



iDesignRES

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

Deliverable 3.1 - Methodology for use-cases implementation

Validation and certification Framework

Deliverable 3.1 - Methodology for use-cases implementation



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1. EXECUTIVE SUMMARY

Deliverable 3.1 details the methodological framework for implementing five real-world test cases and demonstrators (North Sea, Lombardy, Basque Country, South East Europe, and Ukraine) within the Horizon Europe project iDesignRES. The core objective of these case studies is to demonstrate the operationality of the open-source, modular modelling toolbox developed in iDesignRES that supports the integrated planning and optimisation of renewable energy systems across diverse European contexts.

The methodology is founded on a co-design process where regional stakeholders (Need Owners) are central. Insights from interviews and consultations (WP6) are translated into specific, modellable Research Questions (RQ) for each case study. These RQs guide the entire process, ensuring that the modelling addresses real-world planning uncertainties, such as infrastructure investment dilemmas, operational challenges, or other aspects not considered by research modelers.

The project employs a three-layer, multi-model approach¹ to span different spatial and temporal scales. The three-layer, multi-model approach maximizes the utility of individual models to mitigate blind spots and inaccuracies, delivering high regional and temporal resolution without losing sight of the overarching pan-European energy market. Through model coupling, resolution increases with each layer: the hierarchy cascades from long-term European modelling (up to 2060) down to NUTS2 spatial granularity, followed by high-temporal resolution validation and sectoral analysis. This framework allows for bidirectional data flows, where sectoral models can inform higher layers with demand data, resulting in a tightly interwoven, holistic, and coherent assessment of the energy system.

Layer	Focus	Key Models	Function
1: Long-Term System Optimisation (NUTS 0)	Pan-European pathway generation	GENeSYS-MOD, EMPIRE	Determines optimal, long-term decarbonisation pathways to 2060, providing consistent boundary conditions for lower layers (e.g., carbon prices, technology costs).
2: Regional Planning & Operation (NUTS 2)	Spatial allocation and operational feasibility	GeoMEC, JRC-EU-TIMES-OP, EMPIRE	Translates national pathways into regional (NUTS2) infrastructure siting, and stress-tests configurations under high temporal resolution to check for adequacy and flexibility.
3: Detailed Sectoral Analysis	Power grids, gas networks, industrial/building demand	i.a. POMATWO, GGM, EnergyModelsX, industrial model, PyPsa	Provides high-resolution analysis of multi-carrier integrated regional energy systems and of specific components, like electricity market dynamics, hydrogen pipeline repurposing, and industrial demand profiles.

All case studies are anchored in the EU EnVis 2060 scenario framework² (e.g., *REPowerEU++*, *EU Trinity*, *Go RES*), ensuring consistent macroeconomic and policy assumptions. To test resilience, Stress Tests are applied as disruptive variants (e.g., delayed permitting, fossil fuel shortage) to identify vulnerabilities in the system designs.

Crucial to the framework is harmonisation and consistency:

¹ <https://idesignres.eu/models-and-toolboxes/>

² <https://idesignres.eu/results/energy-vision-scenarios/>

- **Data Standardisation:** All data exchange adheres to the IAMC data format for full interoperability and traceability.
- **Model Alignment:** Regular coordination ensures alignment on sectoral and regional representations, including technology definitions and unit conversions, preventing blind spots or double counting.

The methodology enables the custom selection of models for each region, addressing unique challenges and research questions (RQs):

Demonstrator & Core challenges	Research questions (RQs)	Models involved
North Sea Integration of massive offshore wind, hydrogen infrastructure, Nordic hydropower storage.	RQ1: What is the role of the North Sea in the green transition, and how do optimal investment decisions depend on the transition scenario? RQ2: What is the impact of the transition scenario on of selected sub-sectors and regions?	GENeSYS-MOD, GeoMEC, JRC-EU-TIMES-OP, EnergyModelsX, POMATWO, GGM, Transport model, Building sector model, EnergyPLAN
Lombardy Region Decarbonisation of energy-intensive industry, grid congestion, rapid demand growth.	RQ1: What is the cost-effective and technically feasible pathway to decarbonise Lombardy’s industrial system by 2050 through a mix of electrification, hydrogen, CCS, industrial efficiency and sector coupling, under regional spatial constraints? RQ2: How can Lombardy integrate large shares of renewable energy while ensuring grid adequacy and flexibility, considering uncertainties in permitting timelines, infrastructure development rates and regulatory bottlenecks?	GENeSYS-MOD, GeoMEC, JRC-EU-TIMES-OP, DEUSTO (Industry), JRC-EU-TIMES-OP, POMATWO, EnergyPLAN
South-East Europe (GR/BG) Quantifying the system value of BESS/PHES and enhanced regional coordination.	RQ 1: Which is the optimal technology configuration for decarbonizing the Basque industry given a set of technologies, fuels, and emissions price? RQ 2: What are the investment needs regarding the build-up of the technology-related infrastructure required to decarbonize the Basque industry (e.g., power grid networks, natural gas grids)?	GENeSYS-MOD, GeoMEC, JRC-EU-TIMES-OP, POMATWO, Transport model
Basque Country Optimising technology configuration and infrastructure for an industrial cluster under regulatory constraints.	RQ 1: What is the overall value of BESS and PHES for the whole electricity chain? What is the contribution of BESS/PHES to adequacy and flexibility? RQ 2: What is the overall system value of enhanced GR-BG coordination? Need to quantify system costs under silo and regional approaches.	IDR-IIsim (Industry), GENeSYS-MOD, GeoMEC, JRC-EU-TIMES-OP, POMATWO
Ukraine	RQ 1: What energy planning strategy should be considered under high geopolitical tensions in the	EMPIRE,

<p>Integration to the EU power market, develop decarbonization strategies post conflict, and deal with uncertainty in operations in the short term.</p>	<p>next decades? Decentralized energy system vs. a mix scenario policy? RQ2: What measures on security of supply and resilience for critical infrastructure should be prioritized? What to model regarding war attacks and outages in Ukraine? RQ3: What market design reforms will affect or enable Ukraine integration into European Power Markets?</p>	<p>PyPsa, GENeSYS-MOD,</p>
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The next steps involve the pre-kick-off and initial modelling runs for the North Sea and Lombardy cases, followed by an in-person modellers’ meeting to ensure continued technical integration and refinement of the framework.

2. Introduction to use-case methodology

Deliverable 3.1 outlines the methodological framework for implementing the five test cases and demonstrators at the centre of Work Packages 3 and 5 in the iDesignRES project. These test cases play a crucial role in translating the project's modelling innovations into practical tools for energy system planning across diverse regional and sectoral contexts. They are designed to validate the open-source, modular framework developed in WP2, assess its applicability in real-world scenarios, and ensure its relevance to local planning challenges and decision-making needs. The modular framework developed in WP2 is a concrete, operational modelling architecture that specifies how the core models in iDesignRES connect, exchange data, and run consistently under shared scenario assumptions. It is not an abstract concept, but a fully defined system of data standards, model interfaces, workflows, and technical tools that enables the coupling of heterogeneous models across the project.

At its core, the framework consists of four components:

1. **A unified data and scenario backbone:** WP2 created a harmonised dataset—including technology costs, fuel prices, CO₂ trajectories, demand projections, and resource potentials—available in a standard IAMC format. These data files define the boundary conditions for all models and ensure that each test case starts from the same scenario assumptions. Model input files, versions, and scenario variants are stored in a shared, version-controlled environment and mirrored to Zenodo and the Scenario Explorer.
2. **Standardised model interfaces and I/O templates:** WP2 developed precise templates that define what each model must receive and what it must output. These templates specify variables, units, spatial and temporal aggregation, and naming conventions. For example, GENESYS-MOD outputs capacities and energy balances in IAMC long-term format, GeoMEC consumes and spatialises them, and JRC-EU-TIMES requires hourly load and capacity files in a standardised structure. This guarantees that models remain plug-compatible.
3. **A modular model stack with defined coupling logic:** The framework specifies the order in which models run, what information they exchange, and how feedback loops operate. The modular architecture is structured into layers (e.g. long-term system optimisation → spatial allocation → operational validation → market or demand models), and WP2 documented the conditions under which a model can be inserted, replaced, or omitted depending on the case study. This creates a flexible system where each model is a “module” with a defined role.
4. **A technical infrastructure for data exchange and consistency checks:** WP2 provided the internal tools and procedures to ensure that data passed between models is validated, versioned, documented, and reproducible. This includes metadata requirements, consistency checks (e.g. NUTS resolution, time resolution, technology mapping), and rules for scenario inheritance. All models must register the exact version of the data and model code they use, ensuring traceability of every modelling step.

The methodology described in the present deliverable 3.1 contributes directly to Expected Outcome 4 (EO4), which calls for an open-source tool to support the planning and optimisation of renewable and low-emission energy systems and infrastructure in specific geographical areas. This is achieved through the application of the standardised, open-source, and modular modelling framework and multi-physic components developed in WP1 and 2, which allows to use a customized selection of energy system component models such as large scale energy system models, grid or building models, according to the technical, economic, and institutional conditions of a given region.

These customisations are tested and validated across five case-studies (i.e. North-Sea countries, Lombardy, South-East Europe, Basque Country, Ukraine), covering different geographies and system

configurations in Europe. This process is central to PR7 and enables the project to demonstrate how iDesignRES models can be operationalised and adapted to a range of use-cases, from highly industrialised regions (e.g. Lombardy region) to macro-regional systems (e.g. North-Sea region). Each use-case is covered by local partners, such as LE2C, RVO, ESO, PPC, IPTO, NORD, DIXI, and ACLIMA, who bring in-depth knowledge of local systems and actors. Their input ensures that the project's tools are grounded in operational realities and compatible with existing planning practices.

A key methodological pillar of this deliverable is the co-design process with regional stakeholders, which ensures that the modelling work in WP3 and WP5 (i.e. the modelling of the case studies) is driven by real-world uncertainties and decision needs. This process is closely coordinated with WP6, where structured interviews and consultations have been conducted to identify stakeholder priorities. These insights are used to define research questions for each test case, which then guide the selection and configuration of models, data inputs, scenarios and model outputs.

By integrating stakeholder input, project-wide modelling standards, and test-case specific challenges, this deliverable lays the foundation for a robust and adaptable modelling framework that can support energy transition planning across Europe, both within the project and beyond.

3. Research design framework

3.1. Creating the case studies - finding a research question

3.1.1. Inclusion of need owners in research question development

A central methodological aim of Work Package 3 (WP3) in iDesignRES is to ensure that the implementation of demonstrators and test cases is directly informed by the specific challenges and planning needs of the regions and need owners involved. In this context, suiting research questions for each test case and demonstrator acts as a bridge between stakeholder-defined uncertainties and the technical modelling framework of iDesignRES. They serve as the centre around which modelling tools, data, and scenarios are configured and coupled. The process of formulating research questions was carried out collaboratively between task leaders and regional stakeholders, supported by findings from stakeholder interviews and engagement activities conducted in WP6. These interviews offer insights into local energy transition challenges, decision-making processes, data availability, institutional arrangements, and planning bottlenecks. Rather than being fixed or purely academic in nature, the research questions in WP3 are designed cooperatively, practically, and responsive to real-world needs. See the appendix for the interview questionnaire.

To ensure coherence across all test applications, the process for developing research questions was harmonised across all five instances, namely North-Sea region, Lombardy region, Basque Country, South-East Europe and Ukraine. Each institution was responsible for initiating discussions with regional stakeholders within their country, guided by a common interview structure and coordination mechanism derived from WP6. This allows for alignment in both form and depth of the questions across diverse use cases, while allowing regional specificity to be preserved. Conducting the interviews within each of the institution's home countries lowered the entry barrier for the interviews by enabling the stakeholders to speak their own language. A research question in this context in the end should not simply be a topic of interest, but a specific, modellable question that links stakeholder concerns with analytical capabilities. It should identify a key planning uncertainty, investment dilemma, or operational challenge that can be explored through simulation, optimisation, and scenario analysis. Importantly, it must be answerable using the iDesignRES modelling framework or component tools. For instance, a regional authority in the North-Sea region facing uncertainty about electrification versus hydrogen deployment may ask: "What is the future role of Nordic hydropower storage in investment and operation?".

3.1.2. Breaking down the overarching research questions into modellable subquestions

Each research question then must be shaped by both local context and available modelling capabilities. Therefore, in a next step, the broader research questions need to be broken down further into modellable subquestions for the available models in iDesignRES. The questions were reviewed and refined through feedback between modelling teams, stakeholders, and WP3 and WP6 coordination partners. The modelling teams take the overarching research question asked by the regional stakeholders and evaluate how their respective model can help answer aspects of the initial research question. By combining the different models with their respective subquestion, we are then able to paint a complete picture and answer the whole research question. One primary subquestion would then be, how will the overall energy system in Europe develop given certain scenario assumptions about the future? This would be answered by the energy system model GENeSYS-MOD and give the boundary conditions for a Nordic energy system.

A consecutive model (GeoMEC – model) would then ask a geographically more precise question of how these installed capacities will be distributed on NUTS2-level within the Nordic countries. With operational models, we can then test the system’s adequacy to always meet the demand. With this increase in geographical and operational insights, more technically detailed models can then examine the operation of the hydropower storages and what potential stress such as droughts cause for the operation of hydropower storages. By linking these models and research questions, we can then answer the initial question posed by local stakeholders: “What is the future role of Nordic hydropower storage in investment and operation?”, giving insights into the long-term investments, locations, role in the operation of the overall system, and individual operation of a hydropower storage.

3.1.3. Identify and define the needed output/results to answer the research questions

Clearly defining the needed outputs and results is a crucial step in making the research questions formulated for each iDesignRES case study analytically answerable. The definition of output metrics translates qualitative stakeholder concerns into measurable indicators that can be produced by models. This process is grounded in the feedback collected from local need owners, gathered during case study meetings, consortium discussions, and structured interviews conducted in WP6. These interactions ensure that the selected metrics, such as system costs, CO₂ emissions, flexibility needs, or energy security indicators, are directly relevant to regional decision-making contexts. The corresponding questionnaires used in WP6 guide this process, helping stakeholders articulate what outputs are necessary to inform their planning challenges and what level of detail is required.

Defining the output metrics early and precisely is essential for two reasons. First, it ensures that the research questions remain answerable within the iDesignRES modelling framework by linking stakeholder needs to quantifiable outcomes. Second, it streamlines the model selection and coupling process, since each required output determines which models need to be involved and how they must interact to generate the necessary indicators. For example, if stakeholders need information on electricity prices or grid congestion, operational or market-coupling models such as POMATWO or Plan4RES will be required; if the focus lies on long-term system costs or technology investment pathways, GENeSYS-MOD or JRC-EU-TIMES-OP will provide the relevant outputs.

3.2. Selecting the models

Each test case will apply a selection of models from these layers, based on the research question and the modelling capacity within the task. Model selection is not only a technical decision but a methodological one, grounded in the specific analytical needs of the region and the data that can be made available. It also depends on stakeholder preferences for output granularity, scenario realism, and interpretability. Each modelling setup is documented in detail, including the rationale for model selection, data sources used, and scenario assumptions. This transparency ensures that the results are traceable and reproducible, both across test cases and within stakeholder decision-making processes.

The coupling of models across layers follows a flexible strategy. We apply sequential coupling when results from a higher-level model are used as inputs or constraints in a lower-level model (e.g., using GENeSYS-MOD outputs as boundary conditions for GeoMEC). In general, we soft-couple the models since they are not directly linked but share harmonised inputs, assumptions, or scenario structures. The

selection of the models for each case study is chosen based on feasibility, stakeholder relevance, and the nature of the research question.

In the following, we will describe the models within iDesingRES’s three-layer structure (cf. **Figure 1**). Table 1 summarizes the models in iDesignRES.

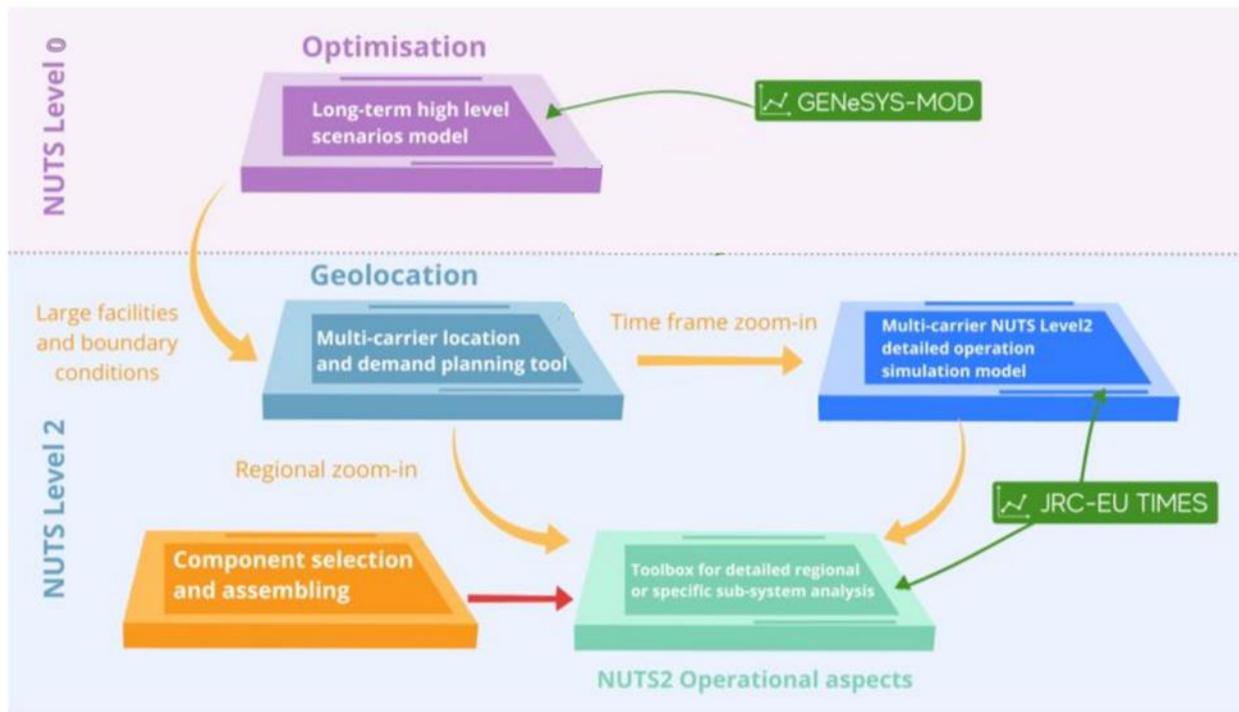


Figure 1: The iDesignRES three-layer approach. The multi-layered modelling framework for energy system planning spans across different spatial scales, from national-level (NUTS 0) optimisation with GENeSYS-MOD to regional-level (NUTS 2) geolocation, component selection, and detailed simulations using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

3.2.1. Layer 1 – Long-Term System Optimisation

GENeSYS-MOD: GENeSYS-MOD is a cost-optimisation model for pan-European long-term energy system planning. It provides scenario-based pathways toward decarbonisation across power, transport, industry, and buildings by modelling technology investments, energy use, emissions and system costs under policy and technological constraints. The model serves as a foundational tool in iDesignRES, generating consistent boundary conditions and transition trajectories for downstream regional and technological or sector specific models.

3.2.2. Layer 2 – Regional Planning & Operation

GeoMEC: This model enables spatially explicit optimisation of infrastructure development for electricity, heat, and hydrogen at regional (NUTS2) scales. It incorporates region-specific parameters and constraints (e.g. renewable potentials, capacity factors, and techno-economic factors) to produce cost-optimal

layouts for infrastructure deployment and capacity expansion. Its key purpose is to translate system-level scenarios into actionable infrastructure decisions in specific territories.

JRC-EU-TIMES-OP: JRC-EU-TIMES-OP assesses operational feasibility of regional energy systems designed by GeoMEC at high temporal resolution. It complements planning tools by stress-testing configurations under realistic operational constraints, e.g., during low renewable energy availability or peak demand. It helps to validate whether regional system configurations are adequate and flexible to meet the energy demands.

3.2.3. Layer 3 – Power System and Market Models

POMATWO: POMATWO simulates the structure and behaviour of fully competitive wholesale electricity markets and redispatch. It includes functionalities to simulate the behaviour of prosumers that act under different market pricing schemes. It is especially useful for analysing market design impacts and price dynamics in use-case regions.

SMS++ / Plan4RES: SMS++ and Plan4RES offer highly detailed DC/AC power-flow and unit commitment modelling across national and cross-border grids. Their key role is to optimise investment and dispatch while incorporating seasonal storage, grid constraints, and technology-specific behaviours. These models are crucial for validating realistic electricity system expansion and operation strategies in large-scale networks.

GGM / MGNET / EMPIRE: GGM and MGNET simulate investment and repurposing decisions in pan-European gas, hydrogen, and CO₂ networks using a mixed-integer LP formulation. They are essential for examining the evolving role of gas infrastructures during the energy transition, including the feasibility and cost-effectiveness of converting natural gas pipelines to carry hydrogen or CO₂. EMPIRE model has integrated GGM into its power system modelling making it a full multi-carrier energy system model.

3.2.4. Layer 3 – Sector-Specific Demand Models

Industry Demand Model: IDR-IIsim is an open-source compiler designed to bridge the gap between process-level industrial data and large-scale energy system or circular economy models. Its primary aim is to process declarative, data-driven industrial models described in YAML format and automatically generate validated, executable Python classes. This development facilitates the flow of information among industry experts, programmers, and public policy makers. The industrial process is described declaratively in a structured YAML format and translated into production-ready Python code. This resulting class can process production data to accurately estimate energy and material demands and emissions. This capability aids in quantifying material requirements, identifying circular economy initiatives, and evaluating future policy scenarios.

Building Demand Model: The model estimates the hourly energy needs and consumption of different types of buildings (residential and tertiary), distinguishing between their end use and the fuel used. To do this, it uses specific geometric data at the building level and a characterization of building archetypes that are used for the energy characterization of the building stock at NUTS Level 2. The model considers, among other aspects, the area, height, and occupancy profiles for the characterization of the building sector, as well as the climate data necessary for adaptation to the specific location selected. The model allows for the evaluation of the effect of measures such as energy rehabilitation, the adoption of technologies such as solar photovoltaics, or the replacement of heating equipment, enabling the comparison of different scenarios for the deployment of decarbonization strategies and technologies.

Transport Model: This model is a long-term planning tool which determines vehicle stock development, mode shift and the deployment of different fuelling infrastructure types. It can be soft-coupled with energy system models by using the fuelling prices, upper-level bounds to modal shifts and technology adoption, as well as scenario-dependent data (i.e. demand projections, adoption rates, policies). The model is designed to be applied at NUTS-2 or NUTS-3 level. It is important to emphasize that careful local calibration and data research is needed to ensure the accuracy and robustness of modelling results.

3.2.5. Layer 3 – Multi-Carrier System Components (EnergyModelsX)

The energy system optimization model *EnergyModelsX* was extended with multiple new descriptions for different technology types as outlined below. These different packages can be combined into a bottom-up energy model for analysing the energy system at the desired temporal, spatial, and technical resolution. A receding horizon framework compatible with all described technologies was also developed within the project to provide the capability of operational stress testing an energy system at both high temporal and technical resolution. The following technologies were further developed in the project:

Hydro & Batteries: The hydro and battery modules within the existing *EnergyModels-RenewableProducers* package simulate cascaded reservoirs with inflow profiles and PQ-curves and short-term battery systems with a lifetime and corresponding storage capacity losses. They are used to evaluate system flexibility, short- and long-term storage performance, and optimal utilisation of storage in regional system operation.

Hydrogen System: The *EnergyModelsHydrogen* package models electrolyser technologies, reformers, hydrogen storage, and compression dynamics. Hence, it provides an improved description of how hydrogen can provide flexibility to the energy system.

District Heat & Heat Pumps: The *EnergyModelsHeat* package covers district heating networks, heat pumps, thermal storage, and heat recovery. It enables modelling of decentralised and centralised heating strategies, particularly relevant in urban contexts and industry clusters.

Geographical Linkage: The *EnergyModelsGeography* package enables spatial coupling of energy areas via transmission corridors. It models energy flow across different regions and energy carriers, supporting realistic assessments of infrastructure integration, congestion, and cross-border system operation.

The utilized packages will depend on the application. The required functionality within a case study will impact the chosen packages for the respective application.

3.2.6. Validation Model

EnergyPLAN: EnergyPLAN simulates hourly operational dynamics of national or regional energy systems, covering power, heat, and transport. It is used in iDesignRES to validate investment scenarios and planning assumptions generated by optimisation models. It offers a bottom-up simulation-based check on whether system configurations can deliver energy reliably under realistic operational patterns.

Table 1: Overview of models in iDesignRES.

Layer	Model Name	Model Type	Spatial Scale	Sectoral Focus	Temporal Resolution	Key Inputs	Key Outputs	Purpose & Use
1	GENeSYS-MOD (TUB)	Bottom-up Energy System - Optimisation	EU / National	Power, transport, industry, buildings, hydrogen	5-year steps to 2060	Technology costs, policy targets, fuel prices, demands	Technology deployment, energy mix, emissions, system costs	Scenario analysis and pathway generation at EU scale, boundary conditions for Layer 2
2a	GeoMEC (E3M)	Energy System / Infrastructure Planning	NUTS2	Electricity, heat, hydrogen networks	Seasonal/ daily time slices	RES potentials, demand profiles, cost data, land use	Optimal network layouts, energy flows, infrastructure needs	Regional infrastructure and siting optimisation
2b	JRC-EU-TIMES-OP (PSI)	Energy System (Operation)	NUTS2	Electricity and heating	Season/ Week/ Hour	Capacity of technologies. Time series for demand, Resource profiles, techno-economic parameters	Sub-annual integrated system operation, Supply adequacy and flexibility need	Operational validation and stress testing of system configurations
3	POMATWO (TUB)	Electricity Market Simulation	Zonal / Regional	Electricity markets	Hourly (multi-stage)	Market zones, supply bids, demand profiles,	Market clearing prices, redispatch schedules	Simulation of electricity market stages including Zonal/Nodal

						network constraints		wholesale markets and redispatch
3	Plan4RES/SMS++ (EDF)	Power System Optimisation	EU / Regional	Electricity, flexibility, storage	Hourly	RES profiles, technology costs, flexibility constraints, grid topology	System cost, flexibility indicators, generation dispatch, unit commitment	Detailed investment and dispatch planning with AC/DC power flows
3	GGM / MGNET/EMPIRE (NTNU)	Gas System Investment Planning integrated in a multi-carrier model	Pan-European	Natural gas, hydrogen, CO2, transport	Annual 2020-50	Pipeline data, supply/demand forecasts, repurposing options	Pipeline investment/repurposing, gas flow patterns	Optimisation of future gas infrastructure under transition scenarios
3	Industry Demand Model (Deusto)	Industrial Demand Modelling	Sectoral / Process level	Industry (cement, steel, etc.)	Annual	Production volumes, process recipes, emission factors	Energy/material demand, emissions per process	Estimate process-specific energy and emissions intensity
3	Building Demand Model (Tecnalia)	Building Demand Simulation	NUTS2 / Building	Buildings (electricity, heating)	Hourly	Building archetypes, weather, retrofit options	Hourly electricity and heat demand	Model energy demand in buildings and assess retrofit impacts
3	Solar PV model (Tecnalia)	PV Supply Simulation	Building	Buildings (PV)	Hourly	Building types, location	PV supply profiles, prosumer shares	Provide PV profiles and prosumer data

3	Transport Model (TU Wien)	Transport Demand and Modal Shift	National / Regional	Passenger and freight transport	Annual	Modal shares, consumer types, prices, infrastructure	Modal/drivetra in mix, energy demand, emissions	Assess modal shifts, EV uptake, and infrastructure needs
3	Energy-ModelsX (SINTEF)	Bottom-up energy system - multi horizon and receding horizon capabilities, both operational and investment	Up to the user, NUTS2 for stress testing	Depending on chosen packages, Electricity, heat, hydrogen networks	Fully flexible, can be varying	Technological parameters, fuel prices, demands	Dispatch of different technologies within the modelled energy system, emissions, total system costs	Operational validation with improved technological descriptions
3	Combined Heat and Power (SINTEF)	Thermodynamics based model	Plant	(Bio)CHP for heat and power	None	Desired production for heat and electricity, biomass input	Optimal plant design for a CHP plant, including CAPEX and OPEX	Data generation for differing biomass input
3	Wind module (SINTEF)	Wind power supply simulator	Coordinates based	Power generation	Hourly	Windfarm parameters and location as well as power function	Electricity generation profile for a given wind farm	Calculation of wind power profiles to be utilized by other models
Valid.	EnergyPLAN	Energy System (Simulation)	National / Regional	All sectors (electricity, heat, transport)	Hourly	Demand, supply, policy constraints, techno-economic parameters	Energy balances, curtailment, import/export needs	Cross-model validation and operational feasibility checks

3.3. Selecting the underlying scenario

All scenario narratives (e.g. *REPowerEU++*, *EU Trinity*) are developed in WP2. Each scenario includes:

- A consistent storyline (e.g. *EU Trinity* follows the logic of increasing erosion of international cooperation)
- Macroeconomic and policy assumptions (GDP, carbon price, renewable targets)
- Sectoral development trajectories (e.g. heating electrification, EV uptake)
- Key system parameters (e.g. technology learning curves, potentials)

These narratives are documented in Bahrani et al. (2026). An overview of the key narratives of the scenarios is depicted in Figure 2.

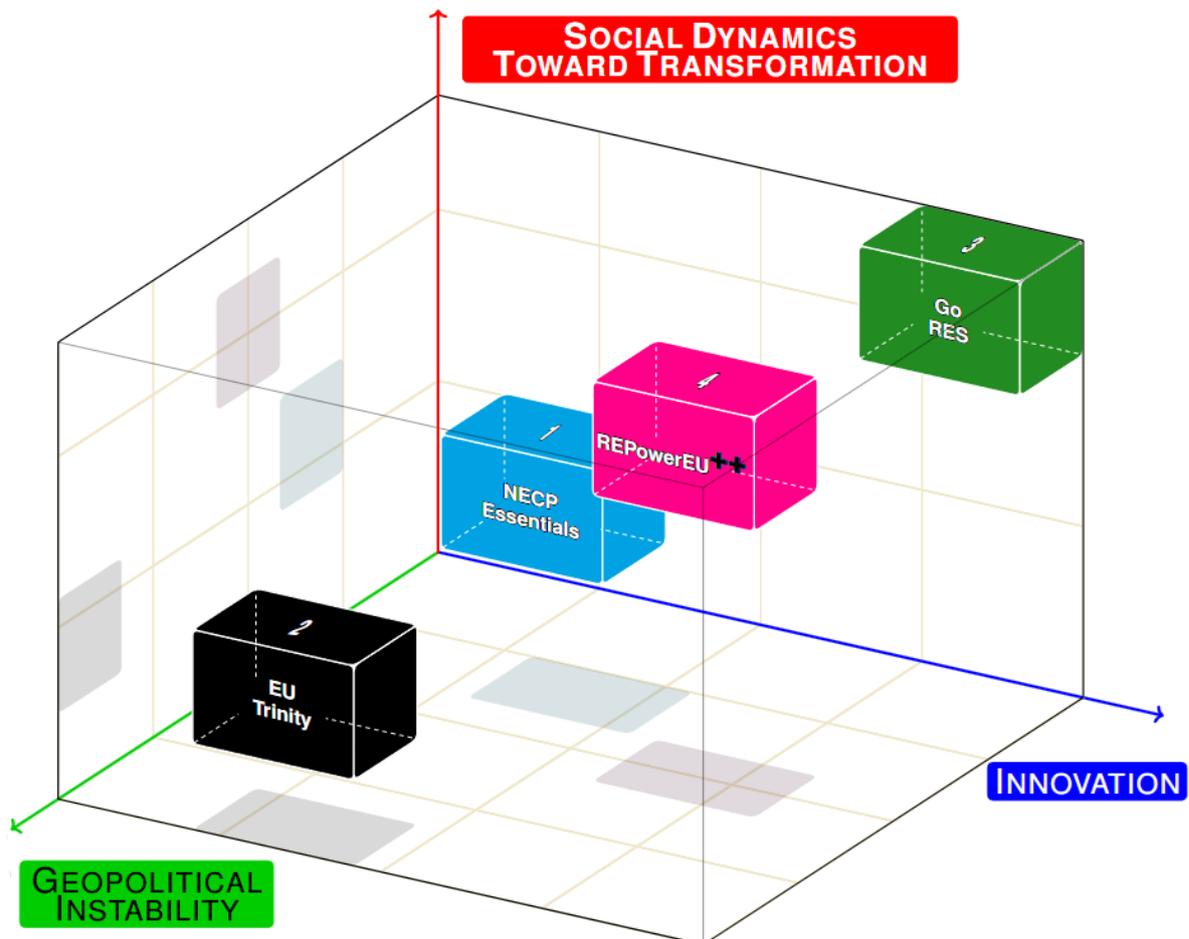


Figure 2: EU EnVis 2060 scenarios. The three dimensions of geopolitical instability, social dynamics towards transformation, and innovation create the space for the four EU Energy Vision 2060 scenarios, namely *EU Trinity*, *NECP Essentials*, *REPowerEU++* and *GoRES*.

Based on the research question and the challenges identified, each test case will be assigned a suitable scenario.

3.4. Input data for the case studies

All case studies within iDesignRES are based on a harmonised input data framework designed to ensure consistency, traceability, and reproducibility across all modelling layers. The foundation of this framework is the base data provided by GENeSYS-MOD, which constitutes the central reference dataset for all scenario-driven analyses. The complete set of scenario input parameters, including technology costs, energy demand projections, fuel price trajectories, policy variables, and emission targets, is available via Zenodo³ and the iDesignRES Scenario Explorer⁴. The scenario development and parametrisation process follows the methodology described in Barani et al. (2026), which establishes the quantitative backbone for all use cases and ensures full alignment with the overarching European scenarios applied in iDesignRES.

During the early phase of the modelling process, data requirements for each model and case study are systematically assessed to identify potential data gaps. Where specific models require input data not covered by the GENeSYS-MOD database, for example, detailed electricity grid topology, spatially resolved demand profiles, or NUTS2-level energy balances, these needs are documented in the central data input–output mapping file described in Deliverable 2.1. This file serves as a coordination instrument across the consortium, ensuring that all additional data requirements are flagged and that resources are allocated to the responsible partners for data collection. Each modelling team contributes to filling the identified data gaps using recognised and validated data sources, ensuring that all datasets meet the methodological and quality standards established in Work Packages 1&2.

To maintain full internal coherence, any additional sourced data that is scenario-dependent follows the same parametrisation logic as used in the EU EnVis 2060 scenarios by Barani et al. (2026). This guarantees that all scenario data extensions remain consistent with the shared storyline and boundary conditions. Regular modellers’ meetings are held throughout the process to discuss the parametrisation of new data, to review the consistency of assumptions across models, and to resolve any methodological discrepancies before integration into the common data environment. This iterative review mechanism ensures that all model inputs, regardless of their origin, reflect the same scenario logic and maintain interoperability between models.

An essential component of the data definition process is the integration of regional need owners and stakeholders. Each case study involves local partners who play a key role in shaping the research question and defining case-specific conditions. Their expertise ensures that locally relevant data, such as industrial structure, infrastructure availability, regulatory constraints, or technology deployment plans, are appropriately represented in the models if necessary. The inclusion of stakeholder-provided data is based on structured discussions and iterative validation between the modelling teams and the respective regional partners. This collaborative approach ensures that the model inputs are not only technically consistent but also contextually grounded in the realities of each demonstration region.

Finally, all data handling follows strict traceability requirements. Each dataset, model run, and resulting output is attributed to a defined input data version and clearly labelled within the consortium’s shared data repository. This metadata structure ensures that the provenance of every model result can be verified. Upon completion of the modelling work, the full input datasets for each case study, including the GENeSYS-MOD base data and all supplementary regional data, will be made publicly available on Zenodo and linked to the Scenario Explorer. Each dataset will be associated with the corresponding model instance and case study documentation, ensuring full transparency, reproducibility, and long-term accessibility of all modelling inputs used in iDesignRES.

³ <https://zenodo.org/records/13710869>

⁴ <https://idesignres.apps.ece.iiasa.ac.at/>

3.5. Process for the integration of need owners' requirements

A range of models and tools is being developed in iDesignRES. Applicability of the models varies from a specific system component to the whole European energy system. As they can answer a specific type of research question only at a time, it is necessary to link the models to develop insights into broader research questions pertaining to a test-case. Validating these models for specific test-cases gives the opportunity to incorporate corresponding challenges and needs and thereby test their robustness.

These case-study specific insights are collected from the relevant stakeholders and need-owners via interviews and consultations which are further translated into specific research questions. Translating the research questions into parameterization for models/ tools needs specific steps, and they depend on the data flow between models involved. Some of the need-owners' requirements (which can be qualitative or quantitative) have to be translated into the input data and scenarios of the models. On the other hand, model outputs need to ensure the research questions are answered appropriately and lucidly. For each test-case, the broad research questions of the need owners are first broken down to map individual models and thereby the needed interlinking and dataflow/ feedback is established between them. For a specific test case, each model's input data sets are aligned with case-study specific insights as discussed in the previous subsection. This will require incorporating any boundary conditions, policy inputs, and even updating data points specific to a test-case region. IIASA Scenario Explorer will contain the complete set of data relevant to a particular test-case. Via the IAMC common definition, each model will dynamically map and update the requisite input parameters/ constraints to align with the specificities of the test-case region. With the cloud hub platform being established in WP4, dynamic interlinking and execution of the models in the cloud will be tested and implemented in some test cases.

The models being applied to answer a broad research question for a test-case region can generate outputs at different dimensions. It is therefore important to develop relevant output, indicators, and metrics which then can be easily assessed by the need-owners for decision making. This is dependent on the model linking protocol, how the information transfer/ feedback happens between the models and how the indicators/ metrics are calculated. Calculation of these system indicators (e.g., cost, emission, energy security, flexibility) should be automatic based on automatic execution of the models in the cloud -hub. This will enable the need-owners to make informed decisions based on parametric execution of the models. IIASA scenario explorer and the cloud hosted visualization tools being developed in the WP5 can be used to dynamically report the system performance indicators based on cloud-based execution of the models for the test cases.

3.6. Determine stress test options

As part of the iDesignRES research design framework, this methodological approach outlines how stress testing will be conducted to assess the robustness, flexibility, and resilience of regional energy system models and configurations. It supports and complements the broader process of integrated energy system design, which includes defining case studies, selecting models and input data, constructing scenario narratives, and implementing a validation strategy.

Stress testing contributes by introducing extreme or disruptive variants to scenario narratives, to:

- Evaluate how well the system copes under adverse or unexpected developments
- Test the limits and adaptive capacity of different modelling approaches
- Identify vulnerabilities in infrastructure, supply, or market integration
- Support planning for resilient, low-carbon energy systems across Europe

This is a common methodological framework that all case studies are encouraged to follow. However, the final design and implementation of stress test variants will be tailored to each case study, reflecting its unique context and system characteristics.

The stress testing framework will be applied across the five iDesignRES case studies:

- **North Sea** – Offshore wind integration, cross-border flows, hydrogen infrastructure
- **South-East Europe (SEE)** – Coal phase-out, gas dependency, regional energy security
- **Greater Basque Country** – Decentralised RES, industrial electrification, local grid flexibility
- **Lombardy** – Urban electrification, industrial symbiosis, self-production, biomethane
- **Ukraine** – Energy system recovery, energy and infrastructure resilience, decentralisation

Each region presents distinct technological, institutional, and infrastructural challenges. The stress test methodology is designed to be flexible enough to accommodate these regional differences while ensuring consistency in approach across the project.

3.6.1. Methodological steps for stress test design

Step 1: Define Core Uncertainty Dimensions

Four common uncertainty dimensions have been identified to structure the design of stress tests. These represent areas of deep uncertainty with high potential system impact:

1. **Fossil Fuel Phase-Out / Supply Shortage:**
Tests the system's sensitivity to delayed fossil fuel retirement or external supply disruptions (e.g., geopolitical constraints on gas imports, particularly relevant for SEE and Ukraine).
2. **Infrastructure Availability and Reliability:**
Tests infrastructure build-out constraints or failures, such as delays in HVDC or hydrogen pipelines (e.g., North Sea), limited distribution grid capacity (e.g., Lombardy), or constrained cross-border transmission (e.g., SEE).
3. **Wholesale Price Volatility:**
Explores the economic resilience of the system under highly variable market conditions due to intermittent renewables, fuel price instability, or demand surges.

These dimensions are defined to be compatible with the broader narrative logic of the EnVis-2060 scenario framework and to reflect real challenges identified in the use cases.

Step 2: Align Stress Tests with EnVis-2060 Narratives

Stress tests will be applied as disruptive variants of some of the four EnVis-2060 scenario pathways:

Table 2: Core characteristics of EnVis 2060 scenario pathways

Scenario	Core Characteristics
Go RES	Innovation-led, rapid RES deployment, high electrification
RePowerEU++	Energy independence through diversified supply and infrastructure investment
EU Trinity	Fragmented political alignment, regional disparities in decarbonisation
NECP Essentials	Continuation of existing national plans and trends

Each stress test will modify, or "stress" one or more assumptions embedded in these narratives, such as the pace of infrastructure development, fuel availability, or public acceptance of initiatives like nuclear expansion. The goal is to evaluate the system's response under adverse or strained conditions. Stress

variants assess the resilience of each narrative by applying "what-if" scenarios (e.g., what if renewable energy system (RES) infrastructure is delayed in the Go RES scenario? What if there is a supply shortage in the EU Trinity case?).

Step 3: Contextualise stress variants by case study

Stress variants will be co-developed in each case study. Illustrative examples based on current system characteristics include:

Table 3: Illustrative stress test variants by use case

Use case	Illustrative Stress Test Variants
North Sea	Offshore wind underperformance; HVDC infrastructure delays; hydrogen pipeline bottlenecks
South-East Europe	Coal phase-out postponed; gas import crisis; cross-border transmission constraints.
Greater Basque Country	Local grid congestion under EV/heat pump uptake; industrial electrification overload
Lombardy	peak electricity demand under cold/hot years, grid bottlenecks, biogas and biomethane supply volatility; hydrogen chain development delays
Ukraine	fossil shortages; weak interconnection with EU power systems; nuclear deployment

These are exploratory and not prescriptive: each case study will define the final stress scenarios in alignment with its data, stakeholder insights, and modelling scope.

Step 4: Define Stress Test assessment indicators

To evaluate the impact of stress scenarios, a suite of Stress Test Assessment Indicators will be used. These indicators support comparison across the main scenarios and the stress test cases.

Table 4: Illustrative example of stress test assessment indicators

Stress Impact Area	Indicator
Technical Reliability and System Stability	Loss of Load Expectation (LOLE)
	Energy not served
	Curtailed of renewables
	Flexibility demand vs. availability
Infrastructure Utilisation and Bottlenecks	Grid congestion hours
	Interconnector or pipeline capacity saturation, additions
	Storage cycles and state-of-charge profiles
Economic and Market Impacts	Wholesale price volatility index
	Cost differentials between baseline and stressed cases
	Dispatchable capacity cost increases

Resilience and energy security

Import dependency share

Carbon emissions

Additional capacity required

The selected indicators will be tailored to each model's capabilities and regional priorities.

3.6.2. Integration into the modelling workflow

Stress tests will be implemented after the core scenario runs and used to explore the boundary conditions and edge cases of each design. They will help to:

- Identify the limits of current system designs under strain
- Reveal where flexibility, backup, or redundancy are insufficient
- Test how different models handle non-linear or disrupted dynamics
- Provide insights into where strategic interventions (e.g., storage, dispatchable backup) are most critical

Each case study will document the rationale, assumptions, and results of its stress tests as part of its integrated design process.

This stress testing methodology is a shared framework that will guide how each iDesignRES case study probes the resilience and adaptability of its energy system models. While the core dimensions and approach are consistent, the final stress scenarios will be customised and agreed upon in each regional context, ensuring that the process remains grounded in local challenges and priorities.

By embedding structured uncertainty into the system design process, iDesignRES supports the development of future energy systems that are not only clean and cost-effective but also resilient to disruption and capable of adapting to uncertain trajectories.

3.7. Validation strategy

EnergyPLAN is a techno-economic simulation tool used for advanced energy system analysis with a focus on the Smart Energy System approach where all energy sectors and their potential sector coupling and storage technologies are included (Lund et al. 2021). It models an energy system as a copper plate where groups of technologies are grouped into categories. This allows EnergyPLAN to simulate hourly operation of an energy system in a leap-year within seconds. EnergyPLAN's data structure is shown in **Figure 3**. Showing potential inputs, operational simulation possibilities and the outputs of EnergyPLAN.

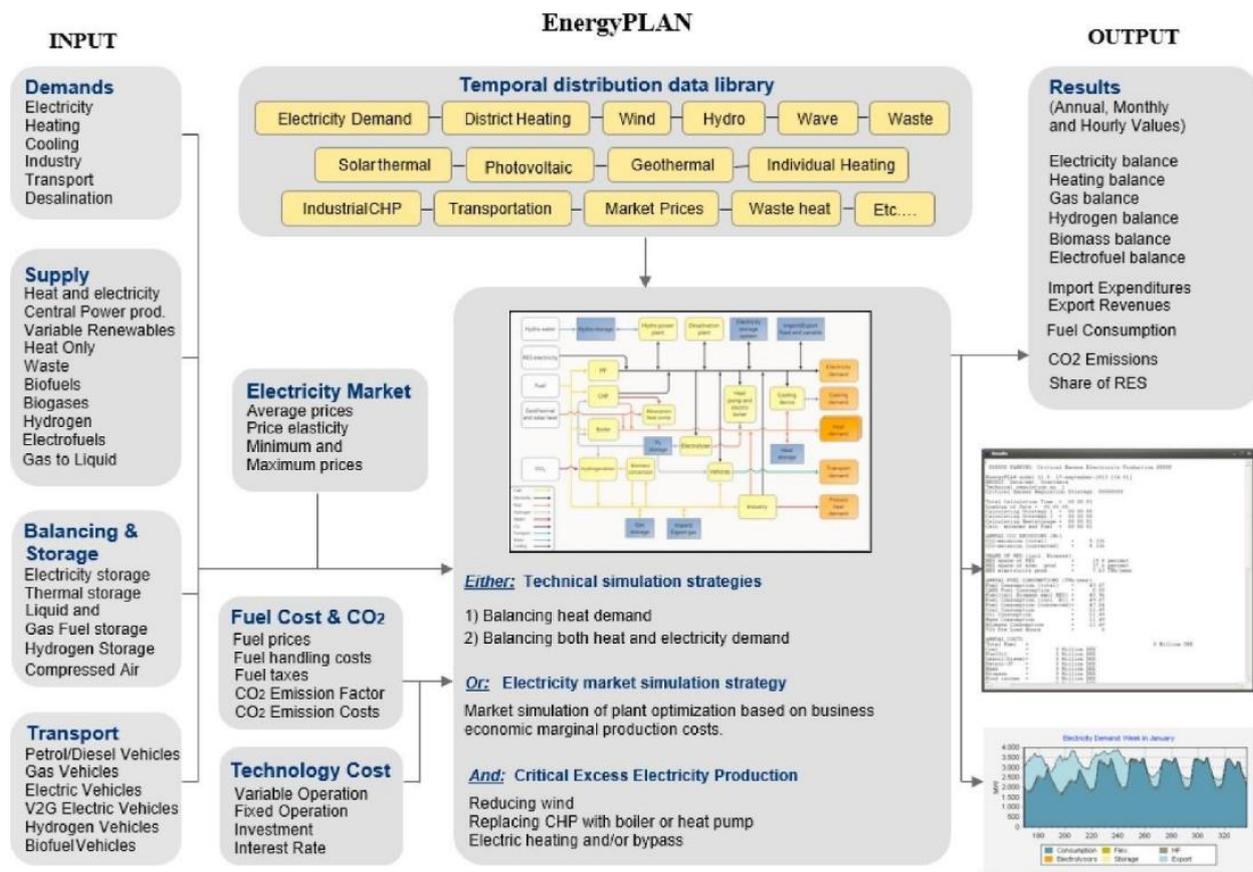


Figure 3: Overview of EnergyPLAN. Key input and output as well as sectoral representation of the model.

EnergyPLAN simulates the hourly operation of an energy system and provides the hourly operational data as well as summed results for monthly and yearly operation of the defined energy system. This both relates to energy flows in the energy system, CO₂ emissions by fuel consumption, and imports and exports of energy to and from the system. It also includes costs as they relate to investments, operation and maintenance (yearly fixed and variable), fuels (imports and exports), CO₂ quotas, and electricity (imports and exports).

EnergyPLAN has received ongoing development since 1999 and has been widely used within research for at least 315 peer-reviewed paper (July 2022 number) (Østergaard et al. 2022). It has previously been used to replicate historic operations of energy systems based on statistics, as well as a replication of simulation results of other energy system tools, such as MODEST (Lund et al. 2016), H2RES (Lund et al. 2007), LUT Energy System Transition model (Lopez et al. 2022), EnFloMatch (Laitinen et al. 2021), and Markal/TIMES (Theilufsen et al. 2019).

Analyses with EnergyPLAN has typically been analysed using Primary Energy Supply, CO₂ emissions, costs and Critical Excess Electricity Production (CEEP) as criteria for analyses (Østergaard 2015). CEEP is electricity that is produced in a given hour but cannot be used, stored or exported, and will in a real case typically result in e.g. curtailment of wind power, though CEEP has shown to be a useful metric for analyses. Validation will be based on yearly values for these factors, identifying how and why these factors differ based on the operation of the different technologies in the different tools. The validation process will be an iterative process, as to ensure that all aspects are considered.

4. Securing consistency and harmonisation...

For the upcoming test cases we will need to ensure consistency and harmonisation not only between the models but also between each of the test cases. The framework to do so is described below.

4.1. ...between the models

The first harmonisation exercises were carried out during the test case for the Spanish energy system, which involved the models Plan4RES, MGET, the regional building model, POMATWO, and the transport model. This pilot demonstrated how multi-sectoral models could be coupled coherently across different spatial and temporal layers. Specifically, Plan4RES with POMATWO represented the chained electricity market operation from seasonal to intraday and redispatch stages, MGET simulated gas and hydrogen infrastructure development and repurposing, while the building and transport models provided detailed, regionally grounded demand profiles. Through this exercise, the project gained crucial insights into how to align sectoral models methodologically, particularly the need for standardised data structures, consistent technology cost definitions, and clearly defined workflows for scenario propagation between energy sectors. It also showed the importance of transparent data documentation, unified treatment of capacity and operational constraints, and the consistent application of scenario parameters, such as those provided by GENeSYS-MOD.

Building upon these experiences, Deliverable 2.1 defined the formal rules and standards for securing consistency and harmonisation across all iDesignRES modelling teams. These standards were so far primarily applied to the core modelling teams, GENeSYS-MOD, GeoMEC, and JRC-EU-TIMES-OP, but shall be equally binding for all other models integrated into the case studies. The rules defined in D2.1 establish a unified modelling framework grounded in four principles.

First, all models are aligned with a shared scenario narrative derived from WP2, ensuring identical boundary conditions for carbon pricing, technology costs, energy demand, and policy assumptions. Second, all input and output exchanges follow the IAMC data format, providing a uniform tabular structure that ensures full interoperability and traceability of data. Third, model interface protocols define the exchange points and the variables to be shared, such as generation capacities, cost coefficients, demand profiles, or flexibility indicators, harmonised in units, temporal resolution, and spatial aggregation. Fourth, a continuous iteration and validation cycle among the modelling teams guarantees convergence of results. Outputs from one model are systematically validated in others, discrepancies are identified, and assumptions are adjusted to maintain consistency across layers.

This combination of practical experience from the Spanish mini test case and the formalised standards in Deliverable 2.1 ensures that iDesignRES maintains a coherent, reproducible, and transparent modelling environment across all test cases and work packages. In the following, aspects for further standardisation and harmonisation are elaborated.

4.1.1. IAMC data format

All data used and generated within iDesignRES follows the Integrated Assessment Modelling Consortium (IAMC) data format⁵ to ensure consistency, interoperability, and comparability across models and scenarios. The IAMC format provides a structured and standardised way of representing quantitative model data, consisting of a set of variables. This format allows different modelling tools, ranging from

⁵ <https://docs.ece.iiasa.ac.at/iamc.html>

energy system and macroeconomic models to sectoral and geospatial analyses, to exchange results seamlessly and to store both input and output data in a common, machine-readable tabular structure (typically in CSV or Excel format). The IAMC standard is widely used in the international research community and forms the basis for platforms such as the IIASA Scenario Explorer. Within iDesignRES, all participating models comply with this format for both input and output data. Whenever new indicators or case-specific variables are required during the project, they are formally integrated into the shared IAMC variable dictionary through a pull request procedure. This ensures that any extensions are transparently documented, approved by the consortium, and consistent with the established naming conventions and unit standards. Adhering to the IAMC structure guarantees the traceability of results across work packages and facilitates the alignment of iDesignRES outcomes with broader European and global scenario frameworks.

4.1.2. Sectoral representation

We need to align the sectoral representations of each of the connected models. Therefore, we have regular exchange meetings between the modelling teams to discuss sector by sector and technology by technology to make results comparable. This includes e.g. the conversion of units, comparison of endogenous or exogenous energy demands, technological detail (e.g. different types of heat pumps), different fuels (e.g. hydrogen, synthetic gas, ammonia) or inclusion of sectors such as district heat. The results and input parameters are adjusted between the models to consider the different sectoral representations and ensure that each model examines a comparable part of the energy system without creating blind spots or double counting of energy production or demand.

4.1.3. Regional and temporal representation

Further, we performed and will further perform alignments on the regional and temporal level. Input parameters and output variables need to be correctly interpreted so country specific data coming from GENeSYS-MOD is adequately handled by GeoMEC to translate that into NUTS2 level results. The power system models then need to translate the NUTS2 level results into node-based results representing the electricity grid.

The same accounts for the temporal resolution. We need to secure that demand and production profiles are in an adequate format. GENeSYS-MOD for example cannot provide hourly production profiles due to the computational complexity. Here we will develop solutions to provide models with higher resolution if needed. To further align on the model coupling details, we will have an in-person meeting of the modelling teams at the beginning of the test case phase early 2026, and continuous meetings throughout the case studies.

4.1.4. Model assumptions

Key to yielding usable and transparent results is highlighting the implicit and explicit assumptions underlying each of the models. This for example includes the availability of curtailment of energy, certain fixed security margins for dispatchable technologies, limits on the expansion rate of technology or simply assumptions on how fast a nuclear power plant could be realised. Here, the expertise of each modelling team is needed to communicate the specific properties of their model and help interpreting the results as well as harmonize some of the model properties and assumptions to fit the other models.

4.2. ...between the case studies

To ensure full consistency, harmonisation, and transparency across the iDesignRES case studies, a common methodological and data framework is applied to all modelling activities. Each case study operates under the same overarching scenario set, the EU EnVis 2060 scenarios, which define the shared boundary conditions for carbon pricing, energy demand, technology costs, and infrastructure development. This guarantees that regional analyses and model applications remain aligned with the long-term European transition pathways developed in Work Package 2.

Model version control is an equally critical component of harmonisation. All models applied in the case studies are versioned, and the specific version used in each modelling exercise is explicitly recorded and linked to the corresponding outputs. Versioning ensures that results can be reproduced, compared, and verified over time. These metadata, together with the input datasets, are uploaded to Zenodo and the Scenario Explorer. This system provides transparent documentation of which data, parameters, and model versions have been used and how they relate to the overarching scenario framework.

Each case study report includes a standardised representation of model configurations, documenting the exact model and data versions used, along with any justified deviations introduced to account for regional or sectoral specificities. Such deviations, e.g. region-specific demand profiles, industrial structure adjustments, or local infrastructure assumptions, are recorded in the structured reports for each of the case studies to maintain methodological comparability. Harmonisation is further supported through a shared data exchange protocol, which requires all models to follow the IAMC data format for inputs and outputs, allowing seamless integration and consistent interpretation across work packages. Regular coordination meetings among the core modelling teams provide an additional layer of quality assurance, facilitating early identification of inconsistencies in scenario assumptions, data transformations, or variable definitions.

Beyond technical alignment, harmonisation also encompasses the procedural dimension of modelling: each case study follows the same workflow for scenario implementation, data pre-processing, and output validation, as defined in Deliverable 2.1. The adoption of this standardised process, combined with open documentation and centralised version management, ensures that all case studies in iDesignRES are not only comparable and interoperable but also fully transparent and reproducible.

5. North-Sea case - macro region test case

5.1. Use case overview

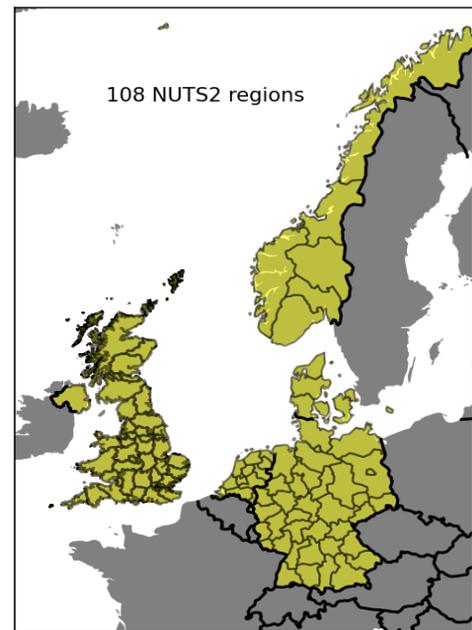
The North Sea case study considers the macro-region consisting of the North Sea basin itself and the surrounding countries, i.e. GB, NL, DE, DK, NO. The region is characterized by fast-growing wind energy, by large hydropower and water storage capacity, and by high offshore oil and gas exploitation. There is a well-developed subsea infrastructure with pipelines for natural gas transport, and multiple high-voltage DC electricity interconnectors between countries. Key drivers and uncertainties with major impact on the future development of the region are the costs of new technologies (e.g. DC grids, floating wind, carbon capture and storage, hydrogen storage), technology maturity and supply chain readiness, level of international alignment and cooperation, decarbonisation urgency and political ambitions, the growth of hydrogen demand, the speed of offshore wind capacity buildout.

Needs and need owners:

- Governmental agencies (e.g. RVO in the Netherlands) who provide knowledge basis for policy development: Need tools and analyses with well-documented baselines and harmonized input data, that consider construction lead times and social and regulatory inertia. Hybrid model approach with gradually increasing granularity and detail level, which includes balanced objectives of cost, energy efficiency, resilience and implementability.
- Power market operators (e.g. Nord Pool) need to consider the interaction of different commodities (gas and hydrogen) with power market, especially their impact on power price formation. The evolution of the power market, e.g. the emergence of real-time markets and new flexibility products are of high interest.
- Network operators (e.g. Gassco, Statnett, Energinet, National Grid): Decision support for system planning with an integrated multi-carrier approach considering electricity, gas and hydrogen infrastructure

Challenges for the region:

- Integration of offshore wind – transmitting the energy to consumption centres, and balancing the variability of wind on multiple time scales
- Offshore energy transmission infrastructure planning
- Understanding the need for flexibility and balancing of renewable energy, considering existing and new energy exchange, storage and demand flexibility



Case study timeline:

	2025	2026											
Activity	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Workshops	w1			w2			w3				w4		
GeoMEC				M1									
JRC-EU-TIMES-OP					M2								
EnergyPLAN						M3							
Electricity sector						M4							
Transport sector						M5							
Buildings sector						M6							
Offshore infrastructure						M7							
Component level						M8							
Reports/publications										draft		P1	D3.2

w: workshops, M1-8: model runs and produces preliminary results, P: publication, D3.2: deliverable.



Figure 4: Workshop discussion on the main challenges, opportunities and questions that will shape the North Sea’s energy transition.

5.2. Research questions

Based on the case study objective and discussions amongst partners and stakeholders, two main research questions have been specified. The first addresses the development of North Sea energy infrastructure at NUTS2 level. The second addresses how the overall development affects specific sub-sectors and sub-regions when analysed in more detail. The second research question is split into several sub-questions.

Thus, the case study will investigate the following research questions (RQs):

RQ 1: What is the role of the North Sea in the green transition, and how do optimal investment decisions depend on the transition scenario?

- How does the North Sea region’s energy transition pathway evolve in each scenario?
- How much offshore wind power capacity is realised in the North Sea, and where is transmission capacity suggested?

- What is the split between electricity, natural gas and hydrogen infrastructure?
- To what extent is the North Sea transmission infrastructure used for transfer of wind power to shore vs. transfer of energy between surrounding countries?
- How is infrastructure for transport and permanent storage of CO₂ deployed?

RQ 2: What is the impact of the transition scenario on selected sub-sectors and regions?

- **RQ2.1 (Electricity sector):** Where will grid congestion appear, and how are temporal and spatial variations in electricity prices? This question addresses the electricity sector from the power market perspective. Large changes in generation capacity and power consumption will have a large impact on the power system. Specific questions addressed are:
 - Is the solution found by the energy system planning models adequate when simulated in a more detailed electricity market model?
 - Where are the major grid bottlenecks / sections with high power price gradients?
 - What are power flow characteristics, including import/export between price zones?
- **RQ2.2 (Offshore transmission infrastructure):** What is the optimal offshore energy transmission infrastructure development? This question goes deeper into the issue of offshore energy infrastructure planning with higher sub-NUTS2 geographical resolution, considering both electricity and gas/hydrogen pipeline infrastructure. Specific questions addressed are:
 - What is the most efficient method for transporting offshore generated energy to the shore?
 - To what extent can existing gas pipelines be used to transport energy in the form of hydrogen?
 - What is the optimal balance between HVDC electricity transmission and hydrogen-based transport to ensure cost efficiency and system reliability?
- **RQ2.3 (Transport sector):** What are the needs for and impact of infrastructure and energy supply for ports and distribution logistics? Within the larger question of the North Sea energy transition, questions surrounding the infrastructure need and energy supply for ports and distribution logistics are relevant. Two particularly important aspects will be addressed:
 - With the decarbonization of the maritime sector and of the connected distribution logistics on land, road and rail, what is the required energy supply infrastructure (for fuelling and charging) and how do current ports and mode infrastructures need to change?
 - How does this new infrastructure affect optimal operations in the logistics which are sensitive to operational efficiencies, fuel prices, as well as tariff or tax structures?
- **RQ2.4 (Component level): How do different flexibility sources contribute to energy balancing in an integrated energy system?** This question addresses phenomena that may be missed in linear planning models by considering more detailed physics-based modelling and analysis of selected components. Simpler models tend to be overly optimistic because they ignore many constraints that can be captured with more detailed modelling. The research question considers the operation of the energy system for a given configuration, with an emphasis on hydropower with storage, optimal use of electrical/gas transmission, hydrogen value chains, and multiple flexibility sources including electrical/gas storage. Specific questions to address are:
 - Is there sufficient operational flexibility in the solutions found by the energy system planning models?
 - To what extent is multi-carrier integration contributing to energy system balancing?

To answer the research questions, the following model outputs are needed:

- **RQ1**

- The amount (MW) and geographical distribution (country/offshore region) of offshore wind in the North Sea.
- The amount (MW, km) of offshore transmission infrastructure for electricity, hydrogen, natural gas, and CO₂, between various regions in and around the North Sea.
- Energy exchange between regions (MWh/year, time-series) for different energy carriers.
- Deployment and utilisation of carbon storage facilities
- **RQ2.1 (electricity)**
 - Time-series of power flows in the electricity grid (MW)
 - Time-series of electricity prices or marginal costs of supply per region (EUR/MWh)
- **RQ2.2 (offshore networks)**
 - Detailed offshore transmission capacity for electricity, natural gas and hydrogen (MW), on a sub-NUTS2 level.
 - Utilisation of this infrastructure, as time-series (MW) or annual values (MWh/year)
- **RQ2.3 (transport)**
 - Energy demand (MWh) in North Sea ports and onshore distribution logistics
 - Port infrastructure investments (MW or equivalent), including capacities for fuelling and charging
 - Time-series for the operations of logistics, including fuel prices
- **RQ2.4 (components)**
 - NL building sector energy demand breakdown per type (MWh/year)
 - Time-series of the utilisation of flexible hydropower, offshore storage, demand flexibility and energy exchanges between regions and between electricity, gas and hydrogen

5.2.1. Modelling RQ 1 – Role of the North Sea

For this research question, the optimal energy system development at NUTS2 geographical granularity will be computed for two different energy system scenarios. Comparison between the scenarios will give information on the degree to which observed development trends are dependent on scenario assumptions.

The following models will be applied:

- **GeoMEC:** Provides energy infrastructure capacities per NUTS2 region and offshore areas, using as starting point the outputs from the GENESYS-MOD (stored in the scenario database).
- **JRC-EU-TIMES-OP:** Provides additional operational information (time-series outputs) by simulating the systems identified with the GeoMEC model in an operational model at a higher temporal resolution. This will also validate that the GeoMEC solution is adequate.
- **EnergyPLAN:** Contribute by validating GeoMEC and JRC-EU-TIMES-OP results by independent analysis, using as far as possible the same input assumptions.

5.2.2. Modelling RQ 2 – Sector-wise impacts

To answer this research question, different sector models will be applied for each sector-wise sub-question. The results from GeoMEC and JRC-EU-TIMES-OP will provide the starting points for these higher-resolution analyses. The various models will contribute as follows.

- **POMATWO:** Generates detailed results for the electricity market and will provide outputs required to answer RQ2.1.

- **GGM:** Generates detailed results for the offshore pipeline and grid infrastructure investments and will provide the output needed to answer RQ2.2.
- **Transport sector model:** Generates detailed results for the transport sector and will provide outputs required to answer RQ2.3.
- **Building sector model:** Simulates the construction of the building sector for each region in the Netherlands. The analysis will provide information about how the energy consumption of these buildings is broken down by region, distinguishing between building types, ages, etc. The model will provide simulation results of demand by building type, end use, estimated equipment types, and the potential for deploying solar photovoltaic energy in buildings. This data can be used to estimate the potential flexibility that the building sector can provide in different regions. This will contribute to answer RQ2.4
- **EnergyModelsX:** Considers detailed component models for renewable energy technologies (hydropower, solar, wind), hydrogen, transmission and storage, and will combine these in a receding horizon simulation of a sub-system of the North Sea region. This generates output to answer RQ 2.4.
- **EnergyPLAN:** Will contribute to RQ2.4 by providing sector coupling results at lower spatial scale for comparison.
- **JRC-EU-TIMES-OP:** Will contribute to RQ2.3 optimal operations of the logistics at NUTS2 level, and to RQ2.4 by providing input data and results at NUTS2 level for comparison/ validation at lower spatial scale by component models.

5.3. Scenario selection and applied stress test

5.3.1. Scenarios

All transition scenarios are relevant, and to gain insight into the role of the North Sea in a wider sense, it is necessary to analyse more than one scenario. At the same time, limiting the scope of the case study is necessary. Hence, two scenarios are selected. This allows for comparison between different green transition pathways and what they imply for the North Sea region, both in terms of investments and operation of the energy system. The two scenarios should differ in ways that are relevant for the North Sea, such as offshore wind development and offshore electricity and pipeline infrastructure. The chosen scenarios are:

1. **Go RES** – a scenario with high and early investments in green technologies, and therefore high offshore wind deployment which is a central factor for the North Sea case.
2. **NECP Essentials** – a moderate scenario with slower deployment of offshore wind, lower electricity demand increase, and considerably more nuclear power in the generation capacity mix.

These two scenarios give quite different projections for the North Sea in terms of offshore wind deployment and energy infrastructure and are expected to give a good foundation for comparisons to address the research questions.

5.3.2. Stress tests

Following the prescription defined in section 3.6, stress tests are suggested to evaluate the resilience of the scenario-based results. These are:

1. Availability of energy infrastructure: Delayed readiness of HVDC and/or hydrogen pipeline infrastructure due to slower technology development, manufacturing value chain limitations, perceived complexity and risk, or regulatory barriers that limit the type of HVDC infrastructure that can be built, favouring simple radials or string solutions over multi-terminal and meshed configurations. This issue is likely to have a large impact on RQ1 on the overall role of the North Sea.
2. Weather events – Dunkelflaute and wind power surplus: Extended periods with low (or very high) wind power output. This tests whether the amount of flexibility in the system is adequate and is expected to impact several sub-questions in RQ2.
3. Cross-border trade is interrupted: Use of offshore energy transmission infrastructure is limited due to reasons such as large-scale sabotage, political shock and desires to be autonomous or similar. As the North Sea is a major energy transport region, this will likely have a large impact on system operations and questions addressed in RQ2.

5.4. Data

Table 5: Data needs for the models in the North-Sea case study

Model name	Data need
GENeSYS-MOD	-
GeoMEC	<p>Spatial RES potentials at NUTS2 level</p> <p>Land-use restrictions and protected areas</p> <p>Demand profiles, cost data</p>
EnergyPLAN	<p>As EnergyPLAN will be used for validation purposes all Capacity, Emissions, Final energy, Levelized cost, Network, Primary Energy, and Secondary Energy data will be needed for EnergyPLAN. Some data might need to be adjusted or interpreted before inserting into EnergyPLAN, though this will be an iterative process.</p>
JRC-EU-TIMES-OP	<p>Besides investment decisions or capacity expansion plans, and technology activity levels at annual-scale from GeoMEC at NUTS2 regions, JRC-EU-TIMES-OP requires hourly demand profiles of end-use energy carriers (electricity, hydrogen, synthetic fuels, etc.) by sector, as well as local wind, solar, and other RES supply profiles at hourly resolution.</p> <p>Any policy, non-technical, operational constraints and other techno-economic data aligning with GeoMEC</p>
Pomatwo	<p>Market and price assumptions, generation (installed capacities, generator characteristics and location, availabilities, historical generation profiles), demand (time series of nodal demand, time-dependent inflows to storage, fixed cross-border or inter-zonal exchanges), network constraints (zonal/aggregated) and line parameters, operational profiles from JRC-EU TIMES-OP.</p>
GGM	<p>Investment decisions and capacity expansion plans from GeoMEC.</p> <p>Pipeline data, supply/demand forecasts, repurposing options</p>
Transport sector model	<p>Modal shares, consumer types, prices, infrastructure</p>
Building sector model	<p>Building stock, retrofit options, weather data</p>
EnergyModelsX	<p>Investment decisions and capacity expansion plans from GeoMEC.</p> <p>Demand profiles.</p> <p>Technical parameters for each component type included in the modelling.</p>

6. Lombardy region – industrial test case

6.1. Use case overview

Lombardy is one of the most industrialised and energy-intensive NUTS2 regions in Europe. It generates more than 20% of Italy's GDP and accounts for approximately 18% of national final energy consumption. The region hosts an extensive concentration of energy-intensive and hard-to-abate industrial sectors, including chemicals, metallurgy, cement, paper, manufacturing, and machinery. This industrial structure, together with a high reliance on natural gas for electricity generation and civil heating, makes Lombardy's decarbonisation particularly challenging.



The region features a heterogeneous territorial configuration: metropolitan areas such as Milan, Bergamo and Brescia show high and rapidly evolving energy demand, driven by electrification, digitalisation and new large-scale loads (e.g., data centres). In contrast, rural and peripheral provinces display lower demand, stricter land-use constraints and more pronounced local opposition to renewable energy infrastructures. This spatial diversity translates into uneven opportunities for RES deployment and differing infrastructure needs across the region.

Despite these challenges, Lombardy has historically been a frontrunner in renewable energy deployment, particularly in photovoltaic and hydropower generation. In alignment with national targets defined in Italy's PNIEC 2024 and the regional "Piano Regionale Energia, Ambiente e Clima" (PREAC), Lombardy aims to reduce final energy consumption by 30% by 2030 and to exceed a 30% share of RES in final consumption. Achieving these objectives requires deep transformations across industrial processes, heating, power generation and transport - relying on electrification, hydrogen, CCS, efficiency and flexibility resources.

These characteristics represent a context where multiple transition bottlenecks converge: high energy demand, limited RES hosting capacity, strong permitting delays, fragmented data availability and increasingly stressed electricity grid conditions. To identify the needs and expectations of regional actors, three targeted interviews were conducted with key stakeholders:

1. Regione Lombardia (policy and planning authority);
2. RSE – Ricerca sul Sistema Energetico (technical authority), and;
3. GSE – Gestore dei Servizi Energetici (national RES and energy services operator).

The interviews reveal a coherent set of shared challenges across institutional, technical and industrial perspectives, including:

- High industrial energy demand and limited low-carbon alternatives - especially in hard-to-abate sectors.
- Grid congestion and insufficient hosting capacity for new RES - creating delays and curtailment risks for new RES installations.
- Slow and uncertain permitting procedures - affecting RES, hydrogen and CCS infrastructure.
- Spatial limitations and social acceptance barriers - linked to land-use constraints and local opposition.
- Rapid growth in electricity demand - driven by electrification, heat pumps, e-mobility and data centres.
- Data fragmentation and lack of standardisation - limiting evidence-based planning and modelling accuracy.

Insights from stakeholders also highlight strong interest in advanced scenario analysis, AI-enhanced tools, grid impact assessments, and flexible visualisation features—confirming the relevance of iDesignRES for supporting regional decision-making.

Proposed case study timeline & milestones

Activity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec 26
Workshops	W1			W2			W3			W4		
GENeSYS-MOD		M1										
GeoMEC			M2									
DEUSTO				M3								
JRC-EU-TIMES-OP					M4							
POMATWO						M5						
Integration & consistency checks							M6					
Reports / publications										Draft	P1	D3.2

w: workshops, M1-5: model runs and produces preliminary results, P: publication, D3.2: deliverable.

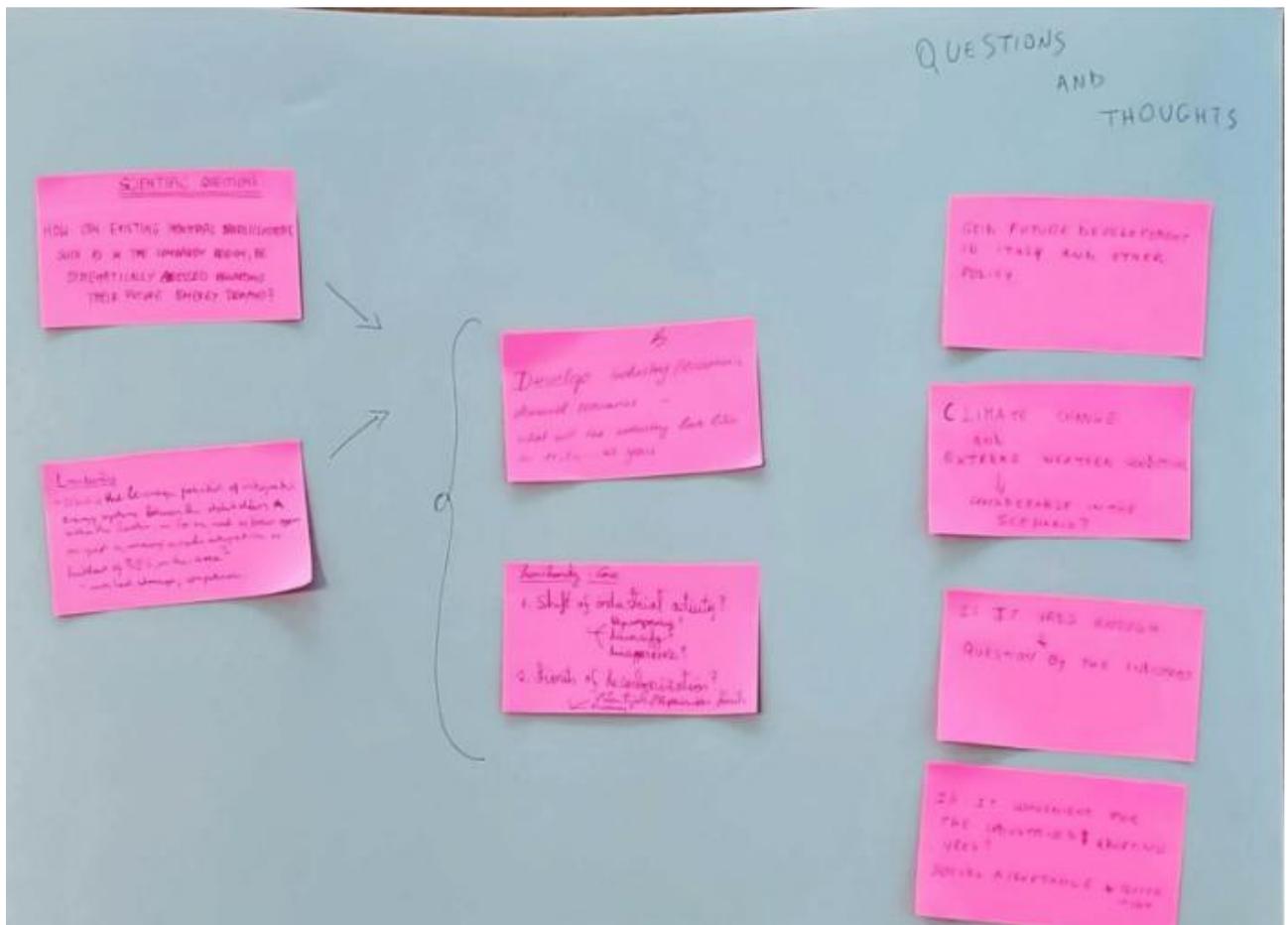


Figure 5: Workshop discussion on the main challenges, opportunities and questions that will shape the Lombardy’s energy transition. Poster output developed in the discussion.

6.2. Research questions

Based on the challenges above and aligned with WP3 requirements, the Lombardy demonstrator is structured around two modellable, stakeholder-informed Research Questions (RQ), each accompanied by specific sub-questions relevant to modelling teams.

6.2.1. RQ1 – Industrial Decarbonisation pathways for Lombardy

What is the cost-effective and technically feasible pathway to decarbonise Lombardy’s industrial system by 2050 through a mix of electrification, hydrogen, CCS, industrial efficiency and sector coupling, under regional spatial constraints?

Sub-questions:

- What combinations of electrification, hydrogen and CCS minimise system costs in hard-to-abate sectors?
 - → Answered by: **GENeSYS-MOD, GeoMEC and DEUSTO**

- How sensitive are industrial pathways to hydrogen availability, price and infrastructure rollout?
 - → Answered by: **GENeSYS-MOD, GeoMEC DEUSTO**
- How do spatial constraints affect the integration of on-site and off-site RES for industrial consumers?
 - → Answered by: **GeoMEC, GENeSYS-MOD**
- Are the resulting industrial electrification and hydrogen pathways operationally feasible from a system perspective?
 - → Answered by: **JRC-EU-TIMES-OP, supported by POMATWO**

To determine a cost-effective and technically feasible pathway for decarbonising Lombardy's industrial system by 2050, the study employs a coupled multi-model framework. This approach integrates macro-energy system optimisation with high-resolution spatial, sectoral, and operational analyses. The specific contributions of each model to the sub-questions of RQ1 are detailed below. Model input and output parameters for this case study are listed in tables in the Appendix.

6.2.1.1. Long-Term Decarbonisation Trajectories and Techno-Economic Optimisation

GENeSYS-MOD serves as the primary architect for the overall decarbonisation strategy, directly addressing the sub-question regarding the cost-optimal combinations of electrification, hydrogen, and Carbon Capture and Storage (CCS). It provides the macro-economic boundary conditions for the region.

- **Role:** It identifies the least-cost pathway for Europe and Italy, ensuring that regional industrial changes in Lombardy are consistent with wider EU climate targets (e.g., PNIEC 2024).
- **Key Output Parameters:** The model provides **CO₂ emission reduction trajectories (MtCO₂ /yr)**, **system-wide investment needs (M€)**, and the **cost-optimal technology mix (GW installed capacity)** for the industrial sector up to 2060. It also outputs **long-term energy carrier demand (TWh or PJ)** for electricity, hydrogen, and heat.

6.2.1.2. Sector-Specific Realism and Process Transformation

While GENeSYS-MOD provides the macro-pathway, **DEUSTO** introduces necessary sectoral granularity to hard-to-abate sectors (chemicals, cement, metallurgy, paper), refining the analysis of how sensitive pathways are to technology switching and fuel costs.

- **Role:** DEUSTO validates technical feasibility by modelling specific industrial processes. It translates the macro-level energy demands into detailed production realities, answering sub-questions on the feasibility of hydrogen and electrification uptake in specific industries.
- **Key Output Parameters:** DEUSTO generates **technology switching curves** (e.g., rate of kiln or furnace replacement), **fuel substitution patterns** (PJ per fuel type), and **sector-specific decarbonisation costs (€/tonne product)**. It ensures that the projected demand profiles are consistent with technical limits on retrofit rates and switching speeds.

6.2.1.3. Spatial Constraints and Resource Availability

GeoMEC addresses the sub-question regarding how spatial constraints affect the integration of on-site and off-site Renewable Energy Sources (RES). It enhances the economic optimisation in GENeSYS-MOD and DEUSTO by enforcing physical realities.

- **Role:** It links territorial restrictions to industrial transformation costs by calculating the optimal RES capacity considering land-use restrictions and protected areas at the NUTS2 level.
- **Key Output Parameters:** The model provides optimal **capacity expansions (GW per NUTS2)** and **energy flows (TWh)**.

6.2.1.4. Operational Feasibility and System Adequacy

To answer the sub-question on whether the resulting pathways are operationally feasible from a system perspective, **JRC-EU-TIMES-OP** performs high-resolution temporal analysis.

- **Role:** This model validates that the scenarios generated by the long-term planners (GENeSYS-MOD/DEUSTO/GeoMEC) do not create unmanageable stress on the grid. It identifies flexibility requirements and checks if the industrial electrification creates system adequacy issues.
- **Key Output Parameters:** Crucially, this model calculates **hourly operational feasibility** (dispatch profiles in MW), **flexibility requirements** (ramping needs in MW/h), and performs **system adequacy checks** (e.g. **Loss of Load Expectation (LOLE)** or unserved energy (MWh)) to ensure security of supply.

6.2.1.5. Market Dynamics and Price Signals

POMATWO complements the operational analysis by providing power market realism, addressing questions on how infrastructure rollout and price signals influence industrial transformation.

- **Role:** It models the electricity market to show how industrial electrification or hydrogen deployment influences prices and identifies congestion.
- **Key Output Parameters:** The model outputs **electricity prices (€/MWh)**, identifies **congestion events** (hours/year or volume in MW), and quantifies the **market impact of industrial electrification** (price delta in €/MWh). This reveals the price-driven incentives or disincentives for industry transformation.

6.2.2. RQ2 – Large-Scale RES Integration & System Resilience

How can Lombardy integrate large shares of renewable energy while ensuring grid adequacy and flexibility, considering uncertainties in permitting timelines, infrastructure development rates and regulatory bottlenecks?

Sub-questions:

- What grid reinforcement and flexibility investments are required to integrate high-RES shares?
 - → Answered by: **GeoMEC** and **GENeSYS-MOD**

- How do transmission grid bottlenecks influence curtailment, price formation and system stability?
 - → Answered by: **POMATWO**, supported by **JRC-EU-TIMES-OP**
- What operational challenges emerge under high electrification and demand growth scenarios?
 - → Answered by: **JRC-EU-TIMES-OP**
- How do spatial constraints and permitting delays affect realistic RES deployment?
 - → Answered by: **GeoMEC**, **GENeSYS-MOD**

To address the challenges of integrating high shares of variable renewable energy while maintaining system stability, the study utilises a coupled framework that spans long-term investment planning, spatial constraints, and high-resolution operational analysis.

6.2.2.1. Strategic System Design and Investment Planning

GENeSYS-MOD establishes the macro-level boundary conditions, defining the overarching strategy for RES deployment. It addresses the sub-question regarding the necessary investments for high-RES shares by optimising the long-term energy mix.

- **Role:** It determines the cost-optimal trajectory for RES deployment across the region, ensuring that generation capacity keeps pace with increasing electrification. It acts as the baseline for subsequent operational models by defining the required capacity mix.
- **Key Output Parameters:** The model outputs the **installed generation capacity (GW)** by technology type, **total system investment costs (M€)**, and the **national demand for flexibility and storage (GWh)** required to balance inter-annual variations.

6.2.2.2. Spatial Feasibility and Permitting Constraints

GeoMEC serves as the spatial reality check, directly answering how spatial constraints and permitting delays affect realistic RES deployment. It determines an optimal and feasible distribution of energy capacity on a NUTS2 level.

- **Role:** It calculates the optimal renewable energy capacity of Lombardy at the NUTS2 level, accounting for land-use restrictions and exclusion zones. It also models the impact of "bottlenecks" in permitting by setting limits on build-out rates.
- **Key Output Parameters:** The model provides **spatially explicit RES capacity installations (GW per NUTS2 zone)**, **maximum annual expansion rates (GW/year)**, and **spatial constraints driving curtailment risks**. These outputs quantify the physical upper bounds of RES integration.

6.2.2.3. Industrial Demand Flexibility

DEUSTO refines the demand side of the equation, ensuring that the system analysis reflects realistic industrial loads. It connects the industrial transition (RQ1) to the grid stability question (RQ2).

- **Role:** It generates high-fidelity load profiles for hard-to-abate sectors, identifying the potential for demand-side response. By modelling process-level characteristics, it highlights where industry can offer flexibility as a resilience lever.
- **Key Output Parameters:** DEUSTO provides **refined hourly industrial demand profiles (MW)**, quantifying the **potential for load shifting (MWh)** and the specific **flexibility characteristics** of electrified industrial processes.

6.2.2.4. Operational Adequacy and System Security

JRC-EU-TIMES-OP is the primary tool for assessing operational feasibility, answering sub-questions regarding operational challenges and system stress events.

- **Role:** It validates the adequacy of the proposed generation mix at a high temporal resolution. It identifies critical periods of grid stress where supply may struggle to meet demand due to RE variability.
- **Key Output Parameters:** This model is responsible for calculating **Loss of Load Expectation (LOLE, hours/year)** and **Unserviced Energy (MWh)**, which are the primary metrics for system adequacy. It also quantifies **curtailment levels (TWh or % of generation)** and **hourly flexibility requirements (MW ramping)**.

6.2.2.5. Market Dynamics and Network Congestion

POMATWO analyses the economic and infrastructural consequences of the transition, addressing how transmission bottlenecks influence price formation and stability.

- **Role:** It simulates the electricity market to reveal how RES integration affects price volatility and where grid congestion occurs. It highlights locations where regulatory or infrastructure interventions are necessary to prevent market fragmentation.
- **Key Output Parameters:** The model outputs **zonal marginal electricity prices (€/MWh)**, **price volatility metrics**, and **congestion patterns (MW restricted flow)**. It also tracks **curtailment propagation** caused specifically by network constraints rather than over-generation.

6.3. Scenario selection and applied stress test

6.3.1. Scenario selection

The Lombardy test case applies two contrasting EU EnVis scenarios, **REPowerEU++** and **EU Trinity**, to explore how different policy, economic and infrastructural contexts shape industrial decarbonisation pathways (RQ1) and regional RES integration and system resilience (RQ2).

1. REPowerEU++ (strong European scenario with robust industrial and energy policy)

This scenario represents a high-cooperation, investment-intensive pathway with accelerated RES deployment, strong industrial policy support and rapid electrification. This scenario allows assessing the *upper bound* of technological feasibility in Lombardy: maximum RES build-out, fast permitting, hydrogen ramp-up and strong infrastructure development. It provides the ideal setting for answering RQ1 under favourable conditions and for evaluating whether Lombardy's electricity grid can host substantial additional RES capacity (RQ2).

2. EU Trinity (economic decline scenario with limited international trade and weaker climate policy)

This scenario, by contrast, embodies a fragmented, low-cooperation Europe with slower infrastructure delivery, constrained international trade, and weaker climate policy signals. For Lombardy, this scenario reflects a high-uncertainty environment where industrial investments face volatile conditions, permitting is slow and heterogeneous across provinces, and grid upgrades may lag demand growth. This is particularly relevant for assessing system resilience (RQ2) and industrial vulnerability to fuel price and infrastructure uncertainty (RQ1).

The combination of these two scenario families allows the modelling chain to explore both the upper and lower boundaries of Lombardy's decarbonisation trajectory, supporting regional policy-makers (Regione Lombardia) and technical authorities (RSE) in strategic planning, infrastructure prioritisation and long-term risk assessment.

6.3.2. Applied Stress tests and rationale

To complement the scenario analysis and evaluate the robustness of Lombardy's energy transition under conditions of uncertainty, two stress tests were selected in full alignment with the iDesignRES stress-testing framework. These stress tests reflect the main vulnerabilities identified during interviews with Regione Lombardia, RSE and GSE, and capture the structural risks most relevant for answering RQ1 and RQ2.

Stress Test 1 – Infrastructure Availability & Reliability Stress

This stress test examines how constraints in infrastructure development affect both industrial decarbonisation and energy system resilience. It is particularly relevant to Lombardy, where stakeholders highlighted persistent permitting delays, limited hosting capacity, and uneven regional infrastructure readiness.

Main elements

- Reduced rate of RES deployment due to permitting delays
- Slower development of transmission and distribution reinforcements
- Limited availability of hydrogen transport/storage infrastructure
- Constraints on biomethane/biogas availability due to regional feedstock limits

Connection to RQs

- **RQ1** → Limited RES availability constrains electrification and hydrogen uptake, shifting the industrial pathway mix.
- **RQ2** → Tests grid resilience, congestion patterns and flexibility needs.

Stress Test 2 – Fossil Fuel Phase-Out / Supply Shortage

Simulates a significant reduction in natural gas availability for industrial use (e.g., reduced import flows or price shock), combined with accelerated phase-out of legacy thermal assets. Lombardy's industry (chemicals, metallurgy, paper, ceramics) remains heavily gas dependent. Any supply restriction or price volatility directly stresses industrial feasibility and energy system flexibility.

Main elements

- Reduced availability of natural gas for industrial use
- Increased volatility in fossil fuel prices, affecting industrial competitiveness and planning
- Reduced availability of dispatchable thermal capacity during transition

Connection to RQs

- **RQ1** → Forces stronger electrification/hydrogen/CCS adoption
- **RQ2** → Tests adequacy and operational stability under high electrification and reduced dispatchable flexibility.

6.4. Data

Table 6: Data needs for the models in the Lombardy case study

Model name	Data need
GeoMEC	<p>Spatial RES potentials at NUTS2 level</p> <p>Land-use restrictions and protected areas</p> <p>Demand profiles, cost data</p>
JRC-EU-TIMES-OP	<p>Besides investment decisions or capacity expansion plans, and technology activity levels at annual-scale from GeoMEC at NUTS2 regions, JRC-EU-TIMES-OP requires hourly demand profiles of end-use energy carriers (electricity, hydrogen, synthetic fuels, etc.) by sector, as well as local wind, solar, and other RES supply profiles at hourly resolution.</p> <p>Any policy, non-technical, operational constraints and other techno-economic data aligning with GeoMEC</p>
Pomatwo	<p>Market and price assumptions, generation (installed capacities, generator characteristics and location, availabilities, historical generation profiles), demand (time series of nodal demand, time-dependent inflows to storage, fixed cross-border or inter-zonal exchanges), network constraints (zonal/aggregated) and line parameters, operational profiles from JRC-EU TIMES-OP.</p>
Industry model IDR-Ilsim	<p>Full list of Variables, Constants, and Outputs for key industries, including the Quantified Mean & Variance derived from scenario narratives. Technology Costs: CapEx, OpEx, and efficiency curves.</p>

7. Basque Country – industrial demonstrator

7.1. Use case overview

The Basque Country (Euskadi) is a critical strategic node for Spain's energy transition due to its status as a major industrial cluster, characterized by high energy intensity and a strong manufacturing base (steel, cement, glass, and paper).

For the Basque Country, this transition is particularly challenging as its energy mix has historically been highly dependent on fossil fuels. According to the latest energy balance report by the Basque Energy Agency (EVE, 2024), the region's energy self-sufficiency rate is low (approx. 8.7%), highlighting a significant reliance on external supply. The share of renewable energy in final energy consumption stood at 20.4% in 2023, with a mandatory regional target of reaching 32% by 2030 (Basque Law 1/2024).



This context creates a unique dual challenge: the region must rapidly decarbonize its "hard-to-abate" industries to meet climate goals while simultaneously ensuring security of supply and maintaining industrial competitiveness in a region with limited local renewable generation potential compared to other parts of Spain.

Key stakeholders and their needs

To address these challenges, the case study involves three key stakeholders (need owners), each representing a different planning perspective required for a holistic solution:

- EVE (Basque Energy Agency): As the entity responsible for regional strategic planning, EVE needs to integrate techno-economic models to define optimal decarbonization pathways. Their primary need is to evaluate the trade-offs and opportunity costs between different technological routes (e.g., direct electrification vs. green hydrogen) to inform public policy and support the 2030 targets.
- FAEN (Asturias Energy Federation): Acting as a regional coordinator and observer, FAEN provides insights on social acceptance and territorial strategies. Their participation ensures that the Basque approach serves as a reference for neighbouring industrial regions facing similar transition hurdles.
- i-DE (Distribution Network Operator): i-DE focuses on the operational reality of the grid. Their critical need is to anticipate where and when the new industrial demand will cause grid congestion. They require granular investment scenarios to plan the reinforcement of the distribution and transmission networks efficiently, avoiding bottlenecks that could stall industrial electrification.

Challenges for the region

The overarching challenge for the Greater Basque Country is to orchestrate a synchronized transition between industrial demand and infrastructure supply. Specifically, the region faces the risk of a "pace mismatch": if industries electrify faster than the grid can be reinforced (due to permitting or investment limits), or if hydrogen infrastructure (like the Basque Hydrogen Corridor) is delayed, the region could face high operational costs, loss of competitiveness, or supply security risks. This case study aims to model these interdependencies to provide a robust roadmap for investment.

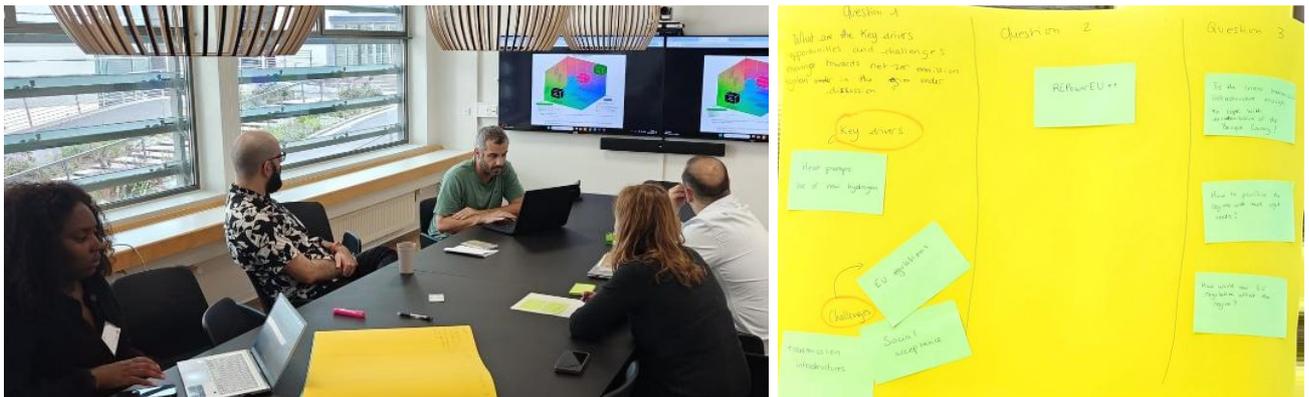


Figure 6: Workshop discussion on the main challenges, opportunities and questions that will shape the Basque Country’s energy transition. Poster output developed in the discussion.

Timeline

Activity & Model(s) Used	2026			2027								
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Workshops	W1					W2				W3		
1. Boundary Conditions (GENeSYS-MOD)	X	X										
2. Industrial Optimization (RQ1 - IDR-Isim)			X	X	X	X						
3. Output Validation - RQ1							X					
4. Grid Coupling & Sim (RQ2 - SMS++ / POMATWO)								X	X	X		
5. Investment Analysis (SMS++ / POMATWO)											X	
6. Final Synthesis (All Models)												X

7.2. Research questions

Based on the overall objective of the case study, the plans in the project proposals, and the interview inputs and discussions during the brainstorming session, the following set of revised research questions (RQ) are proposed:

RQ 1 (Industrial Decarbonization):

- *Question:* Which is the optimal technology configuration for decarbonizing the Basque industry given a set of technologies, fuels, and emissions price?

RQ 2 (Infrastructure Investment):

- *Question:* What are the investment needs regarding the build-up of the technology-related infrastructure required to decarbonize the Basque industry (e.g., power grid networks, natural gas grids)?

Expected output parameters To tackle these challenges and answer the research questions, the following model outputs are needed:

- **RQ 1 Outputs:**
 - The optimal configuration of installed capacity (MW) of decarbonization technologies per industrial sector selected.
 - Total System Cost (€) under different scenarios (configuration).
 - Aggregated (Nuts-2 level) demand profiles (MW, MWh/year) for electricity and hydrogen.
 - CO₂ abatement curves (Tonnes CO₂ avoided/€).
- **RQ 2 Outputs:**
 - Time-series of power flows in the transmission grid (MW).
 - Identification of overloaded lines and nodes (Congestion points).
 - Quantification of necessary reinforcement capacity (MW) and investment cost (€).
 - (*Exploratory*) Nodal capacity analysis at the distribution level.

Scope and Limitations Based on the modelling approach of the iDesignRES project, certain issues are outside the primary scope or difficult to address fully:

- Impacts of different governance, market harmonization, and levels of international cooperation (addressed partly via scenarios).
- Impact of supply chain constraints (addressed partly by comparing scenarios).
- Consideration of optimal placement in terms of voltage level for storage (large centralized units vs. distributed).

The analysis focuses on the **minimization of key Objective Functions** utilizing a sequential coupling strategy between consortium models. This directly addresses the need for detailed outputs and model connectivity.

Phase 1: Industrial Optimization (Answering RQ 1) The **Industry Demand Model (IDR-IIsim)** (Layer 3) will drive this phase, focusing on process-level optimization for the main Basque industries.

- **Narrative to Data:** The central value (Mean) for each parameter is derived by translating the qualitative **GoRES/REPowerEU++** scenario narratives and local industry roadmaps into specific numeric assumptions. The Variance is established by limits defined in the Stress Tests.
- **Model Connection (Input):** The Layer 1 model, **GENeSYS-MOD**, provides the long-term **CO₂ Price and Fuel Trajectories** as boundary conditions for the IDR-IIsim optimization.

- **Objective Function:** The primary objective function seeks to **minimize the overall industrial configuration cost** subject to achieving full industrial decarbonization.
- **Output:** The solution generates the **Optimized Parameter Table** and the resulting **Aggregated Optimized Demand Profiles** (electrical, energy, and material).

Phase 2: Infrastructure Optimization (Answering RQ 2) The optimized demand profiles from Phase 1 are used as mandatory inputs for the infrastructure models.

- **Model Connection (Coupling):** The IDR-IIsim output (optimized demand profile) is sequentially coupled with the Layer 3 infrastructure models. Specifically, **POMATWO** will be used for **transmission grid** analysis, while **SMS++** is currently being evaluated for **distribution grid** modelling capabilities.
- **Objective Function:** The objective is to **minimize the total cost of infrastructure investment** required to support the optimized industrial configuration.
- **Scope:** The analysis identifies the minimum cost infrastructure capable of ensuring energy security, including multi-carrier networks.

7.3. Scenario selection and applied stress test

Scenario Selection and Comparative Analysis In response to the need to focus the modelling effort and align with the iDesignRES framework, the study will concentrate on a comparative analysis of two specific pathways from the European Energy Vision 2060 (EU-EnVis 2060) set: **GoRES** and **REPowerEU++**.

- **GoRES (Technological Optimum Pathway):** Represents the most ambitious pathway (high RES, rapid electrification). Used to determine the **technological optimum** for industrial configuration (RQ 1), aligning with the regional target of 32% renewable energy by 2030.
- **REPowerEU++ (Security and Resilience Pathway):** Emphasizes rapid energy independence and diversification. Crucial given the region's low energy self-sufficiency rate. Used to stress-test the system's **resilience** and determine the **minimum infrastructure investment** (RQ 2) in a constrained context.

Stress Testing The stress testing methodology is designed to introduce a disruptive variant that probes the resilience of the optimal system design against non-economic constraints, focusing on the core uncertainty dimension of **Infrastructure Availability and Reliability**.

- **Stress Test Variant: Slower Grid Reinforcement and Industrial Congestion**
 - *Mechanism:* This test simulates a regulatory or financial bottleneck by artificially **constraining the pace at which new grid infrastructure becomes available** (transmission and distribution assets). This acts as a regulatory variance on the investment trajectory.
 - *Goal:* To evaluate the resilience of the minimum infrastructure investment (RQ 2) under friction. By slowing down the network upgrade rate, the coupled models are forced to determine if the industrial electrification plan (RQ 1) leads to unmanageable stress, quantifying the "Cost of Inaction" (e.g., Energy Not Served).

7.4. Data

Table 7 summarizes the core data needs, the specific nature of the required inputs (Boundary Conditions and Variance), and the designated consortium models responsible for closing the GAPS via the coupling strategy.

Table 7: Core data needs for the applied models in the Basque Country case study

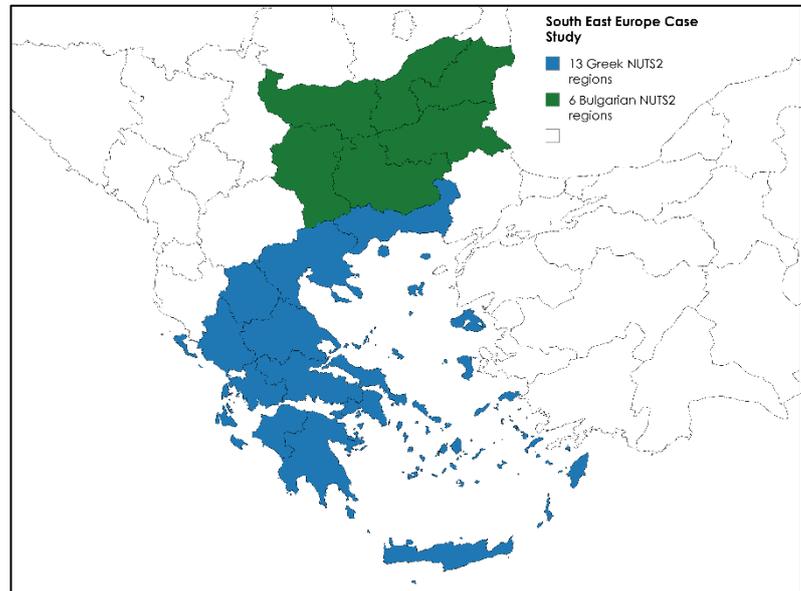
Data Category	Specific Data Required	Collaboration Gaps (GAPs) & Required Model
Policy & Economics	CO₂ Price Projection (Mean & Variance): Exogenous, validated long-term projections of the emissions price, including the variance required for the Stress Tests. Regional GDP projections (NUTS2) to justify investment limits.	Gap 1: Justified CO ₂ Price Projection (Boundary Condition). (Input from GENeSYS-MOD - Layer 1).
Energy & Fuels	Fuel Mix and Price Projections (Mean & Variance): Detailed projections for all energy carriers (e.g., natural gas, imported H ₂ , green H ₂). Must include the uncertainty/variance for stress testing. Electricity price scenarios (wholesale/final).	Gap 2: Fuel Data & Price Projections (Boundary Condition). (Input from GENeSYS-MOD (Layer 1) and GGM / MGNET (Layer 3) for network and commodity cost impact) and POMATWO for analysing the power market, electricity prices and transmission grid congestions.
Technological & Industrial	IDR-IIsim Parameters (RQ1): Full list of Variables, Constants, and Outputs for key industries, including the Quantified Mean & Variance derived from scenario narratives. Technology Costs: CapEx, OpEx, and efficiency curves.	Critical Internal Data Set. (Data collection and quantification driven by the Basque team, informed by Layer 1 scenario narratives).
Infrastructure & Grid	Electrical Infrastructure Model: A simulation tool of the current and planned electrical grid network. Existing network capacity and congestion points. Multi-carrier network data (Natural gas and H ₂ network potential). Required Input: The Aggregated Optimized Demand Profiles from IDR-IIsim.	Gap 3: Electrical Infrastructure Model (Coupling Tool). (To be filled by coupling IDR-IIsim Outputs with Pomatwo ⁶ (Layer 3) or GeoMEC (Layer 2)).

⁶ For specific data needs, refer to table 5 or 6.

8. South east Europe – macro-region demonstrator

8.1. Use case overview

The massive RES penetration in South-Eastern Europe (SEE) during the last decades has brought forward critical balancing and congestion challenges. Flexibility (mainly in the form of Battery Energy Storage Systems – BESS and Pumped Hydro Energy Storage Systems – PHES) and interconnections have a central role in addressing these challenges. The SEE macro-region case aims at quantifying their overall system value, by modelling their impacts on short-term (OPEX) and long-term (CAPEX) system costs.



Need owners

PPC (Generation/Retail Company, GR): As the leading electricity generation and supply company in Greece, PPC operates a diversified portfolio of power plants and renewable energy assets and is actively developing large-scale energy storage projects (BESS and PHES). Analytical tools can help PPC quantify the system-wide value of storage systems investments, including their contribution to adequacy, flexibility, and RES integration.

IPTO (TSO, GR): IPTO is responsible for the operation, control, maintenance and development of the national transmission system. There is a need for a decision-support tool capable of evaluating how distributed storage systems impact system balancing, grid constraints and overall security of supply.

ESO (TSO, BG): As Bulgaria's transmission system operator, ESO shares similar needs with IPTO. In addition, methodologies to assess the operational and economic value of regional coordination with the Greek system, including improved utilization of interconnectors and reduced system balancing costs under joint operation would be valuable considering enhanced cross-border coordination.

In recent years there has been critical momentum for BESS integration in both countries, with GR moving from 0 today to 4.7GW in 2030 while BG moving from 600MW today to 6GW in 2030. Additionally, there are long-term plans for PHES integration to assist flexibility assets development with BG moving from 950MW today to 2.6GW in 2035 while GR is moving from 699MW today to 1.9GW in 2030. The uncertainties about the future integration of these flexible technologies are related to RQ1 that explores their overall value for the whole electricity chain.

Concerning the opportunity for stronger regional coordination, beyond the two existing interconnectors between the two countries (total installed capacity around 1.7GW), a new interconnector is expected to support the integration of the new BG-GR PHES. These uncertainties for interconnections between the two countries are related to RQ2 that addresses the value of enhanced cross-border coordination.

Case study timeline:

	2026							2027					
Case study	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
South-East Europe													

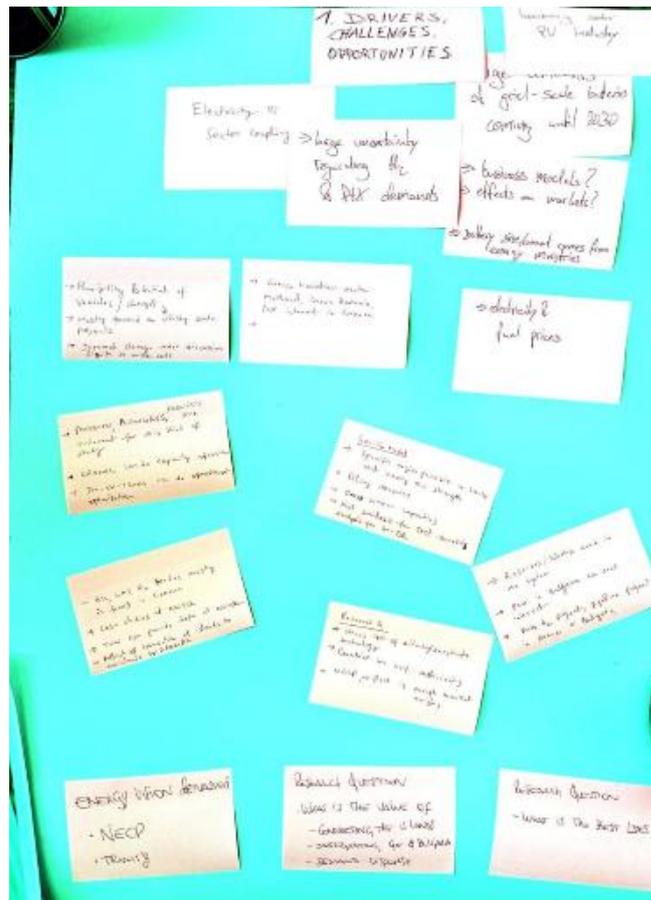


Figure 7: Workshop discussion on the main challenges, opportunities and questions that will shape the European South-East’s energy transition. Poster output developed in the discussion.

8.2. Research questions

Based on the overall objective of the case study, the breakout sessions in the last consortium meeting in Copenhagen and the discussions with the stakeholders the following research questions (RQ) are proposed:

- **RQ 1:** What is the overall value of BESS and PHES for the whole electricity chain? What is the contribution of BESS/PHES to adequacy and flexibility?
 - Uncertainties: Installed power capacity of BESS/PHES per NUTS2 region and future year, duration of BESS/PHES, charging / discharging efficiency of BESS/PHES, maximum daily cycles of BESS/PHES, investment cost of BESS/PHES.

- **RQ 2:** What is the overall system value of enhanced GR-BG coordination? Need to quantify system costs under silo and regional approaches.
 - Uncertainties: Interconnection capacity and positions (per pair of NUTS 2 regions)

To answer the research questions, we expect the following output metrics from the models:

- **RQ 1:** Short-term costs (energy, balancing, congestion) and long-term costs (generation capacity, network reinforcements) without BESS/PHEs and with different BESS/PHEs scenarios.
 - **Short-term costs:** energy cost, redispatch costs, congestion indicators.
 - **Long-term costs:** total system cost breakdown (CAPEX/OPEX/fuel/CO₂), capacity additions deferred, network reinforcement avoided.
 - **Adequacy/flexibility:** Loss of load expectations (LOLE), Energy not served (ENS), Expected ENS (EENS), curtailment, reserve coverage, storage cycles, net firm capacity.
 - **Attribution metrics:** €/kW-yr and €/MWh value of BESS/PHEs; % reduction in LOLE/ENS; €/MWh reduction in redispatch.
- **RQ 2:** Total system costs under isolated GR / isolated BG system operation, and total system costs under coordinated GR-BG system operation. The latter includes a) energy transfers and b) regional reserve sizing and sharing (implying that the reserve capacity requirements are determined by GR-BG TSOs in coordination)
 - **Total system cost:** isolated GR, isolated BG, coordinated GR–BG (compare costs and drivers).
 - **Energy & reserve exchanges:** annual and peak-hour flows; reserve requirements for both cases.
 - **Adequacy/flexibility:** LOLE/ENS changes, reserve margin, curtailment.
 - **Network KPIs:** required interconnection upgrades (MW), utilisation factors, congestions, benefit-cost ratios per corridor.

Since the research questions focus on quantifying whole electricity system value (of BESS, PHEs and interconnections), we need both short-term operation and long-term planning models, capable of representing generation (conventional and RES), network (national and interconnections) and BESS/PHEs. The short-term operation models need to be able to capture intertemporal constraints of BESS/PHEs and conventional generation.

The next two sections focus on how the modelling framework addresses the research questions by detailing how each model contributes specific analytical insights. Since the models are interconnected the overall strategy for both RQs begins with long-term energy system optimization using GENeSYS-MOD. The outputs are then processed by GeoMEC to add spatial resolution at NUTS2 level for the key variables of interest, such as storage siting and cross-border interconnections. The outputs of GeoMEC can be fed into JRC-EU-TIMES-OP combined with TRANSPORT model data, which assesses system adequacy, and operational flexibility. Finally, POMATWO quantifies short-term market effects based on the operational constraints derived from the previous models.

8.2.1. Modelling RQ1 – System value of BESS/PHEs (adequacy & flexibility across the chain)

For this research question, the scenario framework defines a set of uncertainties and stress tests in which, for each NUTS2 region and model year, the installed power of BESS and PHEs, their energy duration (e.g.

1–8 hours for BESS and 6–20 hours for PHES), charging and discharging efficiencies, maximum daily cycles, and investment costs are varied systematically. Within this framework, **GENeSYS-MOD** is used to run both a baseline scenario without storage and multiple storage-enabled variants. These simulations quantify long-term system cost changes, covering CAPEX, fuel expenditure, and CO₂ costs, while also identifying residual peak demand and interconnection requirements. GENeSYS-MOD further provides a consistent trajectory for installed capacities through 2060, which serves as a guiding envelope for the spatial allocation conducted in **GeoMEC**.

Building on these long-term system results, **GeoMEC** allocates BESS capacities to load centres and identifies feasible siting locations for PHES, such as valleys and reservoir systems, while distributing all other energy production capacities across NUTS2 regions. Through its detailed spatial representation, GeoMEC supports the assessment of short-term cost implications and prepares geographically explicit inputs for the **JRC-EU-TIMES-OP** model. The **Transport model** complements this by generating hourly transport demand profiles and evaluating how the availability of storage and the resulting price signals may influence charging behaviours.

At the operational level, **JRC-EU-TIMES-OP** evaluates the adequacy and flexibility contributions of different storage configurations. It assesses metrics such as ramping sufficiency, curtailment levels, utilisation rates of various storage technologies, annual cycling behaviour, and state-of-charge dynamics. **POMATWO** then quantifies the market value of storage by analysing day-ahead and final dispatch price spreads, as well as the reduction in congestion and redispatch costs attributable to different storage portfolios.

Finally, the synthesis step compares scenarios without storage against those with BESS only, PHES only, and hybrid storage configurations. The added value of storage is attributed to both **long-term impacts**, such as capacity deferral, fuel and CO₂ savings, and avoided network reinforcements, and **short-term impacts**, including energy arbitrage gains, congestion mitigation, and reduced balancing requirements.

8.2.2. Modelling RQ2 – System value of enhanced GR-BG coordination (silos vs regional)

The modelling strategy for evaluating the system value of enhanced GR–BG coordination begins with defining a scenario framework in which **interconnection capacity and siting between NUTS2 region pairs** are varied systematically. These uncertainties include existing capacities, incremental expansions (e.g. +X%), and fully coordinated build plans. In addition, different **reserve-sharing regimes** (none, partial, or full) are examined to capture a spectrum of operational coordination levels between the two countries. Within this scenario space, **GENeSYS-MOD** conducts three core optimisation runs: isolated operation of Greece, isolated operation of Bulgaria, and a coordinated GR–BG system. Comparing these runs allows for quantification of total system cost differences, cross-border capacity values, and the effects of coordinated planning across generation, storage, and interconnection infrastructures.

The resulting system-wide capacity envelopes are then translated into spatially explicit infrastructure configurations by **GeoMEC**, which maps coordinated and non-coordinated builds onto specific NUTS2 corridors, applies siting constraints, and specifies candidate values for transfer capacities (TTC/NTC). GeoMEC also determines the spatial distribution of generation assets, enabling a geographically consistent representation of the integrated system. The **Transport model** supplements this by providing hourly transport demand profiles for both countries and capturing how changes in system prices and

coordination-induced effects may alter electric vehicle charging patterns, which feed into operational models.

Operational feasibility is assessed using **JRC-EU-TIMES-OP**, which simulates both isolated (two separate balancing areas) and coordinated operations. The model evaluates adequacy and flexibility performance under correlated and uncorrelated renewable energy and demand patterns, thereby revealing how coordinated operations improve reliability and reduce reserve requirements. **POMATWO** then evaluates the market implications of coordination, using flow-based market coupling to compare outcomes with and without an integrated GR–BG market zone. It assesses price convergence, redispatch cost reductions, welfare impacts, and the economic effects of reserve sharing across the border.

In the synthesis phase, the coordination benefits are decomposed into their main components: **energy transfers**, **capacity credit diversity**, **reserve pooling**, and **congestion relief**. This provides a clear attribution of the sources of system value and enables the identification of **critical interconnection corridors** that deliver the highest benefits. The analysis ultimately reports the net economic and operational gains of coordinated GR–BG system operation compared to siloed national approaches.

8.3. Scenario selection and applied stress test

Our case study will focus on two specific scenarios from the European Energy Vision 2060 (EU-EnVis 2060) set, specifically NECP Essentials and REPowerEU++.

- **NECP Essentials:** This scenario aligns with national energy and climate policies as well as national long-term strategies. It can be used to determine how to meet the targets for flexible technologies (BESS/PHEs), that are already established in the NECPs of both countries and analyzed among the main challenges for the SEE region and affects the whole electricity chain (RQ1).
- **REPowerEU++:** This scenario expresses strong renewable energy integration under geopolitical rivalries and related challenges. It can be used to determine how enhanced regional coordination between GR and BG (RQ2) improves system security and sustainability under global geopolitical tensions.

For the South-East Europe (SEE) case study, the stress testing framework will focus on uncertainties that are directly related to the proposed research questions. The proposed stress tests are:

- **Fossil Fuel Phase-Out & Delayed Storage Development:** Focusing on impact of delayed fossil fuel retirement and additional delays on the approval and development of the storage systems. Directly related to RQ1 reflecting the region's current dependency on gas imports and the role of storage in maintaining adequacy and flexibility.
- **Restricted cross-border transmission availability:** Directly related to RQ2 focusing on capturing delays or limitations in interconnector reinforcements between Greece and Bulgaria and assessing how these constraints reduce system value of coordinated flexibility sharing.

8.4. Data

Based on inputs from the TSOs of Greece and Bulgaria we have already gathered:

- Generation capacity (MW) and production (MWh) per technology, NUTS 2 region and future year

- Demand profiles per NUTS 2 region, season, and future year
- Transfer capacities between different pairs of NUTS 2 regions (including cross-border) per future year.

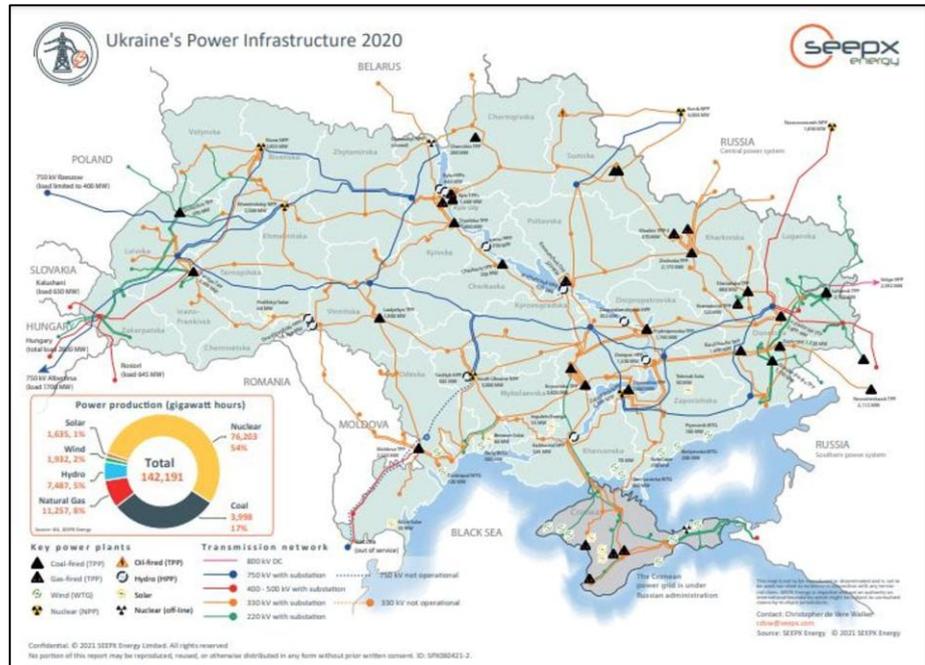
We would like to explore -if available- BESS/ PHES power and energy capacity per NUTS 2 region and future year.

Data needs of the different models can be consulted in Table 5 and 6.

9. Ukraine – grid connection demonstrator

9.1. Use case overview

The Ukrainian expansion case investigates how the iDesignRES toolbox can support Ukraine’s long-term energy transition and its progressive alignment with the EU Green Deal. It focuses on the interconnection between Central European grids and the Ukrainian energy system, with a particular emphasis on electricity and gas, and on the role of cross-border infrastructure in enhancing regional energy security under conditions of high geopolitical uncertainty and post-conflict reconstruction.



Within the overall iDesignRES project validation strategy, Ukraine is implemented as the final use case after the North Sea, Lombardy, South-Eastern Europe and Greater Basque Country cases, thereby leveraging lessons from both macro-regions and industrial clusters.

The case was initially framed around high-ambition transition scenarios (80–90% GHG reduction by 2050) based on coal phase-out, infrastructure modernisation, large-scale deployment of renewables (decentralization), ramp-up of energy efficiency, electro-mobility, and industrial decarbonisation, and their consistency with EU-wide climate-neutrality objectives.

Main challenges in Ukraine

From the perspective of D3.1’s methodology, the Ukrainian case highlights a set of future challenges that must be considered and discussed in the design of validation and stress-test procedures:

- Rebuilding and modernising damaged infrastructure while simultaneously complying with EU climate, market and network codes, which requires consistent coupling between national-level scenarios and high-resolution NUTS-2 planning tools for generation, grids and storage.
- Managing geopolitical and security risks, particularly around gas transit, electricity interconnections and the evolving role of Ukraine in European hydrogen and CO₂ networks, by developing scenario families and stress tests that remain robust under large parameter uncertainties.
- Ensuring a fair and socially acceptable transition, including mitigation of energy poverty, protection of vulnerable consumers, and just transition strategies in coal-dependent regions, which calls for the integration of social indicators and the ethics-regulation interface (ERI) into use-case validation.

- Embedding Ukraine credibly into EU-wide decarbonisation strategies and infrastructure plans, including REPowerEU and long-term net-zero pathways, so that cross-border investments and market reforms contribute to both regional security of supply and deep decarbonisation.
- Analysis of post-conflict scenarios: Develop energy transition strategies for the post-infrastructure investments on generation expansion and grid reinforcements.
- Analysis of in-conflict scenarios and policies: Develop short-to-mid term strategies for the resilience and system-wide flexibility to adapt to outages and pursue decentralized options (e.g. exploit biomass and batteries) for areas to operate under off-grid conditions.

The principal Ukrainian need owners in iDesignRES are Dixi Group LLC (DIXI) and the Institute for Economic Research and Policy Consulting (IER), who act as data providers, scenario co-designers and interfaces to national policy makers, regulators and infrastructure operators. DIXI guides and suggests the gathering and harmonising detailed data on the Ukrainian energy system, as well as for advising on institutional and regulatory context. IER leads the co-definition of model scenarios on Ukraine–EU energy cooperation, organises meetings with governmental actors, and prepares local energy reports and media outputs to ensure that modelling results can be absorbed by national strategy debates.



Figure 8: Workshop discussion on the main challenges, opportunities and questions that will shape Ukraine’s energy transition. Poster output developed in the discussion.

9.2. Research questions

Ukraine dependence on fossil fuels, ageing infrastructure, and centralised power generation have left the system vulnerable to external shocks and military attacks, particularly since Russia’s full-scale invasion, which has severely damaged generation and transmission assets and disrupted energy security. Rebuilding requires massive investment to modernise the grid, expand renewables, and introduce storage and smart-grid technologies while simultaneously securing the system against ongoing targeting.

On the EU integration front, Ukraine shall start to introduce market-oriented reforms, unbundling, and harmonised regulatory frameworks, which remain incomplete and politically sensitive. Electricity-market coupling with the EU by 2027 and deeper gas-market integration are contingent on faster progress in legal, regulatory, and governance reforms, including transparent permitting and support schemes for renewables and vulnerable consumers. Equally critical are financing gaps, investor-confidence issues, and the risk of “lock-in” in fossil-based infrastructure, all of which must be addressed through coordinated EU

and international support, including reconstruction funds, technical assistance, and a clear green-energy roadmap aligned with EU climate and competition standards.

In iDesignRES, IER, DIXI and NTNU engaged in several discussions about the focus for the case given that the post-conflict scenarios remain highly uncertain. Hence, the following research questions will guide and be the first line of the analysis and focus:

- RQ1: What energy planning strategy should be considered under high geopolitical tensions in the next decades?
 - *Decentralized scenario*: Uptake of PV, wind and other. System adaptable for islandic mode under various spatial conditions
 - *Mix scenario*: Bulk generation (Nuclear), more robust transmission (N-3 compliant), and decentralized generation assets
- RQ2: What measures on security of supply and resilience for critical infrastructure should be prioritized? What to model regarding war attacks and outages in Ukraine?
- RQ3: What market design reforms will affect or enable Ukraine integration into European Power Markets?

Case study timeline:

			2026								2027					
Case study	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	
Ukraine	WS1						WS2					WS3				

In addition, the use case is designed to engage the Ministry of Energy of Ukraine, the national TSO Ukrenergo, regulatory authorities and European networks such as ENTSO-E and ENTSOG via the participation of ESO, IPTO and other consortium TSOs. These actors represent the extended circle of need owners for grid expansion planning, cross-border capacity development, RES and hydrogen integration, and market design reforms that affect both Ukraine and neighbouring EU member states. The first workshop (WS1) will be arranged in May 2026 near the border of Ukraine. This first workshop will show some insights on the research questions and discuss it with other modelling teams, stakeholders and interested public. NTNU has started developing the Ukrainian case ahead of the planned timeline to reduce uncertainty on the case given the uncertainty on scenarios of “post-conflict” and “in-conflict”. Hence the aim of WS1 is to refine the questions and show preliminary model results and data calibration.

9.3. Scenario selection and applied stress test

The scenario selection will follow the GO-RES scenario combined with the EU TRINITY scenario. This will highly depend on the first workshop outcome and whether the case focuses on “post-conflict” (long-term scenarios) or “in-conflict” (short-to-medium term) scenarios.

9.4. Data collected and challenges

The initial data collection effort has been undertaken via the open global PyPSA-Earth database as the backbone, configured for Ukraine for the year 2020. Grid topology (buses, lines, transformers) is derived from OpenStreetMap, with line types harmonised to a standard 380 kV bundle while preserving thermal capacities and approximate routing. Renewable resource data (wind, solar, hydro inflows) and weather time series come from ERA5 reanalysis for 2013, mapped to the Ukrainian grid. Demand time series are generated by the SynDem tool, combining weather, population, and SSP2-2030 socioeconomic

projections to form synthetic hourly electricity load profiles by bus; these sum to about 164 TWh for 2020 before regional pruning. Technology and cost data (capital and operating costs, efficiencies, technical lifetimes) are taken from PyPSA-Earth's default techno-economic dataset (US EIA, IEA, and other public sources) but these will be harmonized once the EnVis 2060 scenario has been selected for the case. Existing generation capacities by carrier and large plants are taken from PyPSA-Earth's compiled asset database (e.g. nuclear, thermal, hydro, RES plants up to 2020). The overall goal on the development of the data set for Ukraine is that the data is gathered from open available sources.

Data challenges and assumptions

Key challenges arise from incomplete, inconsistent, or non-public Ukrainian data after 2020. Total demand from SynDem (≈ 132 – 155 TWh depending on regional inclusion of the Russian occupied areas) exceeds NEURC's 116 TWh, and the spatial distribution of this overestimation is unknown, so a simple global scaling cannot be made reliably. Due to security and data-access constraints, capacities and damages from the war will not be represented explicitly; instead, occupied oblasts (Crimea, Sevastopol, most of Luhansk, Donetsk, Zaporizhzhia, Kherson) might be entirely pruned at the administrative level regarding the research questions on resilience and security of supply.

10. Coordination and governance

In work package 3, we coordinate the efforts of all modelling teams, case study leads, and work package coordinators through regular coordination meetings. These meetings bring together modellers and regional teams to review progress, align methodological choices, and verify that all case studies adhere to the agreed modelling standards and data exchange protocols. In these sessions, updates on model coupling progress, data adjustments, and scenario implementation are shared, ensuring that the ongoing work within individual case studies remains consistent with the overarching modelling framework and inter-model linkages defined at the project level.

A dedicated governance structure supports the coordination between case study activities (focused on regional applications and stakeholder engagement) and the overarching model coupling work (focused on technical integration and methodological development). The consistency of model implementation is further ensured by enforcing a structured approach to model and data versioning, which requires every modelling team to document and register the exact version of the model and dataset used in each simulation. All updates, corrections, or extensions are tracked through a centralised repository⁷, providing a transparent audit trail of model evolution and applied data sources.

To facilitate continuous coordination and data reliability, the consortium maintains a shared and actively managed database where model input data, parameter adjustments, and identified data needs are recorded. This database acts as the source of information for harmonised inputs such as technology parameters, demand projections, and scenario-specific assumptions. Any modification or addition is reviewed collectively by the modelling coordination team to preserve consistency across work packages and case studies.

11. Next steps

The next phase of iDesignRES will focus on advancing the implementation of the regional case studies. The immediate priority is the pre-kick-off of the North Sea test case, which will serve as the first large-scale application of the harmonised modelling framework. This preparatory phase will bring together the involved partners to work on the detailed research questions, modelling boundaries, and stakeholder engagement. Parallel to this, the initial modelling efforts for the North Sea and Lombardy cases will commence, using the validated data infrastructure and scenario framework developed in WP2 and WP3. These two test cases will act as methodological prototypes for the subsequent ones, demonstrating the integration of multiple models.

To deepen coordination and accelerate technical integration, an in-person modellers' meeting will be held in early 2026. This workshop will allow all modelling teams to present early results, identify challenges in data exchange and scenario consistency, and align on the procedures for model validation and coupling. The discussions will build directly on the first modelling experiences and will form the basis for refining data standards, workflows, and model interoperability ahead of the next modelling cycle. In parallel, further preparation of the remaining test cases South-East-Europe, the Basque Country and Ukraine, will continue, focusing on further refining research questions with local need owners and ensuring that the regional datasets are complete and consistent with the EU EnVis 2060 scenarios.

⁷ <https://github.com/iDesignRES>

Throughout this period, strong alignment with other tasks and work packages will be maintained, in line with the structure outlined in the Grant Agreement. WP2 will continue to provide the long-term scenario inputs and technology parameters that define the boundary conditions for all test cases, while WP4 will focus on the development and validation of the iDesignRES open-source tools and frameworks that support model integration. Coordination with WP6 will ensure that stakeholder inputs and interviews are continuously incorporated into the case-specific modelling approaches, maintaining the link between technical modelling and real-world needs. Finally, WP7 will oversee the cross-validation and certification process to ensure that the outputs of the modelling work are robust, comparable, and ready for deployment in the demonstrator environments. Collectively, these steps mark the transition of iDesignRES from methodological consolidation to operational implementation, advancing toward integrated, data-driven regional energy transition planning across Europe.

12. References

- Barani, Mostafa, Konstantin Löffler, Pedro Crespo Del Granado, et al. 2026. 'European Energy Vision 2050 and beyond: Designing Scenarios for Europe's Energy Transition'. *Renewable and Sustainable Energy Reviews* 225 (January): 116074. <https://doi.org/10.1016/j.rser.2025.116074>.
- Laitinen, Ari, Oscar Lindholm, Ala Hasan, Francesco Reda, and Åsa Hedman. 2021. 'A Techno-Economic Analysis of an Optimal Self-Sufficient District'. *Energy Conversion and Management* 236 (May): 114041. <https://doi.org/10.1016/j.enconman.2021.114041>.
- Lopez, Gabriel, Arman Aghahosseini, Michael Child, et al. 2022. 'Impacts of Model Structure, Framework, and Flexibility on Perspectives of 100% Renewable Energy Transition Decision-Making'. *Renewable and Sustainable Energy Reviews* 164 (August): 112452. <https://doi.org/10.1016/j.rser.2022.112452>.
- Lund, Henrik, Neven Duić, Goran Krajacić, and Maria Da Graça Carvalho. 2007. 'Two Energy System Analysis Models: A Comparison of Methodologies and Results'. *Energy* 32 (6): 948–54. <https://doi.org/10.1016/j.energy.2006.10.014>.
- Lund, Henrik, Jakob Zinck Thellufsen, Poul Alberg Østergaard, Peter Sorknæs, Iva Ridjan Skov, and Brian Vad Mathiesen. 2021. 'EnergyPLAN – Advanced Analysis of Smart Energy Systems'. *Smart Energy* 1 (February): 100007. <https://doi.org/10.1016/j.segy.2021.100007>.
- Lund, Rasmus, Danica Djuric Ilic, and Louise Trygg. 2016. 'Socioeconomic Potential for Introducing Large-Scale Heat Pumps in District Heating in Denmark'. *Journal of Cleaner Production* 139 (December): 219–29. <https://doi.org/10.1016/j.jclepro.2016.07.135>.
- Østergaard, P.A., H. Lund, J.Z. Thellufsen, P. Sorknæs, and B.V. Mathiesen. 2022. 'Review and Validation of EnergyPLAN'. *Renewable and Sustainable Energy Reviews* 168 (October): 112724. <https://doi.org/10.1016/j.rser.2022.112724>.
- Østergaard, Poul Alberg. 2015. 'Reviewing EnergyPLAN Simulations and Performance Indicator Applications in EnergyPLAN Simulations'. *Applied Energy* 154 (September): 921–33. <https://doi.org/10.1016/j.apenergy.2015.05.086>.
- Thellufsen, Jakob Zinck, Steffen Nielsen, and Henrik Lund. 2019. 'Implementing Cleaner Heating Solutions towards a Future Low-Carbon Scenario in Ireland'. *Journal of Cleaner Production* 214 (March): 377–88. <https://doi.org/10.1016/j.jclepro.2018.12.303>.

13. Appendix

13.1. Model input output tables

Table A: Model inputs, outputs and their contribution to answering Lombardy’s RQ1

Model	Role in RQ1	Input	Output
GENeSYS-MOD	<p>Provides the overall decarbonisation pathway for Europe and Italy.</p> <p>Identifies least-cost combinations of electrification, hydrogen and CCS.</p> <p>Shows the impact of emission constraints and carbon prices on industrial transformation.</p> <p>Ensures consistency of industrial changes within the wider energy system.</p>	<p>Long-term energy service demand projections for Italy’s industrial sectors.</p> <p>Technology cost and efficiency assumptions (fossil, electrified, hydrogen-based, CCS).</p> <p>Policy constraints (EU climate targets, PNIEC 2024).</p> <p>RES potentials</p>	<p>Cost-optimal industrial decarbonisation pathways to 2060.</p> <p>Technology mix evolution for industrial heat demand</p> <p>Long-term energy carrier demand (electricity, hydrogen, heat, fuels).</p> <p>CO₂ emissions reduction trajectories</p> <p>System-wide investment needs.</p>
GeoMEC	<p>Ensures that industrial electrification and hydrogen uptake rely on realistic RES availability</p> <p>Provides spatial constraints that limit feasible decarbonisation pathways</p> <p>Links territorial restrictions to</p>	<p>Spatial RES potentials at NUTS2 level</p> <p>Land-use restrictions and protected areas</p> <p>Maximum feasible RES capacity considering territorial constraints</p> <p>Scenario-dependent assumptions on permitting and siting</p>	<p>Spatially feasible RES capacity expansion profiles</p> <p>Maps of RES availability for supplying industry</p> <p>Constraints on low-carbon electricity availability used by JRC-EU TIMES-OP</p>

	industrial transformation costs		
DEUSTO	<p>Provides sector-specific realism in industrial transformation</p> <p>Refines pathways generated by GENeSYS-MOD with detailed process-level switching</p> <p>Represents technical and economic feasibility of transitions in chemicals, cement, metallurgy, paper</p> <p>Produces demand profiles that feed into JRC-EU TIMES-OP</p>	<p>Industrial energy demand and production activity levels</p> <p>Technology options for process heat, fuel switching, electrification, hydrogen, CCS</p> <p>Capital and operational costs of industrial process technologies</p> <p>Technical limits on retrofit rates and switching speeds</p>	<p>Technology switching curves and industrial process transformation trajectories</p> <p>Fuel substitution patterns</p> <p>Sector-specific decarbonisation costs</p> <p>Industrial energy demand profiles consistent with chosen technologies</p>
JRC-TIMES-OP	<p>Validates that industrial decarbonisation scenarios are operationally feasible</p> <p>Identifies whether industrial electrification creates new system stress</p> <p>Links industrial transitions with system-level flexibility needs</p>	<p>Industrial energy demand profiles provided by DEUSTO and GENeSYS-MOD or GeoMEC</p> <p>Availability and cost of low-carbon electricity and hydrogen</p> <p>Flexibility options (e.g., electrified heat, storage)</p> <p>Industrial process requirements</p>	<p>Hourly operational feasibility of industrial pathways</p> <p>System adequacy checks for industry-driven demand</p> <p>Flexibility requirements to support industrial electrification</p> <p>Additional operational constraints</p>
POMATWO	<p>Provides power market realism to industrial pathways</p> <p>Shows how industrial electrification or</p>	<p>Energy prices and market assumptions</p> <p>Installed power capacities and electricity grid</p>	<p>Effects of industrial transition on price signals</p> <p>Identification of constraints and</p>

	hydrogen deployment influence prices	Network constraints (aggregated)	possible congestion events
	Identifies price-driven incentives or disincentives for industry transformation	Industrial demand changes from RQ1 scenarios	Market impact of industrial electrification and H ₂ uptake

Table B: Model inputs, outputs and their contribution to answer the research question for answering Lombardy’s RQ2

Model	Input	Output	Role in RQ2
GENeSYS-MOD	RES potentials	Overall system pathways with high RES penetration	Sets the system-wide RES deployment trajectory
	Demand projections	Required electricity generation mix under different constraints	Ensures consistency of RES integration with industrial electrification
	Technology cost assumptions	National demand for flexibility and storage	Provides a baseline for operational models (JRC-EU TIMES-OP)
	Carbon price and policy constraints	Long-term investment needs in RES and supporting technologies	
GeoMEC	Scenario assumptions (permitting, grid development)	Feasible RES build-out under different permitting conditions	Determines how much RES Lombardy can host
	NUTS2 RES potentials	Spatial constraints that drive curtailment risks	Provides the spatial bottlenecks that limit system resilience
	Land-use constraints, exclusion zones	Maximum annual expansion limits	Shapes scenario constraints for JRC-
	Permitting and spatial availability assumptions		

			EU TIMES-OP and POMATWO
DEUSTO	<p>Industrial electrification and hydrogen use pathways (from RQ1)</p> <p>Process-level characteristics affecting load profiles</p>	<p>Refined industrial demand profiles</p>	<p>Ensures that RES integration scenarios reflect realistic industrial loads</p> <p>Provides industrial demand flexibility as a resilience lever</p>
JRC-EU-TIMES-OP	<p>Time-resolved RES generation profiles</p> <p>Industrial electricity demand (from RQ1)</p> <p>Flexibility options and system constraints</p> <p>Installed RES capacities (from GeoMEC)</p>	<p>Operational adequacy assessment</p> <p>Flexibility needs (storage, DR, sector coupling)</p> <p>Curtailment levels and causes</p> <p>Hours of system stress and unserved energy</p>	<p>Validates operational feasibility of the RES pathway</p> <p>Quantifies flexibility needs required for system resilience</p> <p>Identifies critical periods of grid stress</p>
POMATWO	<p>Market and price assumptions</p> <p>Network constraints (zonal/aggregated)</p> <p>Operational profiles from JRC-EU TIMES-OP</p>	<p>Congestion patterns</p> <p>Price volatility and marginal price formation</p> <p>Curtailment propagation across the system</p>	<p>Shows how RES integration affects market behaviour</p> <p>Identifies locations where congestion undermines system resilience</p> <p>Highlights where regulatory or infrastructure intervention is necessary</p>

Table B: Model inputs, outputs and their contribution to answer the research question for answering Ukraine’s RQ1

Model	Input	Output	Role in RQ1
/EMPIRE / PyPsa	RES potentials	Overall system pathways with high RES penetration	Sets the system-wide RES deployment trajectory
	Demand projections	Required electricity generation mix under different constraints	Ensures consistency of RES integration with industrial electrification
	Technology cost assumptions	National demand for flexibility and storage	Provides the spatial bottlenecks that limit system resilience
	Carbon price and policy constraints	Long-term investment needs in RES and supporting technologies	
	Scenario assumptions (permitting, grid development)	Spatial constraints and outage frequency	
	high Spatial resolution		

13.2. Interview questionnaire

BASIC INFORMATION ON THE INTERVIEWEES:

- Name:
- Position at the institution:
- Years working in the institution:
- Knowledge of Energy System planning tools or software's showcasing Power system or energy modelling, scale 1-to-10

NEEDS AND CHALLENGES IN ENERGY SYSTEM PLANNING.

- Are there any specific regulatory or policy challenges that impact your energy system planning (e.g. electric vehicle integration, renewable energy resources integration, grid expansion, etc.)? Yes (Y)/No(N)/Don't know, Don't Answer (Dk/Da) Can you list them?
- What do you consider to be the main uncertainties towards a working horizon (e.g. 2030, 2050, etc.) in planning the energy demand and the supply of your energy system?
- What are the biggest obstacles you face in integrating renewable energy sources into your system?
- What other significant challenges does your entity currently face in energy systems planning?
- Which of these challenges could be tackled by energy system models?

ENERGY SYSTEMS MODELS USE

- Are there any specific analytical capabilities (e.g. network impact analysis, techno-economic study, generation of scenarios, evaluation and/or comparison of scenarios, key performance indicators and reports generation) that you find essential for your energy system planning?
- How do you prefer to access the tool (web-based/desktop application/mobile app/ other)? What user interface features would make the tool more intuitive and user-friendly (performance/ graphs customization / AI integration / data format management / other)?
- How would you integrate energy system models into your institution work activities, analysis, reporting, or any useful use in your institution?
- Are there any specific steps or processes that need to be followed for successful implementation? Please, specify.

TOOL DEVELOPMENT AND BENEFITS.

- What tools or models are you currently using or have interest in using in the future?
- In your view, what are the main limitations or problems on using energy system models?
- Are there any innovative features or technologies you would like to see incorporated into the tool? Are there any specific enhancements you foresee needing in the near future?
- How could iDesignRES energy and power system modelling benefit your daily activity?

SECURITY AND PRIVACY ASPECTS.

- What are your main concerns regarding the security and privacy of the data used in the tool and what measures would you expect us to implement to ensure data protection? Encryption / Backup/ Access Control / Confidentiality /Physical Security/Privacy Preference/ Storage Limitation

INNOVATION AND FUTURE DEVELOPMENT NEEDS.

- What emerging challenges (e.g. artificial intelligence integration, cybersecurity, etc.) do you foresee that the iDesignRES developments should be able to tackle?



iDesignRES

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

More information on iDesignRES project:



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



<https://idesignres.eu/>



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