, pipeline diameter, length, gas composition, density, temperature, and linepack (gas stored within the pipeline). Depending on computational complexity and data availability, different formulations (LP relaxation, MIP, Taylor approximations) are available; the most appropriate formulation will be selected for each test case, based on data availability and the scope of the analysis. The electricity transmission network can be represented using a DC power flow formulation, either in phase-angle or PTDF form. Simplified N-1 system security criteria can be applied to ensure system robustness. Additionally, JRC-EU-TIMES-OP can consider operational constraints (e.g., ramping rates) also for non-electricity generation technologies, such as Power-to-X technologies (e.g., electrolysers) or methanation and storage technologies, whose operational constraints are beyond the scope of GeoMEC. Therefore, these modelling extensions provide additional operational insights that are either absent or represented in a simplified way due to the inherent coarse temporal resolution in GeoMEC. However, the presence of operational constraints, such as unit commitment, already in the planning model facilitates the alignment of the planning and operational modes of the energy system, as it increases the likelihood of investments compatible with operational constraints and bottlenecks. Therefore, we can already achieve adequate capacity expansion from the planning model. This also facilitates the convergence of GeoMEC and JRC-EU-TIMES-OP and can reduce the number of feedback loops during validation.

Operational modelling extensions for JRC-EU-TIMES-OP can be activated as an add-on (as required) for a specific test case to support research questions as discussed in the Deliverable D3.1 based on data availability and computational complexity. The core TIMES modelling framework as well as the modelling extensions (variables, parameters, equations etc.) are highly documented in open and transparent way (https://iea-etsap.org/index.php/documentation). TIMES code containing all the modelling features is available openly at (https://github.com/etsap-TIMES/TIMES_model).

Table 5: Modelling features to support system operational assessment in the JRC-EU-TIMES-OP model

Feature	Description	Potential Use
Unit Commitment and Dispatch (Panos and Lehtilä, 2016)	Enhances the representation of dispatchable technologies (e.g., power plants, storage, electrolysers) by introducing minimum generation thresholds, ramp limits, start-up/shutdown costs, part-load efficiency losses, and other short-term operational and flexibility constraints. The formulation supports three types of detailing. The basic unit commitment option uses a linearised dispatching formulation with a minimum set of unit commitment parameters. Advanced unit commitment still adopts a linearised formulation with additional parameters for start-up types (cold, warm, and hot), start-up costs differentiated by start-up type, and partial-load efficiency losses during start-up and shut-down. The discrete unit commitment formulation provides flexibility to model individual 'virtual units'. Adoption of a specific formulation will depend on computational complexity and data availability for a given case study. Detailed documentation is available at TIMES_Dispatching_Documentation.pdf	This extension supports analysis of: • The impact of the resource variability introduced by large-scale renewable energy integration on system operation. • System adequacy and flexibility needs • Renewable energy curtailment and demand not served • Use of flexible resources and storage cycling
Electricity and Gas Grid Modelling (Lehtilä et al., 2025)	Electricity networks can be represented using DC Power Flow Modelling via phase-angle or power transfer distribution factor (PTDF) formulations aggregated at regional levels. Gas and hydrogen networks may be represented via Weymouth-based flow equations or simplified capacity limits. The former is also suitable for representing the physical and operational characteristics of gas transport infrastructures. Detailed documentation is available at TIMES_Documentation/User_Notes/TIMES-Grid-Features.pdf at master · etsap-TIMES/TIMES_Documentation · GitHub	This extension allows assessment of: • Infrastructural bottlenecks (electricity grids, gas pipelines (gas, hydrogen, CO_2) • Congestion patterns • Regional imbalances due to infrastructure constraints • Adequacy of infrastructure to deliver energy under normal and extreme conditions (stress-tests)
Ancillary Service Markets (Panos et al., 2019)	The model can represent ancillary service requirements (reserve margins, ramping products, primary, secondary and tertiary reserve) through constraints that ensure sufficient upward and downward flexibility. Not only the demand but also the provision of the different reserve types via technology (but not the activation) are endogenously modelled via market-based mechanisms. This improves the realism of system operation under high variable renewable energy penetration.	By modelling the ancillary services markets, the model can support analyses regarding: • Better representation of the system cost of integrating variable renewable sources • Evaluation of system adequacy, flexibility

Feature	Description	Potential Use
	Detailed documentation is available at https://iea-etsap.org/projects/TIMES-BS-Documentation.pdf	
Residual Load curve (Lehtilä et al., 2014)	By modelling the residual load curve, minimum thermal generation constraints and storage/ peak capacity requirements are represented in the framework. This improves the representation of the impact of the non-dispatchable electricity generation options in system operation. Detailed documentation available at: TIMES-RLDC-Documentation.pdf	This feature of the model is suitable for: • Evaluating the impacts of the integration of large amounts of variable renewable generation on the electricity system • Use of flexible resources (e.g., dispatchable power plants and storage) • Evaluating system adequacy issues.

With the above features derived from extensions of the TIMES modelling framework, the JRC-EU-TIMES-OP transforms the long-term planning structure of JRC-EU-TIMES into a high-resolution, sector-coupled operational model designed for the needs of iDesignRES. With flexible temporal and spatial granularity, detailed operational constraints and a robust interface with GeoMEC, the model provides the analytical foundation for evaluating real-time system operation, identifying operational bottlenecks and supporting stress-test analysis in WP3 and subsequent work packages.

3. Model and Data Linking

A central requirement of WP2 in iDesignRES is to establish a transparent, reproducible and robust workflow for linking the GeoMEC planning model to the JRC-EU-TIMES-OP operational model. Ensuring proper data alignment, consistent definitions and interoperable interfaces between the two tools is therefore essential for producing integrated, cross-model assessments for the case study regions. In addition, the linking framework must ensure that differences in results arise solely from operational constraints embodied in JRC-EU-TIMES-OP, and not from inconsistent data structures or mismatched assumptions between the models. This section describes: i) the conceptual approach for linking, ii) the data and metadata exchanged between the models, iii) the mapping logic used to construct operational model instances, and iv) the harmonisation procedures and interface routines that enable full interoperability across tools and work packages.

3.1 Linking Logic

For answering research questions pertaining to the test cases, the JRC-EU-TIMES-OP system operational model relies on the GeoMEC geolocation planning model for providing the corresponding system configuration (sectoral coverage, technologies, commodities) at the NUTS2 level. Hence, the linking framework follows a planning → operational workflow:

1. GeoMEC produces long-term system configurations for a selected region, year and scenario. The model provides installed capacity, fuel supply structures, energy flows, and activities of technologies for energy supply, conversion, storage, and trades.
2. These outputs are transferred into JRC-EU-TIMES-OP, where they define the static infrastructure against which detailed operational balancing is performed. End-use demands and energy supply (considering losses) balance is ensured for each NUTS2 region and time slices. Additionally, the activity of technologies from GeoMEC (e.g., electricity generation, CO_2 emissions, trade) is provided as boundary conditions (upper limits) to the JRC-EU-TIMES-OP to align with GeoMEC results and reduce the need for multiple feedback loops. For each NUTS2 region, sectoral annual energy demands are also aligned with GeoMEC to ensure the energy supply (considering losses) balance is met for each NUTS2 region and time slices. Demand profiles pertaining to the time slices are derived from the same hourly profiles that GeoMEC uses to calculate intra-annual load

curves. Common techno-economic data and resource profiles for both models are also harmonized.

3. Based on the mapping, capacities are provided exogenously to JRC-EU-TIMES-OP for the corresponding processes and any new investment into these processes is restricted. To address operational infeasibilities, JRC-EU-TIMES-OP allows investment in a set of technological options (e.g., batteries) with lead times of less than 1 year (see Section 5).
4. The operational model evaluates feasibility, calculates operational indicators (demand not served, curtailment, storage cycling, bottlenecks, etc.) and identifies critical reliability or adequacy issues. These indicators form the core of the operational validation strategy introduced in Deliverable D3.1 and enable systematic cross-case comparison.
5. Operational insights inform WP3 stress testing, and where appropriate, are fed back to planning exercises in a controlled manner to avoid iterative convergence issues.

To avoid oscillatory behaviour between planning and operation, the linking logic does not include a fully bidirectional GeoMEC ↔ JRC-EU-TIMES-OP iteration loop; instead, limited feedback is applied only when operational infeasibilities clearly signal the need for structural adjustments. This one-directional but feedback-aware linkage ensures methodological consistency while preventing oscillatory behaviour between the two models. It also ensures that deviations between planning and operational results can be traced to genuine operational constraints (e.g., hourly variability, network limits, fuel coupling) rather than inconsistencies in model inputs. Hence, to support transparency and reproducibility, the linking logic explicitly avoids iterative optimisation loops and instead relies on controlled, unidirectional data flows and harmonisation checks (Section 3.4), consistent with best practices in integrated assessment modelling.

3.2 Data Exchange Workflow

The exchange of data between GeoMEC and JRC-EU-TIMES-OP requires both quantitative inputs and structural metadata to ensure that the operational model faithfully reflects the system configuration produced by the planning model. The workflow is organised around five tightly connected data domains: system configuration, temporal and profile data, infrastructure information, modelling metadata, and feedback.

System configuration

The system configuration provided by GeoMEC defines the structural backbone of each operational model instance. It includes the installed capacities of all supply, conversion, storage and network technologies, together with the commissioning or retirement years where applicable. These capacities are provided with full NUTS2 regional disaggregation so that the JRC-EU-TIMES-OP model inherits the same geographic representation as GeoMEC. Annual energy flows from the planning solution—such as fuel demands in industry, buildings and transport, and annual production from power plants, CHP units, boilers, electrolysers and other conversion technologies—are also transferred. To ensure consistency across the modelling chain, wholesale fuel prices, emission factors, technology efficiencies and availability factors are mapped directly from GeoMEC. All these parameters are extracted automatically from GeoMEC outputs using the mapping procedures described in Section 3.3. Additionally, commissioning/ retirement logic and GeoMEC trade-flow boundaries are transferred to ensure that JRC-EU-TIMES-OP respects the same structural constraints and regional import/ export limits.

Temporal and profile data

A second major input category concerns the temporal and profile data required to transform annual values from GeoMEC into time-resolved operational trajectories. For each region and sector, the JRC-EU-TIMES-OP model integrates hourly or sub-hourly demand profiles from WP1, together with renewable resource profiles for wind, solar and hydro inflows. To ensure consistent information exchange between both models, values pertaining to corresponding time slices will be derived from higher resolution time series. When stress tests require them, additional time series such as price signals or temperature-driven adjustments can be incorporated. Where direct data are unavailable, synthetic or proxy profiles are generated using established profile-shaping routines to reproduce realistic variability while ensuring consistency with GeoMEC aggregates. In cases where full time series cannot be provided, duration curves for electricity or heat can be used as an intermediate representation.

Infrastructure and network data

The third domain is infrastructure and network data, which enables the operational model to capture bottlenecks and regional transfer limitations that GeoMEC cannot fully resolve. JRC-EU-TIMES-OP is flexible in how it represents trade flows at various levels of detail, depending on data availability for a given test case. By default, it can represent the commodity flow using a simple transport model. However, detailed physical properties of the transmission lines and pipelines can also be considered, as outlined in Table 5.

Electricity transmission capacities and PTDF matrices at the NUTS2 level can be considered, allowing flows between aggregated nodes to be represented through simplified DC power-flow constraints. This ensures that regional power exchanges reflect actual network physics approximations and allows detection of congestion patterns invisible to GeoMEC. Similarly, gas, hydrogen and CO_2 network data—including pipeline capacities, transport efficiencies and maximum flow limits—are incorporated to reflect sector-coupled interactions and their spatial constraints. Regional import and export limits are aligned with the boundary conditions embedded in the GeoMEC solution to ensure that the operational model respects the same geographical and market interfaces.

Modelling metadata

Modelling metadata ensures conceptual and numerical consistency between the two tools. This includes harmonised technology nomenclature, commodity names and energy units; consistent definitions for regional sets and NUTS2 groupings; and alignment of TIMES parameter conventions such as efficiency coefficients, availability factors and heating values. IAMC-aligned naming conventions are applied wherever possible to support transparency and cross-model interpretability. These metadata guarantee that GeoMEC and JRC-EU-TIMES-OP refer to the same system components even when their internal structures differ, thereby safeguarding consistency across the entire iDesignRES workflow.

Modeling feedback

Operational insights from the JRC-EU-TIMES-OP model will be fed back to the GeoMEC model, depending on a specific requirement of a research question for a test case. This is to address any operational infeasibility identified by JRC-EU-TIMES-OP with the system configuration provided by GeoMEC and needs recalculation of system portfolio. Operational insights for technologies, including trade infrastructures, are provided to GeoMEC using IAMC variables, which lead GeoMEC to internally modify or add constraints to respect the operational information and to reflect them in planning. By this process GeoMEC attempts to calculate a new system configuration. At each iteration step various system operational indicators are checked and a solution from GeoMEC is accepted when the indicators are within acceptable thresholds. This is further elaborated in Section 5.

3.2.1 Interface Control: Responsibilities, minimum dataset and change management

To ensure that the GeoMEC → JRC-EU-TIMES-OP workflow is reproducible across partners and case studies, we maintain an interface control approach covering (i) responsibility assignment, (ii) a minimum required dataset for each operational run, and (iii) versioning of mapping tables and scripts. This is particularly important because GeoMEC and WP1/ WP3 datasets are evolving in parallel; operational results could be driven by inconsistent inputs rather than true operational constraints.

For each operational instance, the minimum required inputs consist of:

a. The GeoMEC system configuration for the selected year and scenario (installed capacities by region, sectoral annual demands, and key boundary flows)
b. Temporal profiles of demand and renewables consistent with those annual totals and year or scenario specifications.
c. Infrastructure limits (at least transport-style link capacities, with optional PTDF/ pipeline physics where data are available)

Table 6 shows the minimum interface responsibilities by partner or WP required to achieve the coupling.

Table 6: Interface responsibilities for model linking and data coupling

Data / artefact	Provider (WP / partner)	Consumed by (WP / partner)	Frequency / trigger
GeoMEC outputs (capacities, annual demands, annual activities, trade bounds)	GeoMEC team (WP2)	JRC-EU-TIMES-OP	Per scenario/ year/ case study
Demand & RES profiles (hourly/ sub-hourly or representative weeks)	WP1 data teams	JRC-EU-TIMES-OP and GeoMEC (as applicable)	Per case study, updated as datasets mature
Mapping tables (process/ commodity/ parameter/ region)	GeoMEC and JRC-EU-TIMES-OP linking team (WP2)	R-scripts + JRC-EU-TIMES-OP input data builder	Updated when GeoMEC structure changes
R-script / automation pipeline	WP2 (PSI/ other teams as applicable)	Builds JRC-EU-TIMES-OP instances	Updated when interface changes
Stress-test parameter sets and switches	WP3	JRC-EU-TIMES-OP	Per the stress-test definition set

In case of data unavailability at the required resolution, proxy method is used (e.g., synthetic profile generation). Table 7 presents the minimum requirements for each input block and acceptable proxies if the required input is missing.

Table 7: Minimum required inputs and acceptable proxy for a runnable operational instance

Data / artefact	Minimum requirement	Acceptable proxy if missing
Capacities	Installed capacity by NUTS2 and technology group	Aggregated regions; technology aggregation
Annual demands	Sectoral annual fuel demands by NUTS2	Downscaling from higher geography
Temporal profiles	Hourly or representative week load and RES profiles	Synthetic profiles scaled to annual totals
Infrastructure	Link capacities (electricity, gas, hydrogen, CO_2 as relevant)	Transport model bounds and efficiency
Import prices, emissions factors and efficiencies	Consistent techno-economic parameters	Defaults aligned to GeoMEC

3.2.2 Reproducibility and Run Metadata

Versioning and updates are also important components of the interface control and management. Each JRC-EU-TIMES-OP operational run performed within iDesignRES is associated with a clearly defined set of metadata that enables full reproducibility and traceability (Table 8). For every run, the project records the GeoMEC scenario identifier and year, the version of mapping tables and automated exchange scripts used, the temporal profile dataset applied, and the stress-test switches or parameter modifications activated. Solver settings and convergence diagnostics are also retained.

Table 8: Operational run metadata recorded

Metadata item	Purpose
GeoMEC scenario and year	Planning baseline reference
Mapping table version	Structural consistency
Temporal profile dataset	Demand/ RES traceability
Stress-test model modifications set	Scenario transparency
Solver & convergence info	Numerical robustness

This metadata framework ensures that operational results can be reproduced by consortium partners, audited if required by the European Commission, and consistently compared across case studies and stress-test categories. The Scenario Explorer platform of iDesignRES ([Explorer | iDesignRES | Project-internal Scenario Explorer]) will facilitate in this regard for version control and metadata management of data points (both inputs and outputs).

3.3 Mapping of Variables and Parameters between GeoMEC and JRC-EU-TIMES-OP

A central component of the linking workflow is the mapping procedure, which establishes a consistent correspondence between the structural elements of GeoMEC and those of the JRC-EU-TIMES-OP model. Since both tools represent complex energy systems using different internal data structures, nomenclatures and levels of detail, a harmonised mapping is required to ensure that the operational model reproduces the system configuration defined by the planning model without ambiguity. This mapping constitutes the formal interface specification for WP2 and WP3 and is essential for constructing fully interoperable model instances.

Given that the JRC-EU-TIMES-OP model derives from JRC-EU-TIMES, the process begins with a system alignment of technologies, in which GeoMEC's aggregated technology categories are mapped one-to-one or one-to-many to JRC-EU-TIMES process definitions (Figure 4). One-to-one mapping makes information exchange between models easier. However, for specific cases (e.g., discrete unit commitment), the JRC-EU-TIMES-OP model can consider multiple 'synthetic' units, enabling one-to-many mapping. This step ensures that the operational model inherits the appropriate conversion characteristics, efficiencies, fuel inputs, and operational modes associated with each technology. Likewise, all energy commodities, including electricity, gas, hydrogen, heat, CO_2, biomass, liquid fuels and synthetic fuels, are harmonised using the JRC-EU-TIMES commodity taxonomy. This harmonisation ensures that energy flows defined in GeoMEC are translated transparently into the multi-vector operational environment.

A second layer of the mapping addresses key model parameters, such as technology efficiencies, cost parameters, availability factors and emissions coefficients (Figure 6). These must be transferred consistently because otherwise they can lead to artificial discrepancies in system behaviour. The mapping also includes regional structures, in which GeoMEC's spatial definitions are directly translated into NUTS2 regions in JRC-EU-TIMES-OP, ensuring perfect geographic alignment. Similarly, final demand categories from GeoMEC – such as industry, buildings, transport and other sectors – are translated into JRC-EU-TIMES-OP demand commodities so that temporal load profiles and fuel trajectories can be applied accurately (Figure 5).

The mapping procedure is further strengthened by applying the IAMC common definitions, which were used as an initial reference point for aligning the two models. Each IAMC variable was examined and mapped to existing or planned input and output variables of GeneSys-MOD, GeoMEC and JRC-EU-TIMES-OP. However, the IAMC variable list was found to be insufficient for several categories critical to energy-system operation – such as storage dynamics, electrolysers, fuel trade links and multi-vector infrastructures. To address these gaps, the modelling teams in WP2 jointly proposed an extended set of variables and metadata fields tailored to the needs of sector-coupled operational modelling.

Using this expanded IAMC-consistent structure, every GeoMEC process, commodity and relevant output variable is explicitly linked to the corresponding element in JRC-EU-TIMES-OP. This ensures that all necessary information, capacities, demands, commodity flows, and technology characteristics are transferred accurately to support the dynamic generation of operational model instances. The resulting mapping provides a robust and flexible foundation for constructing operational scenarios, validating system flexibility and implementing the stress-test cases developed in WP3.

GeoMec_Name	GeoMec_Description	IAMC_Common_Definitions	JRC-EU-TIMES-OP_Name	JRC-EU-TIMES-OP_Description
Solids_Plant	Solid-fired ST	Electricity|Coal|w/o CCS	EEPP_coal_thermal	Existing Electricity plant - coal_thermal
Gas_CCGT	Gas Plant CCGT	Electricity|Gas|CCGT|w/o CCS	EEPP_naturalgas_CCGT	Existing Electricity plant - naturalgas_CCGT
Gas_OCGT	Gas OCGT	Electricity|Gas|OCGT|w/o CCS	EEPP_naturalgas_OCGT	Existing Electricity plant - naturalgas_OCGT
CCS_Solids	CCS Solids	Electricity|Coal|w/ CCS	EUPCCOHCCSpos20	Supercritical pulverised coal + CCS Seq post combustion
CCS_Gas	CCS Gas	Electricity|Gas|w/ CCS	EUCCGASCCSpos20	CCGT Combined Cycle Gas Turbine + CCS Seq post combustion
CCS_Bio	CCS Biomass	Electricity|Biomass|w/ CCS	EUIGCCWOOCCS01	Biomass Integrated Gasification CC + CCS Seq post combustion
DH_Gas	DH heat plant gas	Heat|Gas	HHTHGAS001	District Heating. Heat.GAS. New
DH_Solids	DH heat plant solids	Heat|Coal	HHTHCOH001	District Heating. Heat.COA. New
DH_Oil	DH heat plant oil	Heat|Oil	HHTHHFO001	District Heating. Heat.OIL. New
DH_Bio	DH heat plant biomas	Heat|Biomass	HHTHBIO001	District Heating. Heat.BIO. New
DH_Geo	DH heat plant geother	Heat|Geothermal	HHTHGEO001	District Heating. Heat.GEO. New
DH_Elec	DH heat plant electric	Heat|Electricity	HHTHELC001	District Heating. Heat.Electricity. New

Figure 4: Screenshot of mapping GeoMEC's processes with JRC-EU-TIMES-OP in Excel

GEOMEC Commodity	GEOMEC Commodity Description	IIASA Final Energy	JRC Commodity	JRC Commodity Description
IndGas	Industrial demand flow of Gas	Final Energy|Industry|Gases|Gas	INDGAS	Natural Gas (IND)
IndH2	Industrial demand flow of hydrogen	Final Energy|Industry|Hydrogen	INDHH2	Hydrogen (IND)
IndHeat	Industrial demand flow of heat	Final Energy|Industry|Heat	INDHTH	High Temperature Heat for IND
IndElec	Industrial demand flow of electricit	Final Energy|Industry|Electricity	INDELC	Electricity (IND)
BuildGas	Buildings demand of gas	Final Energy|Residential and Commercial|Heat|Gas	RSDGAS, COMGAS	Natural Gas (RSD), Natural Gas (COM)
BuildHeat	Buildings demand of heat	Final Energy|Residential and Commercial|Heat	RSDHET, COMHET	Derived heat (RSD), Derived heat (COM)
BuildElec	Buildings demand of electricity	Final Energy|Residential and Commercial|Electricit	RSDELC, COMELC	Electricity (RSD), Electricity (COM)
AgriElec	Agricultural demand of electricity	Final Energy|Agriculture|Electricity	AGRELC	AGR Fuel - Electricity
TransELiq	Transport demand of e-liquids	Final Energy|Transportation|Liquids|Hydrogen	TRALH2	Hydrogen - Liquid (TRA)
TransElec	Transport demand of electricity	Final Energy|Transportation|Electricity	TRAELC	Electricity (TRA)

Figure 5: Screenshot of mapping GeoMEC's demand commodities with JRC-EU-TIMES-OP in Excel

IAMC_Variable	description	Unit	GeoMEC	JRC-EU-TIMES-OP	JRC-EU-TIMES-OP Attribute
Efficiency|Electricity|Biomass|w/ CCS	Conversion efficiency per unit of p	%	Input	Input	ACT_EFF
Efficiency|Electricity|Biomass|w/o CCS	Conversion efficiency per unit of p	%	Input	Input	ACT_EFF
Efficiency|Electricity|Coal|w/ CCS	Conversion efficiency per unit of p	%	Input	Input	ACT_EFF
Efficiency|Electricity|Coal|w/o CCS	Conversion efficiency per unit of p	%	Input	Input	ACT_EFF
Secondary Energy|Heat|Biomass	Net heat generation	EJ/yr	Output	Input	ACT_BND
Secondary Energy|Heat|Coal	Production of centralized heat fro	EJ/yr	Output	Input	ACT_BND
Secondary Energy|Heat|Coal	Net heat generation	EJ/yr	Output	Input	ACT_BND
Secondary Energy|Heat|Coal|Hard coal	Net heat generation	EJ/yr	Output	Input	ACT_BND
Secondary Energy|Heat|Coal|Hard coal|	Net heat generation	EJ/yr	Output	Input	ACT_BND
Capacity|Electricity	Total installed (available) electrici	GW	Output	Input	NCAP_PASTI
Capacity|Electricity|Biomass	Installed (available) capacity to ge	GW	Output	Input	NCAP_PASTI
Capacity|Electricity|Biomass|w/ CCS	Installed (available) capacity to ge	GW	Output	Input	NCAP_PASTI
Capacity|Electricity|Biomass|w/o CCS	Installed (available) capacity to ge	GW	Output	Input	NCAP_PASTI
Capacity|Electricity|Coal	Installed (available) capacity to ge	GW	Output	Input	NCAP_PASTI

Figure 6: Screenshot of mapping IAMC variables to GeoMEC and JRC-EU-TIMES-OP's input/ outputs in Excel

3.4 Construction, Exchanging Parameters and Validation of Operational Model Instances

The construction of a JRC-EU-TIMES-OP model instance relies on the automated exchange of parameters between GeoMEC and the operational model, supported by a robust mapping framework and harmonised data structures. Figure 7 outlines the procedure of generating a model instance of JRC-EU-TIMES based on minimum data inputs as identified in the Table 7. To test the automated input data generation for JRC-EU-TIMES-OP, a script in R has been developed to facilitate transferring the GeoMEC outputs and other parameters to the JRC-EU-TIMES-OP inputs based on the process, commodity, and data mapping tables. The script implements both extraction and transformation steps, converting GeoMEC structures into TIMES parameter sets and ensuring unit, naming and structural consistency. As the GeoMEC model is under development in parallel, the mapping exercise will continue to ensure that both models remain perfectly aligned for application in the test cases. This may lead to changes in the current process and commodity mapping with the addition or removal of new or existing ones. The model instance generation procedure will be further expanded in this regard to include other datasets identified and developed as part of WP1 and WP3 for test cases. This automated interface ensures that the operational model inherits the exact system configuration produced by GeoMEC, while allowing the workflow to remain flexible as data availability improves.

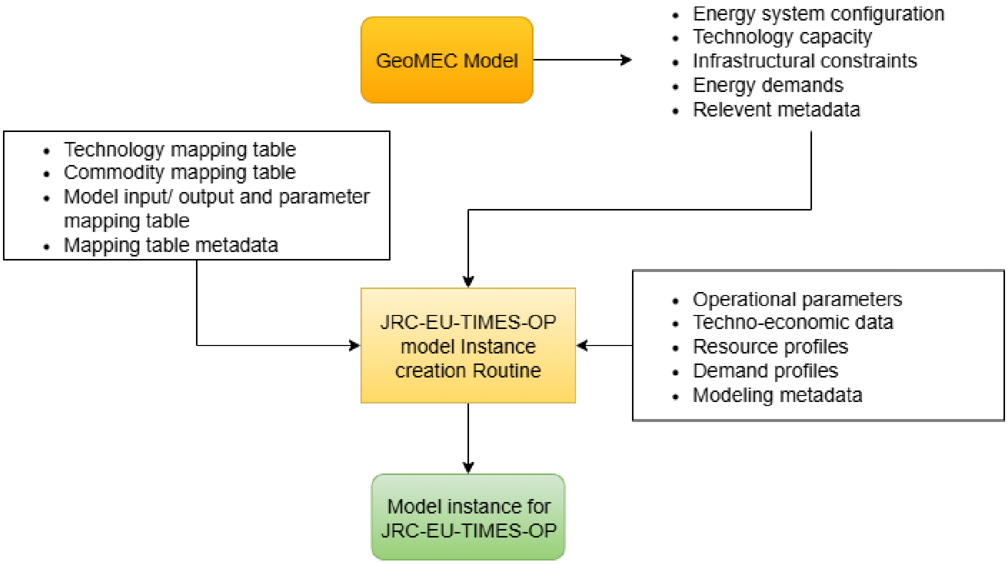

Figure 7: Diagram outlining the linking and model instance generation process

Based on the mapped data, JRC-EU-TIMES-OP constructs a complete operational model instance for the selected analysis year. This step includes generating the TIMES technology set from GeoMEC capacities, constructing commodity balances, embedding synthetic or WP1 resource profiles, applying network constraints, and activating stress-test switches that reflect WP3 requirements. Scenario switches and stress-test parameters defined in WP3 are applied to enable the model instance to simulate the specific operational conditions and disturbances required by the case-study analyses. The result is a self-contained TIMES-based operational model that can be solved directly to assess system feasibility, flexibility, and adequacy.

To ensure coherence between GeoMEC and JRC-EU-TIMES-OP, several harmonisation and consistency checks will be performed during instance construction. Energy balance validation verifies that annual generation, consumption and sectoral fuels match the GeoMEC totals after temporal disaggregation. Installed capacities in the operational model are checked to ensure they reflect GeoMEC's design exactly, without unintended expansions or retirements. Temporal profiles are normalised so that their annual sums correspond to GeoMEC's aggregated values, thereby avoiding distortions in renewable availability or demand patterns. Geographic consistency across WP1, GeoMEC and the operational model is ensured through alignment of NUTS2 regional definitions. Finally, key modelling parameters—such as technology efficiencies, emission factors and variable O&M costs—are harmonised so that any divergences in operational outcomes arise from actual system constraints rather than inconsistent assumptions.

Through this combination of automated data transfer, dynamic model instance creation and rigorous validation, the JRC-EU-TIMES-OP framework provides a reliable and fully aligned operational representation of the GEOMEC-designed energy system. This ensures that subsequent feasibility assessment and stress-test simulations accurately reflect the real operational behaviour of the long-term transition pathways evaluated in iDesignRES.

4. Model Testing with a Prototype

4.1 Prototype model development

The TIMES modelling framework is highly adaptable with respect to input data, assumptions, and model resolution. Consequently, the structure and level of detail of a JRC-EU-TIMES-OP model instance depend on data availability and the specific case study being considered. In practice, TIMES users depend on dedicated data-handling tools to manage the large datasets required by TIMES and to interface with the core model code. For JRC-EU-TIMES and JRC-EU-TIMES-OP, this role is fulfilled by VEDA2, a comprehensive and user-friendly suite of tools for creating, maintaining, browsing, and modifying model input data. VEDA accepts input from various Excel files with flexible, rule-based structures that are well-suited to large, data-intensive, multi-regional energy system models. Based on these inputs, VEDA automatically generates the complete set of files required by the TIMES code. It creates a fully specified model instance formulated in the GAMS algebraic modelling environment. Model compilation and execution are performed by GAMS using an appropriate solver. After model execution, TIMES produces text-based output that is read back into VEDA for post-processing (Figure 8). VEDA offers a structured exploration of results and produces numerical, tabular, and graphical outputs (primarily in Excel), supporting transparent analysis and reporting.

While VEDA2 has been used for rapid prototype development of the JRC-EU-TIMES-OP, it should be acknowledged that it is a commercial tool. Since the JRC-EU-TIMES-OP is being developed as an open-source model, the VEDA2 software will be dropped and replaced by open-source alternatives the IEA-ETSAP community is exploring and currently developing: TIMES/ MIRO[4] and XL2TIMES[5] are two open-source TIMES interfaces that retain the same flexibility and logic as VEDA2. These will be made available to iDesignRES too, since the JRC-EU-TIMES-OP, as part of the iDesignRES modelling framework, will eventually be hosted and solved in the cloud under WP4.

[4] GAMS-dev/TIMES_MIRO: MIRO app for the IEA-ETSAP TIMES model

[5] etsap-TIMES/xl2times: Open source tool to convert TIMES models specified in Excel

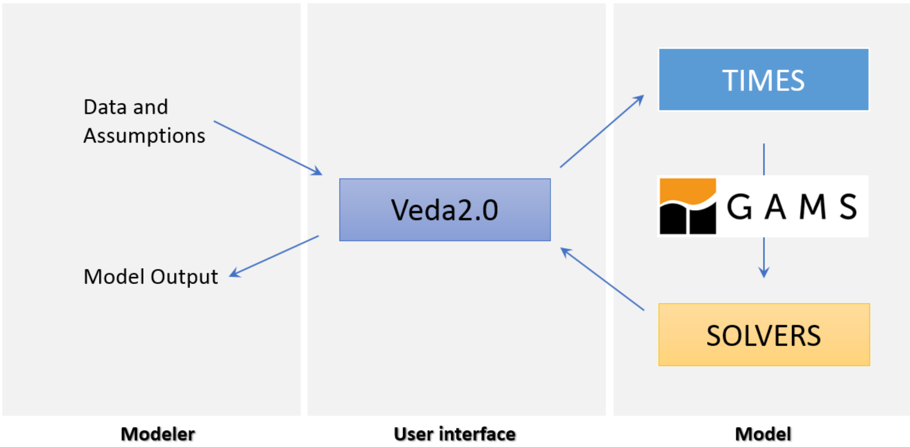

Figure 8: Model development and execution using the TIMES modelling framework[6]

As indicated earlier, the JRC-EU-TIMES-OP model configuration is dependent on GEOMEC's output for a particular year. However, both models undergo development, testing, and mapping in parallel. Therefore, GEOMEC's output is not readily available for model development and testing for JRC-EU-TIMES-OP at the NUTS2 regional level. So, it was decided to use the existing data and model outputs from the JRC-EU-TIMES planning model for 2019 to develop the prototype and test the functionality of JRC-EU-TIMES-OP at higher spatial and temporal resolutions. We consider the current 30 regions in JRC-EU-TIMES (which represent single-node European countries) as a proxy for a version of the JRC-EU-TIMES-OP with 30 NUTS2 regions and test the model's ability to operate at various intra-annual temporal resolutions (12 to 2016 intra-annual time slices).

As GEOMEC's energy demand is limited to final energy consumption (fuels), the first step was to extract fuel demands for various end-use sectors and subsectors from the outputs of the JRC-EU-TIMES model. The fuel demands, which were endogenously determined by the JRC-EU-TIMES model, are now exogenously provided to JRC-EU-TIMES-OP. Energy service demands and all end-use processes of various sectors are deactivated. It should be noted that JRC-EU-TIMES-OP is flexible and can represent end-use demand at various aggregated/ disaggregated levels, depending on GEOMEC's final choice of sub-sectoral breakups. However, due to data unavailability during the testing period, synthetic datasets are generated and used to represent the profiles of fuel consumption and renewable generation pertaining to the time slices. Still, these will be further updated with the datasets being identified and collected in the data task in WP1.

A highly flexible time-slice structure has been introduced into JRC-EU-TIMES-OP to enable its use as an operational stress-testing model for the case-study regions. A new and adaptable time-slice tree has been implemented, allowing the model to achieve detailed temporal granularity while retaining comprehensive supply- and demand-side representation and multi-regional dimensions. This flexible time-slice structure allows the model to operate at various intra-annual temporal resolutions, which is useful for addressing specific data availability issues in a test-case region. As mentioned in Section 2, the primary purpose of incorporating high temporal detail is to assess operational constraints associated with predefined investment decisions from GEOMEC, providing insights into various system operational indicators such as unserved demand (electricity, hydrogen, heat) and potential infrastructure bottlenecks.

[6] Veda 2.0 documentation

In the operational model, the temporal dimension involves multiple levels of tracking. The TIMES framework tracks each energy carrier at the given time-slice level; in other words, a commodity balance equation is generated for every commodity in every time slice. Each of these balance equations also generates a dual value that reflects the commodity's marginal cost at that time-slice level.

The required temporal resolution depends on the technologies, commodities, and research questions under consideration for a test region. For instance, assessing gas network performance during peak hours or ensuring sufficient electricity supply capacity during peak demand requires a finer temporal resolution. Temporal detail spans primary energy carriers (e.g., solar and wind resource variability), the energy conversion sector (e.g., electricity or hydrogen production), and end-use sectors (e.g., electric vehicle charging patterns or heat pump operation). The choice of time slices is driven not only by the research objectives for a test-case but also by the corresponding data availability (Table 7 and Table 9) for the test regions and the number of commodities that must be tracked across the time slices. These data needs have been identified, and the corresponding data are being collected and documented as a part of WP1. Further in the Deliverable D3.1, data needs specific to answering various research questions by JRC-EU-TIMES-OP have been highlighted, which will be further mapped to the actual data availability from the stakeholders in the test regions. The TIMES framework allows user-defined tracking of commodities: for example, commodities requiring challenging or short-term storage (e.g., electricity or hydrogen) necessitate high temporal resolution, whereas easily storable commodities (e.g., oil) can be represented using coarser time slices. The prototype model currently considers system operational features of the JRC-EU-TIMES-OP model's operational features e.g., DC load flow for electricity transmission. However, other operational features, as identified in Table 5 are parametrised to accept input and activate as needed for the test cases.

Table 9: Input dataset needed for JRC-EU-TIMES-OP at a high spatio-temporal resolution

Data description	Provider	Temporal Dimension	Spatial Dimension
Renewable Generation profiles	Solar, wind, hydro, ocean. From WP1	Hourly for a representative year	NUTS2
Demand profiles by fuel and sector	Depends on GEOMEC's sub-sectoral breakup. From WP1	Hourly for a representative year	NUTS2
Technology capacity investments (and vintage if available)	From GEOMEC's output	Annual for the corresponding year	NUTS2
Energy system configuration	Reference energy system topology of GEOMEC for a particular year, i.e., technologies and energy flows considered, together with their trade links	Annual for the corresponding year	NUTS2
Boundary conditions on technology activity, i.e., upper and low bounds on technology output or input	From GEOMEC's results output	Annual or sub-annual (e.g., seasonal), depending on technology and scope of analysis	NUTS2
Technology operational parameters, such as technical parameters for dispatchable resources, transmission grids, and pipelines.	Aligned with GEOMEC's input; from WP1, WP3, WP5 (generic and specific to test cases)	Annual for the corresponding year	NUTS2

Other techno-economic parameters (e.g., technology efficiency, fuel prices, emission factors)	Aligned with GEOMEC's input; from WP1, WP3, WP5 (generic and specific to test cases)	Annual or sub-annual, depending on technology, parameter and scope of analysis	NUTS2

4.2 Modelling insights from the prototype JRC-EU-TIMES-OP

As a proof of concept, the prototype version of the JRC-EU-TIMES-OP model has been tested using four sets of intra-annual time-slice configurations (Table 10). These configurations range from three diurnal time slices per season to representations of one and three weeks per season at hourly resolution. This corresponds to 12, 288, 672, and 2016 time slices per year, respectively. To test the functionality of the JRC-EU-TIME-OP model, hourly demand profiles were introduced for a small subset of commodities on both the supply and demand sides (e.g., electricity demand profiles, solar and wind resource profiles). The model computes an optimal solution for a 30-region (EU27+3), multi-regional, multi-energy-carrier, multi-sectoral energy system. The JRC-EU-TIMES-OP modelling instance for 2016 annual time slices based on JRC-EU-TIMES planning model's input data for the year 2019 is uploaded as a git repository (https://gitea.psi.ch/iDesignRES/JRC_EU_TIMES_OP_idesignres_TS2016) which should be executed with TIMES code [7].

Table 10: Details of the high-temporal time slice tree with key model metrics

Name	Temporal Resolution (number of time slices in the year, seasons/days per season/hours per season	Max number of actual hours represented per time slice	Minimum number of hours represented per time slice	Model Matrix Size in million equations and variables	No. of Non-Zero in the model matrix (in Millions)
TS12	4 seasons / 1 day per season /3 segments per day[8]	1320.0	75.0	0.2 x 0.2	1.02
TS288	4 seasons / 3 days per season[9] / 24 hours per day	63.5	13.0	3 x 4	26.20
TS672	4 seasons / 7 days per season[10] / 24 hours per day	15.5	12.7	7 x 9	74.89
TS2016	4 seasons / 21 days per season[11] / 24 hours per day	5.2	4.2	20 x 26	376.42

As expected, increasing the number of time slices considerably raises the number of commodity balance equations, operational constraints, and other model constraints, thereby expanding the overall model

[7] iDesignRES/JRC_EU_TIMES_OP repository further hosts a document describing the model instance and the TIMES code locations

[8] Day, night, and peak. Peak time slice represents smallest fraction of the day to represent the peak demand condition.

[9] Weekday, Saturday, Sunday

[10] One Week

[11] Three weeks

size. Generally, the number of equations and variables increases linearly with the number of time slices, reflecting the model's resolution scaling. Table 10 illustrates how the model matrix size scales with the number of time slices: increasing the number of time slices from 12 to 2016—a factor of 168—results in a roughly 400-fold increase in matrix size (calculated based on the number of non-zero elements in the model matrix). A larger matrix requires additional time for data compilation and equation generation. Therefore, high temporal resolution has substantial implications for model compilation, as extensively discussed in (Panos and Hassan, 2024), (Sharma et al., 2019), implying that a balance between complexity and value added in the analysis is needed.

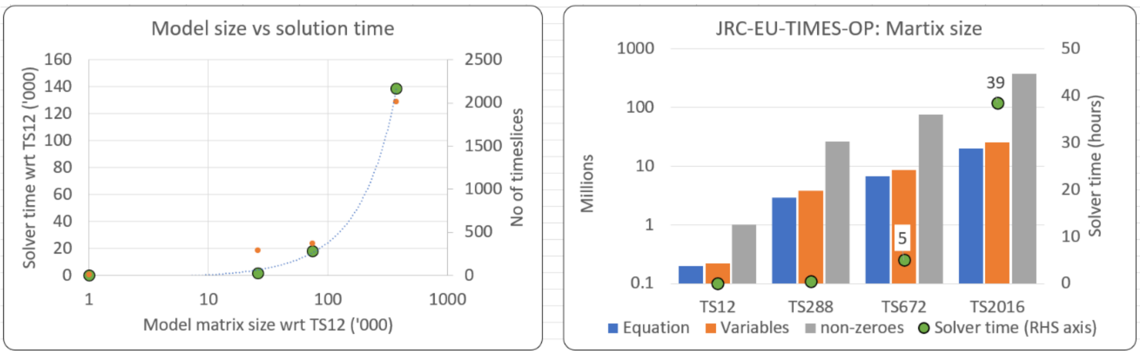

Figure 9: Insights related to model size and solution times

Once the model is generated, the TIMES equations are solved in GAMS using an appropriate optimisation solver. Increasing the number of time slices from 12 to 2016 leads to a 130,000-fold increase in solution time. Figure 9 shows the total computation time, including both compilation and solution phases. Consequently, careful selection of the temporal resolution is crucial to balance computational feasibility with the research questions being addressed, while also considering case-specific data availability.

4.3 Key indicative Outputs from the JRC-EU-TIMES Prototype

The protype JRC-EU-TIMES-OP model optimizes technology activity for thirty European countries. Figure 10 and Figure 11 illustrate electricity supply and sectoral consumption, respectively, across the four time-slice configurations for Germany in 2019. The figures outline the capability of the JRC-EU-TIMES-OP model to optimize the operation of the detailed system configuration available in the JRC-EU-TIMES model for a single year. These results are intended only to illustrate the functionality of the JRC-EU-TIMES-OP model at high spatio-temporal resolution, rather than actual results.

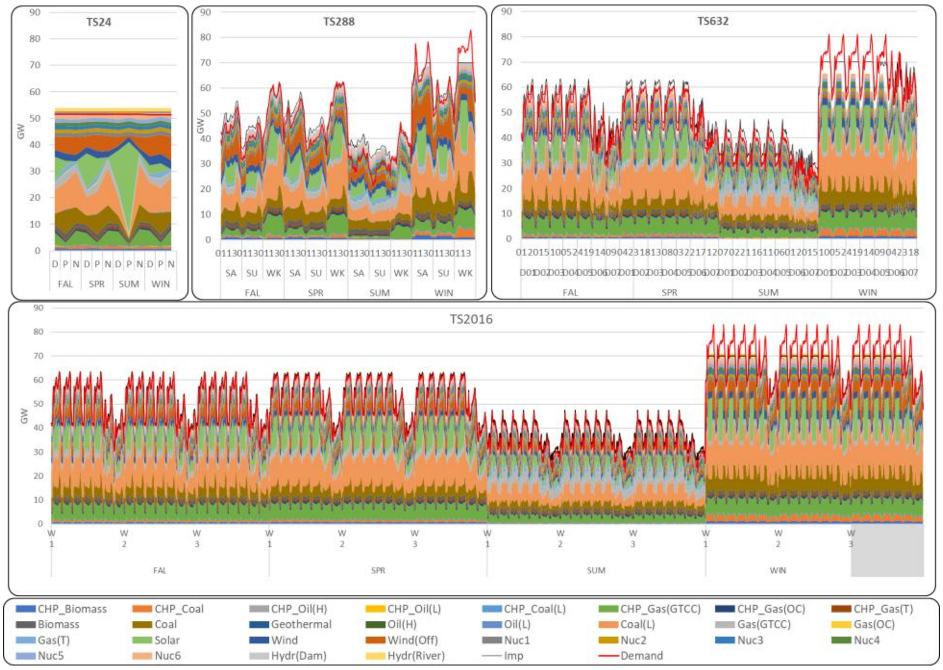

Figure 10: Electricity supply at the four time slice structure in Germany

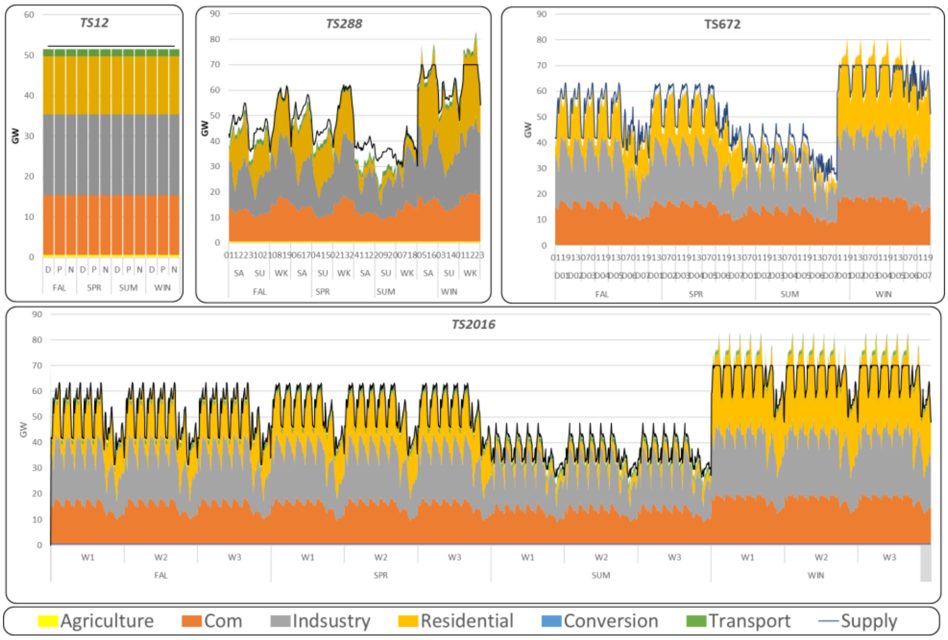

Figure 11: Electricity consumption at the four time slice structure in Germany

4.4 Result Upload Procedure to Scenario Explorer

The initial model outputs are translated into suitable variables for the IAMC common-definition protocol using an R script, based on the mapping tables. To test the result upload procedure to the iDesignRES project-internal Scenario Explorer developed by IIASA, electricity generation by country for various fuel type is uploaded using the Scenario Submission facility (Explorer | iDesignRES | Project-internal Scenario Explorer). As the scenario explorer does not yet support the sub-annual results, only annual information is uploaded.

Figure 12 provides a snapshot of the uploaded data. In the current setup, the data tables written in Excel files are uploaded manually to the scenario explorer. As a future attempt, it will be explored whether automatic uploads using the script are possible to facilitate smoother data exchange between partners/ models. In addition to the model outputs, the Scenario Explorer will contain the input datasets as well for the test cases, which will eventually facilitate cloud hosting and solving of the model. This will be developed as a part of the WP4 of iDesignRES.

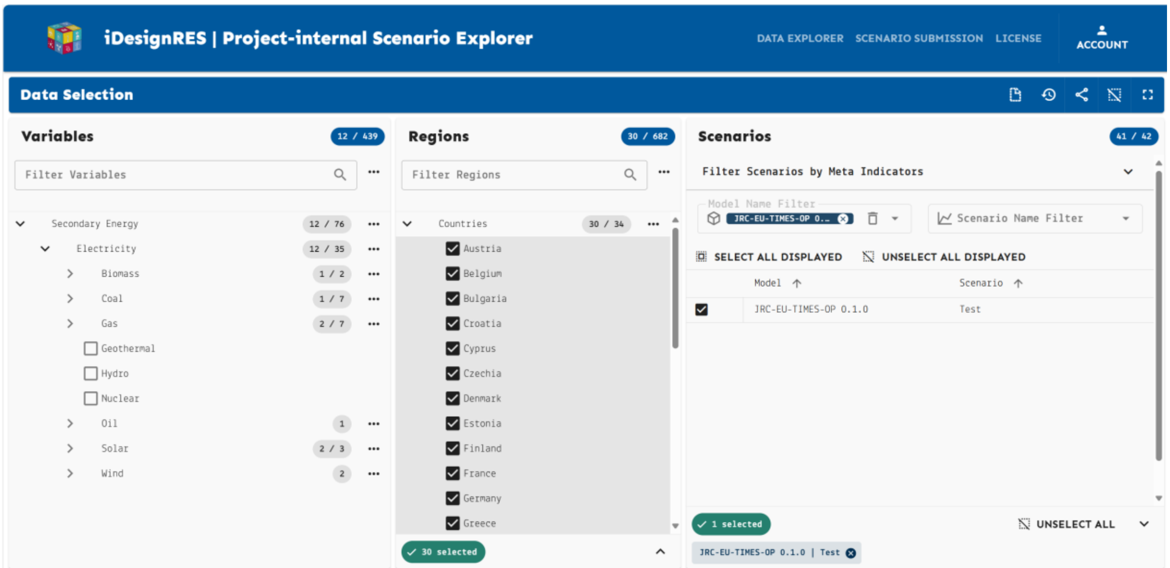

Figure 12: Snapshot of data upload in IIASA scenario Explorer

5. Model Validation Protocol

5.1 Validation Strategy

The GeoMEC planning model operates at a coarse temporal resolution and captures only a subset of the operational constraints that become binding in real-time energy system function. As a result, a system configuration that appears feasible in planning mode may reveal operational bottlenecks when exposed to intra-annual variability, extreme events, or flexibility requirements, leading to the design of a portfolio of energy supply and demand assets that is sub-optimal at the operational stage. The JRC-EU-TIMES-OP model optimises short-term sector-coupled energy system operation and computes high-temporal-resolution activity profiles (i.e., dispatch) for technologies related to the supply and demand of electricity, heat, hydrogen, gas, and other vectors. This enables the evaluation of key operational indicators such as:

- Demand not served (electricity, gas, hydrogen, heat)
- Renewable curtailment and its temporal/spatial patterns
- Storage behaviour, state-of-charge trajectories and cycling frequency
- Use of flexibility resources (hydro-reservoirs, batteries, demand-side management, power-to-X)
- Infrastructure bottlenecks, including network or inter-vector constraints

By using operational indicators, such as those described above, the JRC-EU-TIMES-OP model provides insights into how flexible a system is and how various system resources contribute to its overall operation during periods of low renewable energy or peak demands. In contrast, an inflexible and inadequate system would fail to satisfy energy demand during these periods. These aspects are captured by JRC-EU-TIMES-OP and quantified using the aforementioned system performance-related indicators.

Adequacy metrics can be compared across case studies and stress tests (Table 11). The primary adequacy criterion is Demand Not Served (DNS) by energy vector and region/ time slice. For each operational run, the model reports (i) total DNS (e.g., in MWh or energy-equivalent units); (ii) maximum DNS in any time slice, and (iii) number of scarcity time slices (DNS>0). Complementary adequacy metrics include renewable curtailment rates, frequency of binding network constraints, and storage availability during peak stress periods. Where required by WP3, results can be summarised into small sets of pass/fail flags (e.g., "no scarcity baseline", "scarcity only under defined stress severity") to support consistent reporting across partners.

Table 11: Adequacy metrics in JRC-EU-TIMES-OP and interpretation

Metric	What it measures	Typical interpretation
Demand Not Served (DNS) by vector	Shortfall in meeting demand	Direct adequacy failure signal
Number of scarcity time slices	How often DNS occurs	Frequency/severity proxy
Curtailment rate	Unused renewable due to constraints	High curtailment can signal bottlenecks/flexibility limits
Binding network constraints (e.g., number of transmission lines exceeding 80% loading)	Congestion frequency	Spatial bottlenecks limits on transfers
Storage SOC min/max timing	Flexibility sufficiency	Early depletion or saturation indicates design issue

The validation framework also explicitly identifies examples of infeasible operational behaviour, such as persistent unmet demand in specific hours, storage units being unable to recharge due to sustained deficits, excessive curtailment driven by network congestion, or fuel shortages in hydrogen/ gas supply chains. These outcomes act as diagnostics for identifying structural weaknesses in the GeoMEC-derived configuration.

In fact, the infeasibility in operational validation can present in several ways. First, the model may only achieve feasibility by using DNS variables, indicating insufficient firm capacity, insufficient flexibility, or constrained network transfers in specific regions or hours. Second, the model can show persistent curtailment co-existing with scarcity, a typical signature of network bottlenecks or insufficient cross-vector conversion capacity. Third, storage trajectories may reveal structural issues, such as storage saturation early (no room to absorb surplus) or depleting before critical peak periods (insufficient energy capacity or charging constraints). These diagnostic patterns are explicitly used to distinguish (a) capacity adequacy problems, (b) flexibility/ramping problems, and (c) infrastructure congestion problems, guiding whether feedback to GeoMEC is warranted.

Hence, these indicators allow identification of operational infeasibilities that may not be visible in GeoMEC. Where relevant and upon stakeholder/ user request, operational insights can be fed back to the planning stage to support iterative improvement of the system design (Figure 13). To limit the number of planning-operation iterations and ensure smooth convergence in the linked framework GeoMEC – JRC-EU-TIMES-OP, the JRC-EU-TIMES-OP model includes the option to invest in selected short-lead-time technologies (e.g., batteries or demand-side measures) that can mitigate short-term inadequacies in the GeoMEC-derived energy system configuration. This set of technological options is 'added on' to the system configuration calculated by GeoMEC to examine whether their availability leads to reliable system operation.

In cases where, following a stakeholder/ user request, significant operational infeasibilities are identified and exceed what can be considered an acceptable solution, a feedback loop from JRC-EU-TIMES-OP to GeoMEC can be activated. In such cases, GeoMEC receives detailed results on asset dispatching and flows over interconnectors, as illustrated in Figure 13. Based on these results, GeoMEC's constraints regarding the system balancing and reserve requirements[12], both for generation assets and interconnectors, are tightened. This allows the model to reflect better the observed operational limitations and, where necessary, trigger additional investment to achieve a more feasible and robust capacity planning solution.

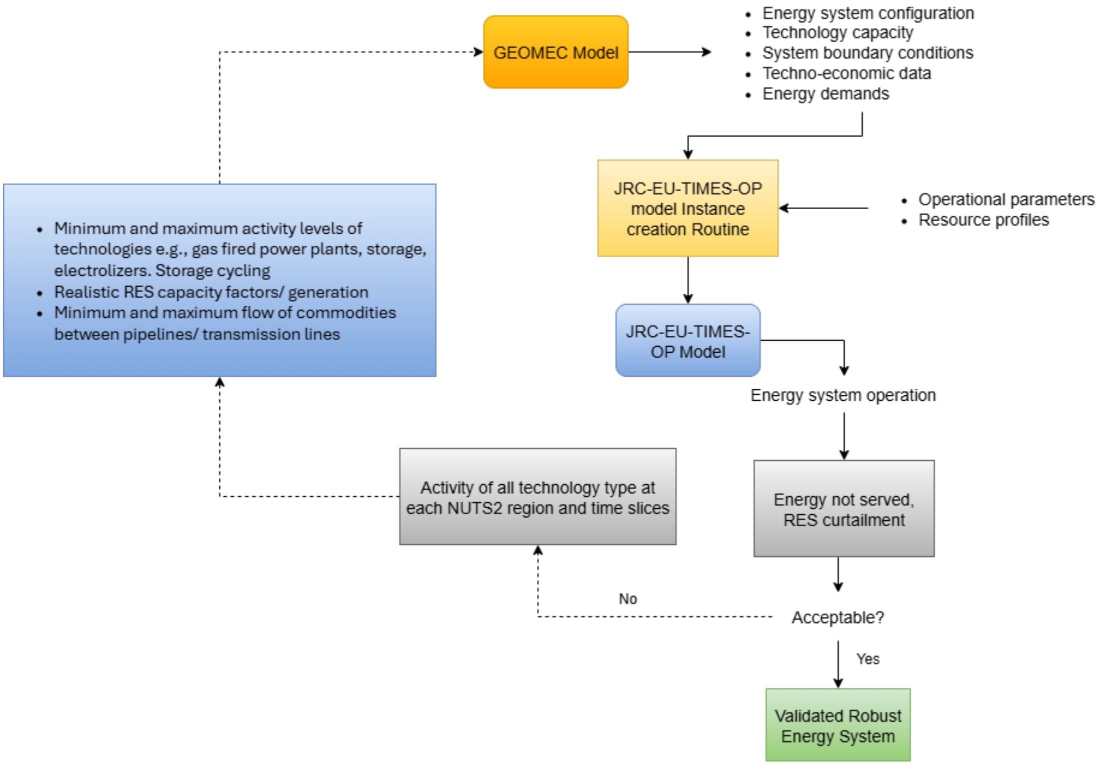

Figure 13: Validation of the integrated energy system by JRC-EU-TIMES-OP model

In addition, the validation strategy follows the principles of transparency, reproducibility and traceability required in EU Horizon projects. This includes clearly documenting the assumptions applied in the operational model instance, the temporal and spatial profiles used for validation, and the criteria for determining adequacy or infeasibility. All validation steps are aligned with WP3 requirements to ensure consistency across models and interoperability of results.

Furthermore, the validation protocol is designed to support the later integration of stress-testing activities (Section 5.2). This ensures that the same operational indicators, such as annual demand, curtailment, flexibility utilisation and storage behaviour, can be used both for baseline validation and for

[12]GeoMEC and JRC-EU-TIMES OP include explicit constraints that reflect the need for operational reserves to maintain short-term system balance and security under normal operating conditions. These reserves cover uncertainties related to demand fluctuations, variable renewable generation, and unforeseen outages, and are bound by the share of installed capacity that must remain available but not fully dispatched. In addition, GeoMEC applies a long-term reserve margin constraint, which ensures that total installed capacity exceeds peak demand by a predefined margin. This reserve margin reflects adequacy considerations over the long term and provides protection against extreme events, capacity outages, and demand surges. A similar reserve margin principle is applied to interconnector flows, whereby the usable transfer capacity between regions is restricted to remain below the nominal technical limit. This reflects security and reliability considerations in cross-regional exchanges, accounting for contingencies, maintenance requirements and operational uncertainty. The difference in the implementation in the two models mainly relies on the time resolution assumed and the system imbalances considered, e.g., JRC-EU-TIMES-OP can also consider the probability of the loss of the largest grid element, when the model endogenously calculates the demand for operating reserves.

stress-test evaluation, thereby creating a consistent and comparable assessment framework across the full modelling chain.

Model-linking needs between GeoMEC and JRC-EU-TIMES-OP, data requirements, and test-case specific research questions are documented and highlighted for each case study region in Deliverable D3.1, which serves as the reference for preparing the JRC-EU-TIMES-OP operational model instances for each case study.

5.2 Stress Testing

Stress testing is a central element of validating whether the system configuration produced by the GeoMEC planning model is robust and resilient under a range of adverse or extreme operating conditions. While long-term planning models evaluate system adequacy under typical or average conditions, operational stress testing examines how the system behaves when exposed to short-term shocks that challenge flexibility, supply security, network resilience and sector-coupled interactions. The stress-testing activities build directly on the validation indicators described in previous subsection, ensuring that system responses under extreme conditions are evaluated using the same operational metrics (e.g., demand not served, storage behaviour, curtailment, bottlenecks). This creates a unified framework linking validation and resilience assessment.

In Task 2.5, a structured stress-test taxonomy and a corresponding stress-test matrix that maps each type of stress event to the iDesignRES partners and models capable of analysing was developed (**Error! Reference source not found.**, Task2-5_StressMatrix_v1.xlsx). These stresses can arise from various factors which can be mapped to transitional and operational stress tests. Transitional stress tests address uncertainty around system development (technological and policy-related, long-term price volatility, socio-economic shifts, etc.). Operational stress tests arise from short-term uncertainties affecting real-time energy system operation, including extreme weather events and unplanned contingencies involving system infrastructure and technologies. The matrix groups stress events into environmental, technical, socio-economic and behavioural categories, and identifies whether they are best analysed with planning models (GeoMEC) or operational models (such as JRC-EU-TIMES-OP). For operational stress tests, JRC-EU-TIMES-OP plays a central role due to its ability to represent high temporal resolution, multi-vector dispatch and flexibility constraints.

The stress-test matrix summarises for each stress event:

- The nature of the shock,
- The affected components of the system (e.g., supply, networks, storage, cross-vector links)
- The time horizon and severity
- And the specific models and partners capable of the analysis.

This mapping ensures a consistent approach across the consortium and provides the basis for selecting the operational stress tests to be implemented for the case-study regions in WP3. In combination with the validation strategy, this means that the OP model first assesses feasibility under normal conditions, and then systematically quantifies how each stress-test condition pushes the system closer to (or beyond) operational limits.

Table 12: Snapshot of the matrix mapping stress-test to models

Mapping stress type and models					System wide transitional stress tests		System wide operational Stress-tests				
					Long-term models		**Operational models**				
Stress/Validation categories	**Stress description**	**Category**	**Comments**	Models	GENeSYS-MOD	GEOMEC	JRC-EU-TIMES-OP	Plan4res			Ilsim
				Scope	Energy System	Energy System	Energy System	Electricity	Heat network	Building	Industry
				Institute	*TUB*	*E3M*	*PSI*	*EDF*	*AAU*	*TEC*	*UD*
Environmental	Mitigation timeline (cap vs budget)	Transitional					NA				NA
Technical	Fossil fuel phase out / supply shortage	Transitional			Yes	Yes	NA	yes			NA
	Nuclear power level of deployment	Transitional			Yes	Yes	NA	yes			NA
	Availability of energy infrastructure	Transitional	H2 pipelines, electricity grids		Yes	Yes	NA	?			NA
	Wholesale prices volatility	Transitional			Yes	Yes		no			NA
	Investment in distirct heat network	Transitional			NA		NA	no	Yes		NA
	Investment in PV/ wind	Transitional			May be		NA	yes			NA
	technological improvements	Transitional	Demand reduction		Yes					yes	Yes
Socio-economic/ political conditions/ shifts	Heat pump adoption	Transitional			May be		NA	no	May be	May be	May be
	Industry relocation	Transitional			May be		NA				
	Economy shifts	Transitional	e.g., more digitalization, AI		May be		NA				
Weather events	Extreme heat wave or cold snaps (demand)	Operational			NA		May be	yes		May be	NA
	Dunkelflaute - Null wind or solar (supply)	Operational			NA		Yes	yes			NA
	Lack of water for hydro (or thermal/CCS) plants (supply)	Operational			NA		Yes	yes			NA
	Shift in hydrological cycle (early snow melt)	Operational			NA		Yes	yes			NA
	Too much solar/ wind	Operational			NA		Yes	yes			NA
System contingency events	Cross border trade is interrupted/ limited	Operational	Technical/ political/ weather. Electricity/ GAS/ H2		NA		Yes	yes			NA
	Unplanned outage of system infrastructures	Operational	Grid, pipelines, nuclear & CCS plants, Electrolizers		NA		May be	may be			NA
	Storage malfunctioning	Operational	Deep self discharge		NA		Yes	may be			NA
Price events	Price volatility for certain energy carriers	Operational	High/ Low. Intra & Extra EU Supply		NA		Yes	no			NA
Societal/ behavioral	Behaviour driven change in heating or e-mobility	Operational	Building/ transport		NA		May be	no		May be	NA
	Walkout/ strikes	Operational	Industry/ transport		NA		No	no			NA
	Demand side flexibility	Operational	Building / Industry		NA		May be	may be			NA

The stress-test matrix provides a consortium-wide allocation of responsibility for each stress category, indicating which partner/model implements each stress event and how results are made comparable across tools. In practice, the matrix shown in Table 12 is read as: (i) stress definition (what is perturbed and by how much), (ii) implementation layer (planning vs operational), and (iii) responsible model/ partner for producing the corresponding KPI outputs. For operational stress categories (e.g., extreme renewable drought weeks, peak-demand cold spells, forced outages, short-term import restrictions), JRC-EU-TIMES-OP is the designated implementation tool because it can apply time-resolved perturbations while respecting sector coupling and infrastructure constraints. This ensures that WP3 stress-test results are consistent across case studies and that responsibilities are clear for delivery timelines.

5.2.1 Categories of Stress Tests and Relevance for JRC-EU-TIMES-OP

Environmental Stress Test

These include prolonged periods of low renewable availability, extreme temperature events (cold spells or heatwaves), and hydrological scarcity. Such events affect both supply and demand and are represented in JRC-EU-TIMES-OP through modified renewable availability factors, altered load shapes and temperature-driven changes in demand. At high temporal resolution, the model can assess the resulting impacts on dispatch patterns, storage cycling, system adequacy and curtailment needs.

Technical and Infrastructure Stress Tests

These represent short-term failures of system assets, such as forced outages of large generators, line congestions, interconnector interruptions, or fuel supply disruptions. JRC-EU-TIMES-OP can simulate these shocks by adjusting technology availability, transfer limits or fuel supply constraints. The model's depiction of multi-vector interactions enables assessing how outages propagate across the electricity, gas, heat, and hydrogen systems, and how flexibility resources compensate for or fail to compensate for such disruptions.

Socio-economic and Market-Driven Stress Tests

Short-term price shocks, carbon price volatility, import restrictions or sudden demand changes fall under this category. As JRC-EU-TIMES-OP supports time-dependent commodity prices and bounded import capacities, it can examine how these signals influence dispatch, curtailment, storage and infrastructure utilisation, as well as system costs at high temporal granularity.

Behavioural Stress Tests

Behavioural shocks include unexpected changes in consumption or flexibility patterns, such as synchronised EV charging peaks, reduced demand response or clustered heating behaviour. These shocks can be represented by modifying load profiles or constraining the availability of demand-side flexibility technologies in JRC-EU-TIMES-OP, allowing the model to assess their effects on peak load, flexibility needs and short-term adequacy.

5.2.2 Scope and Application of the Stress-Test Matrix in iDesignRES

For the case-study regions, the operational model will be used primarily to implement operational stress tests, including:

- Periods of very low renewable output,
- Extreme peak-demand conditions,
- Infrastructure or generator outages,
- Short-term fuel supply disturbances,
- Or combinations of the above.

These tests will be mapped for specific test-cases and will be developed jointly with WP3 and will follow the definitions and input requirements documented in Deliverable D3.1. The stress-test matrix provides the structuring framework for selecting relevant tests and ensuring methodological consistency across partners.

In the JRC-EU-TIMES-OP template, stress tests are implemented through a dedicated set of scenario switches that modify only a controlled subset of inputs, while keeping the GeoMEC-derived capacities and annual demands fixed. These switches modify time-series, availability factors, network capacities or demand levels; they are encoded in the operational model template and activated depending on the stress category selected in WP3. Depending on the stress category, the operational model applies parameter modifications such as: (i) scaling renewable availability profiles (prolonged low-wind/low-solar events), (ii) adjusting demand profiles or peak multipliers (cold spell/heatwave), (iii) reducing technology availability (forced outage of units), (iv) tightening network transfer limits (line/pipeline outage), or (v) tightening import bounds and time-dependent prices (market shock). For transparency, each stress run records the activated switch set, the severity level, and the modified parameters, allowing results to be reproduced and compared across partners. Examples of model modifications for selected stress types are given in Table 13.

In summary, this stress-testing framework ensures that the system configuration designed by GeoMEC is exposed to a comprehensive set of operational challenges, and that JRC-EU-TIMES-OP provides robust evidence on system adequacy, resilience and flexibility under these conditions.

Table 13: Stress-test implementation mapping (what changes in the JRC-EU-TIMES-OP model)

Stress category	What is modified in the model	Example modification type
Low renewable period	RES profiles/availability factors	Scale down wind/solar for selected time slices
Extreme temperature event	Load shape/peak multipliers	Increase heating/cooling peak hours
Forced outage	Availability of technology or links	Reduce availability factor of a process; reduce interconnector capacity
Fuel/import disruption	Import bounds/supply limits	Tighten import caps in peak periods
Behavioural shock	Demand profile shape/DSM availability	Increase synchronized EV charging peak; reduce DSM capacity

6. Conclusion and Next Steps

6.1 Summary of work performed

The deliverable D2.4 has described the development of the first fully functional prototype of the JRC-EU-TIMES-OP model, restructured from the JRC-EU-TIMES long-term energy system planning framework into a high spatial-temporal resolution sector-coupled operational tool suitable for stress-testing the case-study regions. The work performed includes:

- **Definition of the operational modelling framework**, outlining how the planning-oriented TIMES logic is adapted to represent short-term dispatch, infrastructure, flexibility constraints and sector-coupled interactions under high temporal granularity.
- **Configuration of system representation**, including a) selection of temporal structures (from 12 to 2016 time slices per year), b) inclusion of updated synthetic demand and renewable profiles, c) operational representation of electricity, heat, hydrogen, gas and flexibility technologies.
- **Implementation of operational features**, such as dispatch constraints, storage dynamics, unit commitment-like features, curtailment logic, energy gas and electricity infrastructure physics,

ancillary service characteristics, and optional short-lead-time investment options that allow the model to mitigate GeoMEC-derived operational infeasibilities.

- **Prototype model testing**, where the functional prototype is executed using representative JRC-EU-TIMES input data to demonstrate the feasibility of running the model at high spatial-temporal resolution; develop insights on model size, solve time etc. for various spatial-temporal resolutions.
- **Identification of data requirement** as part of WP1, where various data sources are identified within iDesignRES project and beyond (Table 9). For JRC-EU-TIMES-OP PSI provides renewable energy resource profiles (hourly capacity factors) at NUTS2 level for whole Europe [13].
- **Model and data linking protocol** between GeoMEC and JRC-EU-TIMES-OP, including the mapping of variables, parameters and commodities following IAMC-compatible conventions and interfaces, and the identification of data flows required for preparing operational JRC-EU-TIMES-OP model instances
- **Initial validation and stress-testing framework**, including the development of a validation strategy based on operational indicators and the adoption of a stress-test matrix that specifies which models address which stress-test categories.

Overall, the work presented in this deliverable establishes the methodological, computational and interoperability foundations required for the operational model to support WP3 test-case scenarios, stress-testing activities and subsequent cross-model comparisons.

6.2 Lesson Learned

Several lessons emerged during the development of the operational JRC-EU-TIMES-OP prototype:

- **Granularity significantly increases computational burden**. Moving from 12 to 2016 time slices per year results in substantial increases in model matrix size and computational solution time. This emphasises the importance of selecting temporal resolutions consistent with the modelling purpose and the case-study requirements. The same holds for the spatial dimension: expanding the regional representation also increases the model scale and must be carefully balanced with computational feasibility and the stakeholder needs of the analyses performed in the test-case study regions.
- **Data availability at NUTS2 resolution remains limited**. A complete NUTS2 operational model instance requires detailed load profiles, infrastructure data and technology parameters that are still under development in iDesignRES. As a result, the current version relies partly on synthetic or proxy data, which will need refinement in the next phases when the model is to be applied to the case studies. This highlights the need for controlled data substitution procedures and clear documentation to ensure transparency.
- **Model linking requires strict harmonisation of definitions.** Ensuring consistent representation across GEOMEC and JRC-EU-TIMES-OP highlighted the need for harmonised naming conventions, commodity definitions and regional aggregation structures. The IAMC-aligned mapping developed in this deliverable is a crucial step.
- **Iterative planning-operation feedback loops must be carefully managed.** Direct feedback from operational infeasibilities to planning can cause oscillations or convergence issues. The inclusion of short-lead-time flexibility options in the JRC-EU-TIMES-OP model proved useful to minimise unnecessary iterations. Further guidance will be needed to define when operational feedback should, or should not, trigger re-planning in GeoMEC.
- **Stress testing benefits from unified consortium feedback.** The development of the stress-test matrix ensures that all models apply a consistent set of stress events. This improves coherence

[13] From HU project WIMBY [Wimby - wind in my backyard - European funded project]

across work packages and clarifies the role of the JRC-EU-TIMES-OP model relative to other tools. It also ensures comparability of results across regions and modelling teams, which is essential for integration and reporting in iDesignRES.

6.2.1 Assumptions and Limitations

The current operational implementation reflects deliberate methodological choices consistent with the objectives of iDesignRES. Not all infrastructure and technologies can be represented at full physical detail in all case studies, as data availability at NUTS2 resolution remains uneven across Europe. Where detailed data are missing, proxy representations (e.g. aggregated transport constraints, synthetic temporal profiles) are to be applied in a transparent and documented manner. Importantly, these assumptions do not affect the comparative purpose of the operational validation, as all stress-test results are evaluated relative to the same planning-derived baseline.

As WP1 and WP3 datasets mature, these simplifications can be progressively relaxed without changes to the core modelling logic. The modular structure of JRC-EU-TIMES-OP ensures that increased spatial, temporal or infrastructural detail can be incorporated incrementally, preserving methodological consistency across project phases. GeoMEC and JRC-EU-TIMES-OP model and data coupling will continue to improve to enable full-fledged operational model instance generation for performing stress-tests and answering research questions for the test case regions.

6.3 Future work

Future work will focus on completing the operational model instances for each case-study region, strengthening the link between GEOMEC and JRC-EU-TIMES-OP, and preparing the model for the full set of stress tests defined in WP3. These next steps are central for ensuring methodological consistency, interoperability and reproducibility across the modelling chain. The main activities are summarised below.

6.3.1 Link Test-cases

The next stage involves constructing fully functional operational model instances for each case study considered in WP3. This includes:

- **Implementing GeoMEC-derived system configurations**, including technology mixes, regional energy balances, storage capacities and cross-vector conversion infrastructures.
- **Integrating region-specific demand and renewable profiles** produced by WP1, ensuring consistency with the temporal structure selected for each case study. Where necessary, harmonization rules and data substitution procedures will be applied to maintain consistency.
- **Running baseline JRC-EU-TIMES-OP simulations** for each test-case region to identify emerging operational patterns, flexibility needs and potential inadequacies.
- **Enable EnergyPLAN model** for validating North Sea case results by providing necessary input/ outputs from JRC-EU-TIMES-OP model.
- **Preparing the model for stress-testing**, by encoding scenario switches, parameter modifications and availability constraints consistent with the stress-test matrix and the case-study research questions in Deliverable D3.1. This includes documenting all stress-test assumptions to ensure transparency and reproducibility.

This work will enable the operational model to support comparative and stress-testing analyses foreseen in WP3 and subsequent work packages.

6.3.2 Refine model linking

Further refinement of the model linking framework is required to ensure accurate and reproducible coupling between GeoMEC (multi-carrier geolocation planning model) and JRC-EU-TIMES-OP (energy system operation). The following activities are planned:

a. **Finalizing the commodity and parameter mappings** in alignment with the IAMC data format and the GeoMEC data structures.
b. **Harmonizing regional representations**, ensuring that NUTS2 operational regions correspond precisely to GeoMEC's planning regions and to the data produced in WP1.
c. **Improve consistency in temporal structures**, including the alignment of load shapes, renewable profiles, technology availability factors, peak reserve margins, cycling of time slices.
d. **Enhancing interoperability**, by defining a stable input/ output interface allowing GeoMEC results to be imported into JRC-EU-TIMES-OP automatically and reliably.
e. **Refining the treatment of short-lead-time investment options**, ensuring transparent and methodologically consistent with GeoMEC integration into the operational model, as well as clear documentation of when these options are activated.
f. **Documenting all linking workflows**, enabling reproducibility and transparency in accordance with research integrity principles and ensuring that partners and users can understand and replicate modelling steps.

Refining the model linking will be crucial for ensuring methodological consistency across the modelling chain and for enabling robust, transparent stress-test evaluations in WP3. This enables defensible and policy-relevant analysis in iDesignRES.

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iDesignRES

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

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