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Model-based energy planning: A methodology to choose and combine models to support policy decisions

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ABSTRACT

Long-term energy planning increasingly relies on mathematical models offering quantitative insight to support complex policy decisions. However, the increase in their use has meant the proliferation of tools developed at different institutions, with various scopes, dealing with specific aspects of the economy, the power sector, or the climate, with mismatches in temporal or geographic resolution. All this creates a need for using several models concurrently, integrating them to generate a complete perspective on the implications of policy decisions on the energy transition. This article proposes a methodology to categorize and combine energy models and develop a manipulation strategy to answer a target research question. Thus, it gives a formal structure to tasks carried out informally –and suboptimally- in virtually any energy planning project. This methodology is based on structured modeling, a formal mathematical theory conceived for representing and manipulating models. It assumes a soft-linking approach, meaning the models share information without integrating them within the same platform or code. This framework was developed within the European project openENTRANCE, which will develop, use, and disseminate an open, transparent, and integrated modeling platform for assessing low-carbon transition pathways in Europe.

1. Introduction

The development and use of models as decision tools have increased steadily in the past few years given the transition to a zero-carbon energy system. We can find different models including sectoral, macroeconomic, investment, operation, or integrated assessment. These models have different scopes and granularities and have been developed at different institutions within different platforms. Suppose we aim to generate a perspective on all the implications of the energy transition. In that case, it is necessary to use several of these models concurrently, and consistently, integrating them.

Energy planning models simulate different scenarios and evaluate the potential impact of other policy options. However, the complexity and diversity of energy systems often require using multiple models, each with its purpose and level of detail. Soft linking is a technique that allows the integration of multiple models by connecting their inputs and outputs without the need for a detailed representation of the internal workings of each model [1]. This approach can provide a more comprehensive view of the energy system while maintaining the integrity of the individual models.

In recent years, there has been a great effort in the development of open-source models for energy planning and power systems analysis for assessing low-carbon transition pathways, such as the openENTRANCE (open ENergy TRansition ANalyses for a low-Carbon Economy – May 19/April 23) [2] project that aims to developing and disseminating models in an open, transparent and integrated manner, and the ECEMF (The European Climate and Energy Modelling Forum – May 21/Dec 24) [3] that wants to construct a more coherent, unified evidence database

Abbreviations: openENTRANCE, open ENergy TRansition ANalyses for a low-Carbon Economy; ECEMF, The European Climate and Energy Modelling Forum; ESM, Energy System Model; IAMs, Integrated Assessment Models; TIAM, TIMES Integrated Assessment Model; OSeMOSYS, Open-Source Energy Modeling System; IIASA, the International Institute for Applied Systems Analysis; TD, top-down models; BU, Bottom-up models; GDP, Gross Domestic Product; EV, electric vehicle; PSM, Power System Model; SRMC, Short Run Marginal Cost; NTNU, Norwegian University of Science and Technology; TU Berlin, Technical University of Berlin; TNO, Netherlands Organisation for Applied Scientific Research; TU WIEN, Vienna University of Technology; SINTEF, The Foundation for Industrial and Technical Research; TSO, Transmission System Operator; MCA, Multi-Criteria Analysis; CGE, Computable general equilibrium; VRE, Variable Renewable Energy; CMP, common measuring points; DSCP, direction-specific connection points; EU, European Union.

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that will form a concrete basis for action by policymakers in future energy and climate policies decisions. We also observe a strong current policy-driven interest in soft-linking of Energy Systems Models with other models, as emphasized by Kragt et al. [4], Krook et al. [5], and Fattahi et al. [6].

Therefore, categorizing and formalizing the connection between models contributes to establishing a strategy for a specific target research question, providing policymakers and practitioners with a better use of the current tools. The expected outputs aim to fill this knowledge gap by developing a conceptual methodology and enhancing the design and current models' interactions. This paper presents a framework for connecting models that have been developed and applied in the context of openENTRANCE Project, and the focus will be on links with Energy Systems Models (ESMs).

The design of this framework tackles several challenges since energy models have complex data structures where many parameters are stored in different units. In addition, working with models usually implies complicated data manipulations commonly in different programming languages. The main challenges of this framework are: a) setting a standard for the characterization of models, b) determining in what cases two or more models might be used concurrently, c) establishing guidelines for the selection of models that can be used concurrently to assess a particular issue about the energy transition and d) establishing precisely how the models should be executed and how they should communicate (i.e., designing their integration).

Our proposed framework is a general approach based on structured modeling, a formal mathematical theory developed for conceiving, representing, and manipulating a wide variety of models [7]. The framework has been articulated in several sections around four distinct stages (Fig. 1):

- Characterization of models
- Definition of the research question
- Discovery of solution strategies
- Development of a model-manipulation strategy

These stages are discussed in the following sections. The **model characterization** stage presents a literature review mainly focusing on Energy Systems models (ESMs), an overview of energy systems models' main features, and an exploration of the challenges of using ESMs. In this stage, the model characterization is also described, together with the definition and characterization of each model. Next, the meaning of the **research question** (i.e., analysis to be done) should be established in terms of objective, scope, and details. This question, together with the model characteristics, determines the available **solution linking strategies** that can be selected. Here the literature review of linking techniques with ESMs is discussed and a visual mapping of the literature is presented, highlighting the different approaches used and their strengths and weaknesses. Last, a specific procedure to communicate between the models and examine convergence is developed, defining the **model manipulation strategy**. The proposed strategy is applied and validated for a case study taken from project openENTRANCE.

2. Characterization of energy models

2.1. Overview of energy system models

Energy System Models (ESM) have emerged as an important tool to help policymakers at evaluating cost-effective pathways for energy supply options [8,9]. However, these tools often show a limited application to represent the operation behavior of power systems, which can lead to errors that invalidate the long-term planning of the electricity generation portfolio [10–13].

ESM are designed to represent the several dimensions of energy-related problems as consistently as possible and analyze the interaction of different sectors as energy is consumed and produced (e.g., Residential, Power, Industrial, Agriculture, Transport, etc.). The interactions are represented under different assumptions about technical and economic conditions of current and prospecting energy technologies due to the energy policies (i.e., scenario analysis) [14].

Some ESMs are defined as Integrated Assessment Models (IAMs), e.g., TIAM (TIMES Integrated Assessment Model) [15]. Their main difference concerning classical ESMs, which focus primarily on understanding the interactions among the energy sectors under different policy configurations, is that IAMs englobe the energy-climate-economy aspects (i.e., climate changes and society behavior) by considering them into one modeling framework or adding modules to address these aspects to a classical ESM framework, as done on MESSAGEix-GLOBIOM [16]. For this reason, some authors classified IAMs as hybrid models.

Therefore, for our linking analysis, we will also include IAMs and refer to them as ESMs. A review of IAMs was conducted by Nikas et al. [17], where they categorized these models based on several characteristics such as system coverage, mathematical structure, model perspective, geographic scope, forecasting period, endogenous and exogenous technological change, and type of uncertainty treatment. They concluded that many IAMs models would not fall easily into any of the broad classifications available for ESMs.

Different modeling methodologies can be used to build an ESM (Fig. 2), and generally, the classifications of ESM available in the literature are based on these approaches [14,18,19]. The classifications vary depending on the economic and engineering perspectives to be represented. Here we categorize the ESM based on three main aspects:

2.1.1. Technical and economic detail: Bottom-up, Top-down, and hybrid models

Bottom-up models (BU) usually focus on the energy sector from an aggregated perspective, representing its different sectors with a higher detailed technological representation of supply and demand [18,20]. The most known BU models are the MARKAL-TIMES family [21–23], developed by the IEA-ETSAP consortium, composed of researchers from International Energy Agency (IEA) member countries (e.g., TIME SINERGIA [24], TIMES-Sweden [25], and TIMES-PT [26]) and MESSAGE [27], which has been built and maintained at the International Institute for Applied Systems Analysis (IIASA) since the 1980s. Other BU models are the Global Energy System Model (GENeSYS-MOD), an open-source energy system model based on the Open-Source Energy Modeling

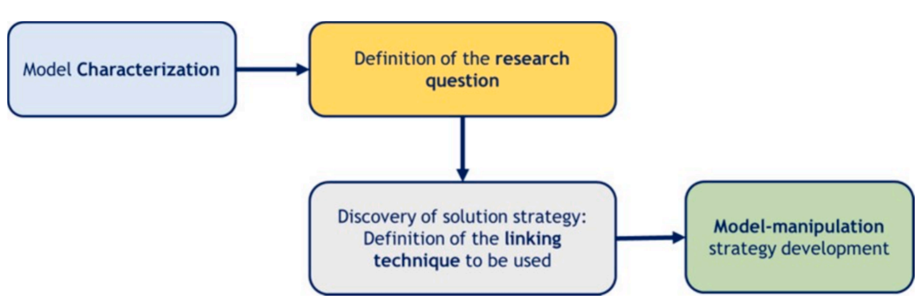


Fig. 1. Proposed framework stages.

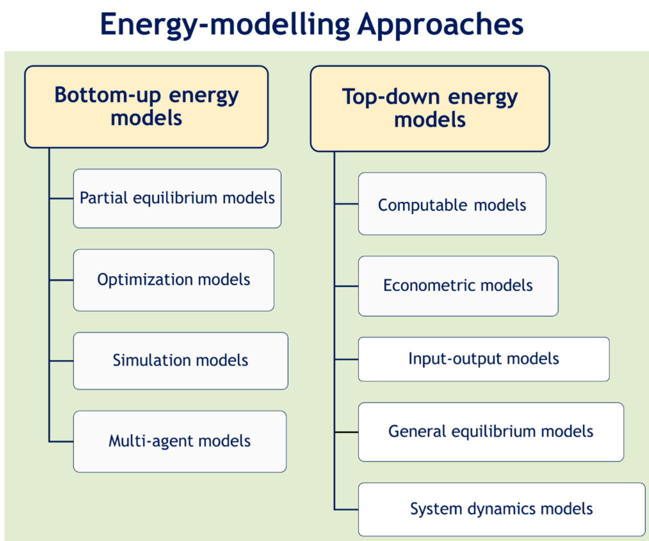


Fig. 2. Energy system modeling approaches. Source: Based on [32].

System (OSeMOSYS) framework [28], and EnergyPLAN, an energy system analysis tool created for the study and research in the design of future sustainable energy solutions developed at the Aalborg University in Denmark [29].

The literature presents a second classification for ESM: top-down models (TD). These models describe the macroeconomic relationships between the energy sector and other sectors of the economy at a national or regional level evaluating the effects of energy and climate policies through maximizing consumer welfare and using feedback loops between economic growth, employment, and welfare [18,20]. The most known are general equilibrium models (GCE), usually known as macroeconomic models, not ESMs [6]. This paper will not further discuss these models as the focus is the soft-linking with BU models. TD will be referred to as a macroeconomic model.

A third type is the hybrid models that address the weakness of TD and BU models, getting the most out of the two approaches [30,31]. An example of a hybrid model can be found in [31], where the approach maintains the technological and sectoral detail of a bottom-up optimization model with aggregated energy demand endogeneity GDP impacts from a macroeconomic model.

2.1.2. Mathematical approaches: Simulation and optimization

In energy planning, simulation models and optimization tools serve different purposes. Simulation models are complex tools that mimic how energy systems (like power plants, grids, and consumers) behave under different scenarios, helping to understand potential future outcomes [32]. Alternatively, optimization models provide the optimal configuration for the energy system due to minimizing the cost of supplying a certain exogenous demand, considering the constraints related to the available technologies and their technical and economic aspects. While simulations provide a detailed picture of system reactions, optimizations seek the most effective strategies for system setup and operation.

2.1.3. Spatial and time scope: Global, regional, and national models

Another standard classification for ESM models considers their spatial and time scope [18,33]. Regarding time scope, they can be short-term models, which use a short temporal horizon (e.g., a year or a couple of years) and examine the energy system for a target year, or long-term models, which perform more extended time analyses from 50 to 100 years. ESM models can have local (city scale), national, regional (i.e., two or more countries), or global scope for spatial classification. We constantly observe a trade-off between the spatial and time ranges and their resolution. As one increases, the other tends to be lower [33].

3. Characterization strategy

Following the ESMs definitions, this section describes the standardized characterization of the models developed, which is the first step in the developed framework, and their application to the openENTRANCE project model suite. This starting exercise allows us to compare the models in terms of their general attributes. This section describes the developed procedure. First, some definitions are presented to clarify the further description. Then, the openENTRANCE suite is presented, highlighting the model objectives and their specific features. After that, the models are grouped according to their similarities.

Firstly, we presented the definition of structured modeling which is the base of our approach. Then, the classification of models is presented. We have developed this classification as a comprehensive attempt to include all the relevant characteristics of the models that allow to:

- Precisely understand the scope of the model and how it can be used to answer policy questions, which is the objective that lies at the core of modeling exercises.
- Design the interaction with other models with the specific aim of answering a policy question that cannot be tackled with a single model.

The classification is presented in the form of model maps, as this visual information is believed to be clearer for both modelers and policymakers. After this, we apply the model maps to the modeling suite in the openENTRANCE, describing their features both comprehensively and succinctly.

3.1. Structured modeling

Structured modeling is an approach to develop and organize models in a systematic and organized way, being largely applied to software development. Other applications are data analysis, and other problem-solving domains. It is also defined as a formal mathematical theory that was developed for conceiving, representing, and manipulating a wide variety of models [7].

In the context of this paper, identifying the policy question is key to defining what models should be used – and how. This is the central stage in structured modeling [34], an approach for model integration that was derived from sound mathematical concepts more than three decades ago. This methodology represents each model as a graph where nodes are model variables, and the edges that join them represent the equations or operations that link them. The representation of the model is, therefore, a graph, which is, in general, hierarchically organized (variables can be organized in levels) and partitioned (the variables of a model can be classified into different sub-contexts). If the graph is acyclic, there are no cross-references in the definition of variables, and no convergence procedures are needed. This considerably facilitates the design and execution of a case study. If there are cycles, then the case study will not be amenable to a solution in only one pass, and iterations may be needed. Acyclic graphs are quite common and have appeared in the case studies of openENTRANCE. Case study design should minimize them in order to simplify the convergence procedure.

Geoffrion [7] states that structured modeling has three main levels [7]: elemental structure, which sees a model composed by discrete elements and aims to capture all the definitional details of a model; generic structure, which focus on capturing the natural familial group elements; and modular structure, which aims to organize generic structure hierarchically to the extent that this seems appropriate and useful, i.e., understanding the model composed by modules according to commonality and similarity, and then grouping this modules into higher order modules. Therefore, the author defines a structure model as “*as an elemental structure together with a generic structure satisfying similarity and a monotone module structure*”. For our approach, a structure model can be understood as the linking structure defined resulting from coupling two different models. Each of these levels can be easily identify as we group and classify the models studied here.

Although structured modeling is arguably the most relevant framework in this context, other methodologies have been proposed for the integration of models, namely logic modeling [7] and graph grammar [35]. We have chosen structured modeling as our base because of its simplicity and solid theoretical background.

3.2. Model dimension definition

As discussed on section 2, ESMs are usually classified based on three main aspects: technological-economic detail, mathematical approach, and time and space scopes. Furthermore, several dimensions are considered when describing the models in a suite. Here, we will classify these dimensions into three distinct groups: **decision space** (that is, the type of decisions that the model can consider), **geographical dimension, and technological scope**, as shown in Fig. 3. The **decision scope** refers to the time scope of the decision dynamics within the energy system that the model covers. This can be long, medium, short, and very short-term, or a combination of these. For instance, it is common that investment models (which deal with long-term decisions) also represent the operation of the system (considering medium- or short-term decision variables).

It is important to distinguish between time horizon (the furthest time considered in a model) and time resolution (the level of detail in the description of time). These two can be confused with each other and, to some degree, are related: limited computing power means that the longer the time horizon, the less time resolution can be included. Conversely, if a high time resolution is used, a shorter time horizon might need to be used.

Geographical scope refers to the physical space (i.e., a city or territory as nodes or graphs) covered by the system represented by the model. This can be the whole world (i.e., global), a region (i.e., regional: a continent, a group of countries, or a country), a zone (i.e., zonal: states or cities inside of a country), or even a more specific location (i.e., local: a district, community, or group of users). This is usually represented by means of the territorial units for statistics (NUTS) in the European context. The **technological scope** refers to the technological sectors considered by the model, such as electricity, gas, heat, and transport. All the technologies considered in the ESMs will be grouped into these sectors.

After that, the granularities are defined for each scope, as it is shown in Fig. 4. In the decision and geographical scope, granularity refers to the time and geographical unit considered in the model for the decision variables, i.e., in the decision scope, decisions may be made yearly, monthly, weekly, daily, and hourly, while in the geographical scope, decisions may be made at global, continent, region, country, zone, province, district, community, or end-user level. The technological scope refers to the specific set of technologies considered in the model, which can belong to one or more sectors (i.e., cross-sector).

Some technologies considered by a model may belong to several sectors. For instance, an electric vehicle (EV), by its consumption, can be considered in the electricity sector, while by its production or service provided, it can be deemed to belong to the transport sector. Other devices, such as electrochemical batteries, just belong to one sector (by their consumption and production).

A hierarchy of models can be set up in the geographical scope, according to their scope and dimension, from the global to the local one, i.e., the output of a global model where decision variables refer to countries (country granularity) can be used as inputs by other models with a finer granularity by disaggregating decisions made by the former. Conversely, decisions made at a local level can also be aggregated (or upscaled) to compute inputs to be considered by models covering a larger scope and having a larger granularity. In the decision scope, something similar happens: outputs of models making longer-term decisions can be taken as input by short and very short-term models.

Normally, longer-term models also include some shorter-term decision processes that long-term decisions depend upon. Longer-term models can also provide input to short-term models. For instance, an energy system model can provide input to a power market model. The input is the demand for power, taking into consideration demands for charging EVs, heat pumps, etc. Conversely, a shorter-term model may provide inputs to a long-term model to be considered by the latter in the decision-making processes. For instance, a PSM (short-term model) can provide to the ESM (long-term model) the hourly Short Run Marginal Cost (SRMC) or the hourly production profile for renewable technologies such as wind and solar. These outputs can be used to update the availability factors of power plants or validate the results for electricity prices and total costs obtained in the long-term model. In the technological scope, usually, this does not happen, i.e., the scope and granularities are independent.

3.3. The openENTRANCE modeling suite

The following energy models constitute the openENTRANCE modeling suite. We provide here a description of each of these models, including key information such as its main objective, special characteristics, and status, as it is shown in Table 1 of these models are described in a series of academic references.

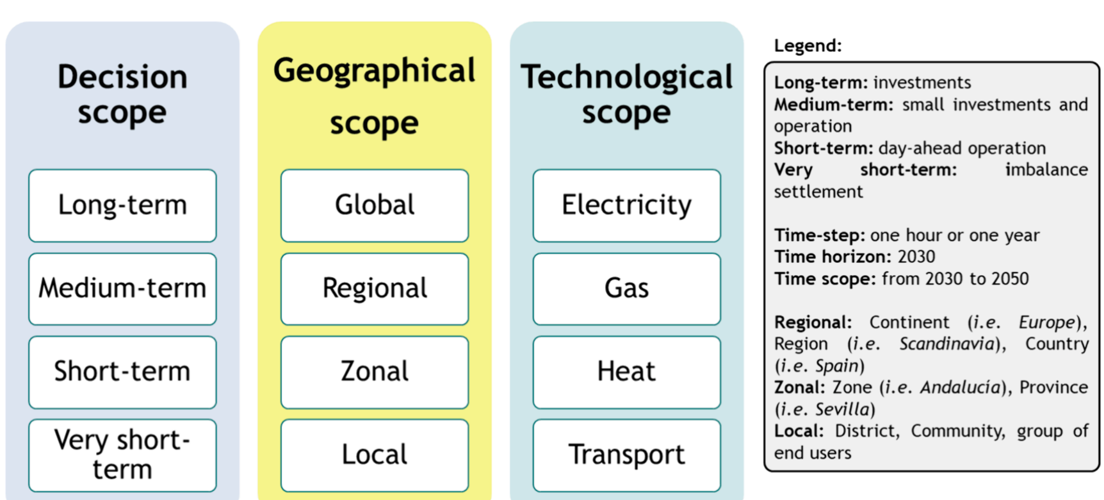


Fig. 3. Dimensions of energy models.

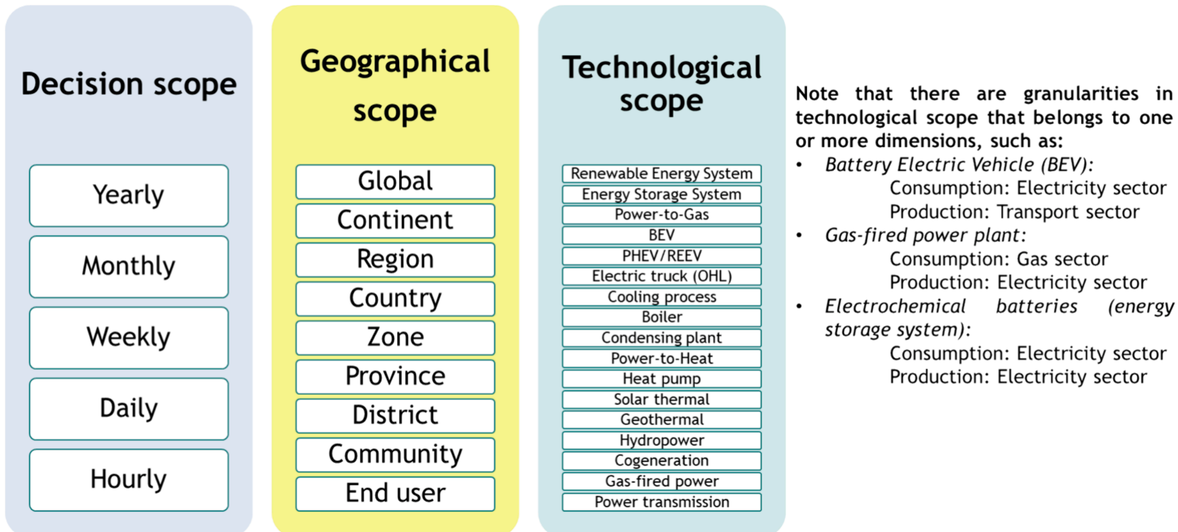


Fig. 4. Granularity of energy models.

3.4. A visual tool to structure models

In Fig. 5, a mapping of the models according to their decision and technological scope is shown, where the latter is represented by colors. Color saturation describes the degree of specificity of the model: saturated colors (blue for transport, yellow for electricity, orange for heat, green for gas) indicate specialized models (i.e., with a narrow scope), while colors more similar to grey indicate more general models. In the decision scope axis, very short-term refers to seconds or minutes, short-term refers to hours up to a week, medium-term refers to weeks up to a couple of years, and long-term refers to more than two years. Different models have slightly different color shades, and the degree of color saturation refers the specificity of the model, i.e., light boxes mean the model can be used in this capacity, but it is not its main application area or where it has mostly been used. A darker color box is the primary focus of the model.

A mapping of the models according to their geographical and decision scopes is shown in Fig. 6. As mentioned above, color saturation describes the degree of specificity of the model: saturated colors indicate very specialized models (i.e., with a narrow scope), while lighter colors indicate more general models. In addition, different models have slightly different color shades, and the degree of color saturation refers the specificity of the model.

3.5. Granularity map

Fig. 7, Fig. 8, Fig. 9 together represent the granularities of the models with respect to the decision (time), and geographical and technological scopes. This map indicates that each model can function over more than one level depending on the input data or on the specificities of the case study. This will also impact the solution times achievable in each case (that is, aiming for higher granularity will result in a higher need for computational resources). This trade-off was always present in the case studies in openENTRANCE.

3.6. Characterization of input and output data

Inputs and outputs of each model can be represented with tables or by means of a graph, as shown in Fig. 10.

All these visual tools are useful when designing a case study, as will be illustrated in the examples included at the end of this document. They easily show different perspectives, model strengths, and complementarities. The idea is to build these lists and graphs and make them available for discussion at the step of defining the case study by the team of experts participating in the analysis.

4. Strategic decision-making: Guiding the methodological approach through the research question

The research question plays an important role to defining what models should be applied, and how they should be used. It also guides researchers in exploring the key variables to solve the problem they are studying. As we navigate towards the implementation of the methodology, understanding the core and context of the research question is essential, requiring a deep analysis by the users.

In structural modeling, we seek an understanding about the parts that a model is composed, its mathematical approach, the variables considered, and the natural familial group elements to be organized in a comprehensive and useful structured. For our approach, a structure model is the linking approach resulting from coupling two or more different models. Each model presents different dimensions that can be identified, grouped, and classified as presented in the previous section. However, once this step is concluded, the decision of the models to be applied will be led by the research question defined and its main goal. Therefore, the path the users take should encompass the following step: a sensitivity analysis of the research question and its definition.

By sensitivity analysis, we mean that the analysis will assess the impacts of one parameter on a specific parameter. For instance, what is the impact on transmission congestion of increasing wind energy? Or what is the impact on energy prices of increasing the proportion of long-term contracts?

Framing a research question as a sensitivity analysis will allow modelers and policymakers to acknowledge their potential impact of variables involved on study outcomes, and their results sensibility to the inputs and outputs available in the models. Therefore, users should treat their research question in a sensibility analysis context to better use the proposed approach. Section 4.1 provides an example of how exploring the definition of the research question that can guide this step.

4.1. Exploring a policy-relevant sensitivity analysis of the research question

The definition of a *research question* should be framed as a *sensitivity analysis as discussed before*. Sensitivity analysis studies how different values of input variables affect a specific output variable under specific conditions. For instance, in case study 3, “Need for flexibility: storage,”

Table 1
openENTRANCE model suite.

Model	Developer	Main objective	Special characteristics
GENeSYS-MOD	TU Berlin	Optimize least-cost configuration and operation	To achieve a cost-optimal energy mix, the model considers a plethora of different technology options, including generation, sector coupling, and storage. Moreover, by allowing for different emission targets (such as emission budgets, yearly emission targets, or emission reduction goals), possible cost-minimizing pathways towards a largely (or even fully) decarbonized energy system can be analyzed.
REMES:EU	NTNU/ SINTEF	Study the effects of macroeconomic policies on the EU economy.	REMES:EU considers the long-term dynamics of prices and demand–supply of commodities compatible with a given scenario (storyline) by considering changes in CO2 budget, sectoral productivity, energy and carbon efficiency, availability of natural resources and changes in technology.
EXIOMOD 2.0	TNO	Measure the environmental and economic impacts of policies	Thanks to its environmental extensions, it establishes the link between the economic activities of various agents and the use of a large number of resources and negative externalities (greenhouse gases, wastes).
EMPIRE	NTNU	Optimize power plants operation and investments in power generation and transmission capacity	EMPIRE incorporates long-term and short-term system dynamics, while optimizing investments under operational uncertainty. By decoupling the optimization of system operation at each investment period from future investment in transmission infrastructure and operation periods, a computationally tractable optimization problem is produced.
openTEPES	COMILLAS	Determine the investments plans of new facilities for supplying the forecasted demand at minimum cost	Multicriteria: the objective function incorporates some of the main quantifiable objectives: generation and transmission investment cost (CAPEX) and expected variable operation costs (including generation emission cost) (system OPEX).The operation model is a network constrained unit commitment (NCUC) including operating reserves with a DC power flow (DCPF) through a detailed power network.
GUSTO	TU WIEN	Optimal investment and dispatch of distributed generation and battery storage and Optimal utilization of small battery storage systems at prosumer level	GUSTO merges the pre-existing models OSCARS and HERE.Optimal capacity allocation and dispatch (distributed generation and battery storage) under special consideration of sector coupling on distribution grid level (electricity, heating/ cooling and gas grid) for meeting the energy services needs of local energy communities. The main task is to maximize the profit for a balancing responsible party under consideration of optimal operational dispatch of battery storage and flexible loads. This includes (i) the minimization of the scheduling forecast deviation of balancing responsible parties (and thus reduction of balancing energy), (ii) the provision of ancillary services to the TSO and (iii) excess energy sold to the wholesale market.
Plan4EU	EDF	i) Optimal capacity expansion, ii) Optimal operation of seasonal storage iii) Economic dispatch at European level	The plan4eu modeling suite is focused on the electricity system, comprises i) a capacity expansion model which finds the best optimal compromise between generation/storage investment and transmission/ distribution expansion for a given long-term horizon, ii) a seasonal storage valuation tool and iii) a European operational dispatch model. All 3 models include uncertainties, a realistic accounting of all technical costs and constraints including system services, for all kinds of centralized and distributed assets. It includes an aggregated modeling of transmission and distribution networks.
FRESH: COM	TU WIEN	Dimension/design and consider the actors' sharing allocation preferences in different local energy community configurations	Based on this model, different allocation and clearing mechanisms of shared local generation among the individual actors can be considered:

(*continued on next page*)

Table 1 (*continued*)

Model	Developer	Main objective	Special characteristics
			static (individual actor's optimum according to predefined allocation scheme) and dynamic (hourly/real time global community optimum exploiting several synergies among actors' load profiles and preferences).
EMPS-W	SINTEF	Long-to-medium term operation of hydrothermal power systems	Optimal dispatch of hydrothermal power systems considering stochastic climate variables such as wind, solar, inflow to hydropower reservoirs and river network topology.
Integrate	SINTEF	Optimal operation and investment path for multi carrier energy systems over a planning horizon of several decades to bring available energy to the end user	It optimizes investments in infrastructure over a planning horizon of several decades to satisfy end user demands in the cost-optimal way, i.e., finding the investment paths minimizing investment and operational costs. As part of the investment analysis, the model also optimizes daily the system operation for representative periods of the year for each alternative system design. This operational optimization can be run independently from the investment analysis.
SCOPE:SD	Fraunhofer IEE	Cross-sectoral capacity expansion planning and economic dispatch optimization for developing long-term, low-carbon energy scenarios	Thanks to the hourly modeling of the supply and demand characteristics of a scenario year, it is possible to model both the renewable energy producers and conventional power plants, as well as the use of storage technologies and flexibility options, in detail. A wide variety of conventional and renewable generation technologies are available for power generation. The necessary flexibility for the integration of renewable power generation is modeled using various storage technologies, load management options, and European cross-border exchanges of energy. Depending on the research question, the heat and transport sector, with their interfaces with the power sector, can be modeled with a high degree of temporal and spatial detail.
e-Transport	SINTEF	Minimize the overall cost of the energy system, including investments, operations, and emissions while meeting the predefined energy demands of electricity, gas, space heating, and tap water heating.	This model is a tool for expansion planning in local energy supply systems with multiple energy carriers. It minimizes energy system costs while meeting predefined energy demands for electricity, space heating, and tap water heating. It can account for many topographical details, making it ideal for local energy planning in municipalities or cities. The model currently uses a nested optimization of mixed integer programming and dynamic programming and calculates the optimal diurnal operation of the entire energy system while providing optimal expansion plans for 20–30 years into the future. The primary user group for the e-Transport model is decision-makers involved in planning local energy service systems. The model is also helpful for local authorities, utilities, and governmental agencies that give investment subsidies based on socioeconomic efficiency.

the sensitivity analysis is structured around the inputs of storage investment and operation strategy. It is further described in D6.1 and in the illustration that appears in the next sections of this paper. The references D6.1 and case study 3 points to the specific exercises within project openENTRANCE that inspired the case studies. The relevant outputs include system operation costs and the optimal grid reinforcements for each case. Further specification of the research question includes:

- Definition of the research policy question
- Definition of the context of the analysis
- Definition of the objectives of the research question
- Definition of expected results
- Specification of the dimensions that need to be covered in the analysis, in terms of:
  - Decision scope and granularity
  - Geographical scope granularity
  - Technological scope and granularity
- Specification of the required input data

All these should be incorporated into the specification of the policy question.

5. Discovery of solution strategies

The development of a solution strategy is not always a straightforward task. This section presents the methodology proposed to discover alternative solution strategies for a case study, including the selection of

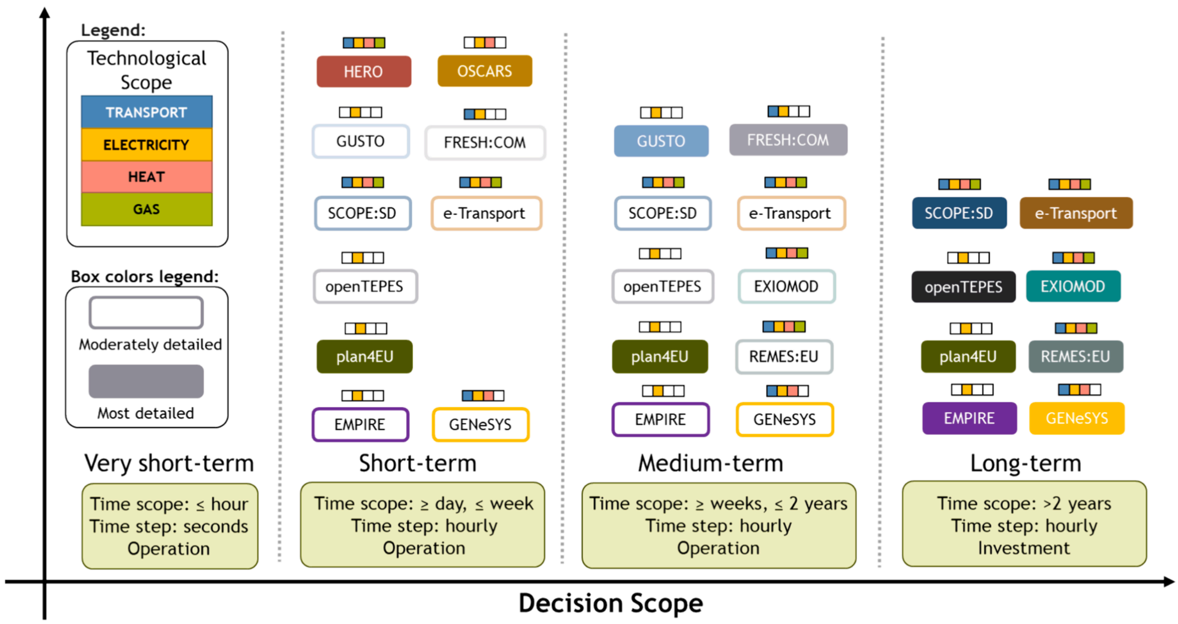


Fig. 5. Model map: decision and technological scope.

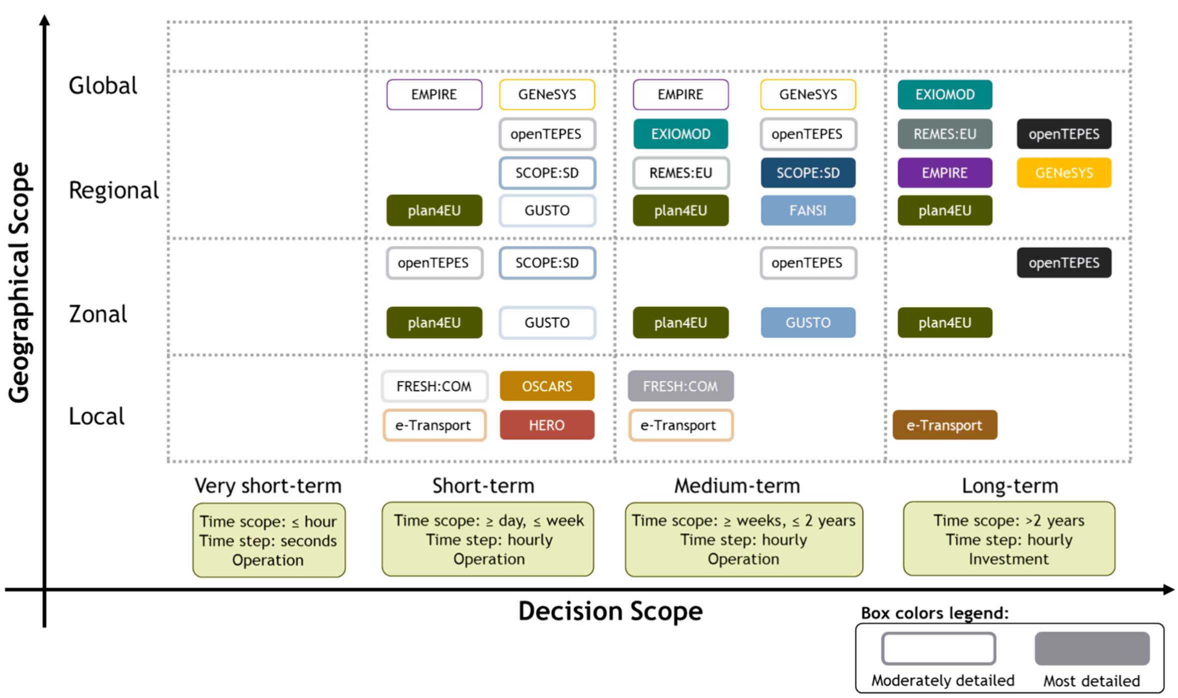


Fig. 6. Model map: geographical and decision scopes.

the models needed to solve a given research question and the definition of the interactions among them. The methodology is structured in the following steps, which will be described in the remaining of this section:

- Definition of candidate model sets
- Input data definition
- Identification of potential links among models
- Characterization of model links

5.1. Definition of candidate model sets

The model or models selected should comply with the requirements of the research question in terms of covering the dimensions (decision scope and granularity, geographical scope granularity, technological scope, and granularity). These requirements can be expressed in tabular form as presented in Table 2.

Then, the available models are filtered through the requirements. We suggest the following order and using the model maps presented above to identify the possible models for the case study. If several scopes are necessary, the filter should identify all the partial fits (i.e., if both a regional and a zonal geographical scope are needed to address a research

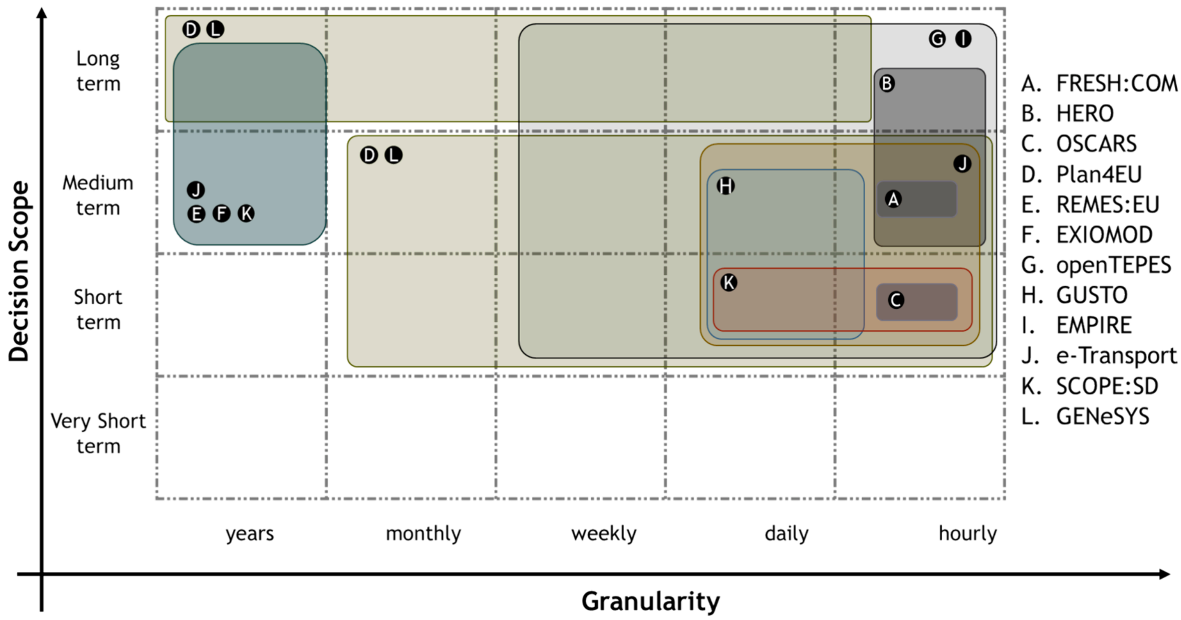


Fig. 7. Granularity map: decision scope.

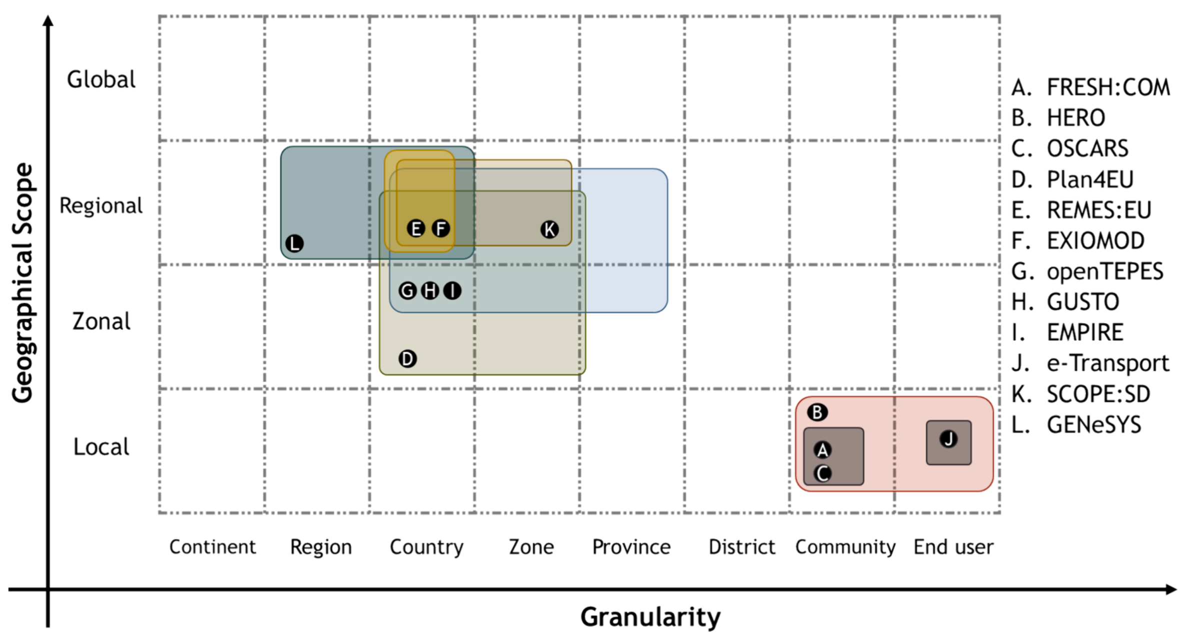


Fig. 8. Granularity map: geographical scope.

question, then both regional and zonal models should be selected, not only the ones that cover the two scopes at the same time).

This information can unveil different possibilities for covering the required dimensions. All these can be valid approaches. Parsimonious sets (that is, the sets that cover all required dimensions with the minimum number of models and without extending into dimensions that are not required to address the research question) should be favoured. It is also desirable to minimize the need for iterations, which might be necessary when the inputs and outputs of models form closed loops. However, given that the existence of loops is only revealed in the next steps, it is advisable to list several candidates sets that might serve the research question.

In addition, assessing energy policies requires the technological detail offered in BU models and the wide perspective of the TD approach. This calls for the combined use of both types of models, *hybrid models*. As a result of this process, we obtain a list of sets and their constituent models, which are conveniently described by their main objective as in Table 3:

5.2. Definition of input data

The definition of model inputs is articulated around two steps: classification and grouping.

5.2.1. Classification

First, all data of the models are taken from the tables filled in the characterization of the model and classified into inputs and outputs following the next format (Tables 4 and 5):

	Battery Electric Vehicle (BEV)	Battery Energy Storage (BES)	Biomass	Boiler	Carbon Capture and Storage (CCS)	Chiller	Coal	Cogeneration. Combined Heat and Power (CHP)	Combined Cycle GasTurbine (CCGT)	Compressed-Air Energy Storage (CAES)	Condensing plant	Cooling process	Demand Response	Energy Storage System (ESS)	Fuel Cell Electric Vehicle (FCEV)	Gas Turbine	Gas-fired power	Geothermal	Hardcoal	Heat	Heat pump
FRESH:COM		✓												✓						✓	✓
GUSTO														✓			✓				
plan4EU	✓	✓	✓				✓		✓	✓			✓	✓			✓	✓	✓	✓	
REMES:EU			✓				✓												✓	✓	✓
EXIOMOD							✓	✓						✓			✓	✓	✓	✓	✓
openTEPES		✓	✓				✓	✓	✓					✓		✓	✓	✓	✓		
EMPS-W			✓				✓	✓	✓				✓	✓		✓	✓	✓	✓		
EMPIRE	✓	✓	✓				✓	✓	✓					✓		✓	✓	✓	✓	✓	
INTEGRATE	✓	✓	✓	✓				✓	✓		✓	✓		✓	✓	✓				✓	✓
SCOPE:SD	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
GENeSYS	✓	✓	✓				✓	✓			✓			✓	✓		✓	✓		✓	✓

	Hydrogen (H2)	Hydro power Large	Hydro power small	Internal-Combustion Engine Vehicles (ICEV)	Lignite	Methane	Natural Gas	Nuclear	Ocean	Oil	Overhead Line Electric truck (OHL)	Plug-in Hybrid Electric Vehicle (PHEV)	Range Extended Electric Vehicle (REEV)	Power transmission	Power-to-Gas	Power-to-Heat	Pumped-Storage Hydro (PHS)	Renewable Energy System (RES)	Solar PV Rooftop	Solar PV Utility	Solar Thermal (CSP)	Wind Offshore	Wind Onshore
FRESH:COM														✓	✓	✓		✓	✓	✓			✓
GUSTO																		✓					
plan4EU		✓	✓		✓			✓	✓	✓				✓			✓	✓		✓	✓	✓	✓
REMES:EU	✓	✓	✓		✓	✓	✓			✓				✓				✓					
EXIOMOD		✓	✓		✓	✓	✓	✓		✓											✓	✓	
openTEPES		✓	✓		✓	✓	✓	✓	✓	✓				✓			✓	✓		✓	✓	✓	✓
EMPS-W		✓	✓		✓	✓	✓	✓	✓	✓				✓			✓	✓		✓	✓	✓	✓
EMPIRE		✓	✓		✓	✓	✓	✓						✓		✓		✓			✓	✓	✓
INTEGRATE	✓	✓	✓	✓	✓		✓	✓		✓		✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
SCOPE:SD			✓	✓			✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
GENeSYS		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓

Fig. 9. Granularity map: technological scope.

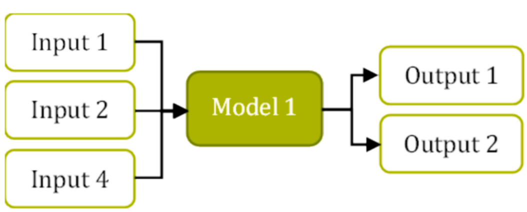


Fig. 10. Sample of the graph to represent the composition of a model.

Table 2
Sample of the format of characteristics required.

	Decision scope	Geographical scope	Technological scope
Dimensions			
Granularity			

5.2.2. *Grouping*

As a first step, each granularity on the technological scope of each model is identified, and the following format is filled (Table 6):

Then, both inputs and outputs of each model are grouped by granularity on technological scope according to the following format (Table 7):

5.3. *Identification of potential links among models*

After the classification and grouping steps, heterogeneous and homogeneous data are defined. In structured modeling, *heterogeneous data* refers to variables that only exist in one model, while *homogeneous* variables are common to at least two models. Homogeneous variables reveal the potential links between models, as the input/output of one model could be the input/output of another.

Note that input/output must be analyzed regarding function, given that names, labels, or specific units might vary. openENTRANCE's nomenclature, which is based on the IAMC format, aims at helping in this task: definitions are standard.

As an example, considering group G1 presented in Table 7, the models share same variables either as input or outputs. In this paper, common variables are referred as a number label, i.e., input X and output X representing the same variable X. From Table 7, we can observe

Table 3
Sample of format for a model or set of models.

Set	Models	Objective	Approach (BU vs. TD vs. hybrid)
1	*Model 1*		
1	*Model 2*		
2	*Model 3*		

Table 4
Sample of format for the classification of data as an input.

Input	Model 1	Model 2	Model 3
Input 1	*X*		*X*
Input 2	*X*		
Input 3		*X*	
Input 4	*X*		*X*

that *input 3* (Model 2) is equal to *output 3* (Model 3), and *input 4* (Models 1 and 3) is equal to *output 4* (Model 2). Therefore, to classify the common variables as homogenous and heterogenous data, a color scheme is used. Green color represents the homogenous variables, while yellow the heterogenous variables. A sample format for this example is shown in Table 8.

5.4. *Characterization of model links*

5.4.1. *Identifying the need of linking: EMS modeling challenges*

One of the objectives is to determine in what cases two or more models might be used concurrently and establish the guidelines for the selection of models that can be used concurrently to assess a particular issue about the energy transition. The limitations of individual models can be addressed by linking them with complementary models that can overcome the identified constraints, thereby enhancing the overall modeling capability. Fattahi et al. [6] summarized the challenges faced by ESMs in seven main points (Fig. 11), where most challenges were associated with the representation of the power sector. Based on the review of nineteen IAMs, they identify the capabilities and shortcomings of current energy system models and explore their performance using a Multi-Criteria Analysis (MCA) to identify the modeling gaps of the models analyzed. The main energy modeling gaps identify by Fattahi et al. [6] are presenting in Table 9.

Table 5
Sample of format for the classification of data as an output.

Output	Model 1	Model 2	Model 3
Output 1	*X*	*X*	
Output 2	*X*		*X*
Output 3			*X*
Output 4		*X*	

Table 6
Sample of format to identify each granularity on the technological scope.

Granularity	Model 1	Model 2	Model 3
G1	*X*	*X*	*X*
G2		*X*	
G3	*X*		

Table 7
Sample of format to group each input/output into each granularity.

G1					
Model 1		Model 2		Model 3	
Input	Output	Input	Output	Input	Output
Input 1	*Output 1*	*Input 3*	*Output 1*	*Input 1*	*Output 2*
Input 2	*Output 2*		*Output 4*	*Input 4*	*Output 3*
Input 4					

ESMs face substantial challenges in the energy systems transition towards a low-carbon economy, as stated by Fattahi et al. [6], where most are related to representing some power sector operational aspects, e. g., flexibility. Three of their five suggestions to face ESMs gaps rely on linking ESMs with other models, highlighted in yellow in Table 9. The green frames refer to soft-linking possibilities we identified as alternative suggestions to fill ESM gaps by coupling with regional models or more detailed models.

Pfenninger et al. [14] identified four ESM modeling paradigms to face the twenty-first-century energy modeling challenges: optimization, simulation, ESMs primarily focusing on the power sector, and qualitative and mixed-method. They address four main challenges that align with what was identified by Fattahi et al. [6], adding a new one: balancing uncertainty, transparency, and reproducibility. From the review of Pfenninger et al. [14], we can understand that the limitations of existing energy models have become increasingly apparent in twenty-first-century energy systems.

However, the current models still play a significant role and serve as the foundation for much of the analysis that informs policy-making in many countries and regions. Pfenninger et al. [14] propose combining methods from different sources and other fields to face these shortcomings. Other authors also use the coupling of different models as an answer to address the limitations of ESMs [5,10,36–38].

Over the last decade, several research projects have attempted (some still ongoing) to explore the linking possibilities between CGE and ESMs [5,38–40]. More recently, we have observed a higher number of papers addressing the linking connection of ESMs and sector models, specifically power systems models, to address the features of the technical operation due to the increasing amount of VRE forecasted for the future. Deane et al. [10] performed several evaluations running the PSM used with different configurations of technical constraints to capture its implications on the reliability of the electrical portfolio calculated by an ESM. Collins et al. [41] identified the gaps in the literature to capture power systems impacts of variability in ESMs by reviewing prominent ESMs methodologies. They concluded that unidirectional soft-linking allows for a good robustness check of ESM results by leveraging the strengths of an operational PSM to gain additional insights into long-term energy system model results. If it is a bi-directional soft-linking, it also allows for increased solution optimality. Das et al. [42] acknowledged that linking approaches are attractive to represent the intermittency of VRE in power systems operation in long-term planning when apart from data availability, and proper model linking method is in place. Helisto et al. [11] categorized many energy systems planning studies and investigated the impacts of modeling methods on VRE integration. They compared different types of linking with PSMs, such as unidirectional soft-linking, bi-directional soft-linking, and integrated linking with ESMs and capacity expansion planning models. Brinkerink et al. [43] implemented a soft-linking approach for coupling an IAM and a PSM with a global spatial resolution. Després et al. [18] state that an energy modeling tool that could integrate the main features of power systems would be of great interest. Unfortunately, no tool for their knowledge could achieve this full integration.

The following section presents the techniques employed in the literature to link ESMs with other models. It will include a visual mapping of the reviewed literature, highlighting the approaches used and their strengths and weaknesses.

5.4.2. *Connecting ESMs: Linking techniques*

In the literature, we frequently find two main linking with ESMs:

(a) Linking ESM and Top-down models, e.g., CCE models, provides complementary information on the macroeconomic aspects of the Energy System.
(b) Linking ESM with sectoral models, such as energy market and power system models, provides more details of operational constraints related to sector technologies, e.g., heat pumps, power plants, unit commitment, etc.

Each model coupled with the ESM will add a different perspective to the energy system planning problem. Models in linking group (a) will provide what we call a "global perspective", providing more information on the interdependencies of the energy sector with the remaining economy (i.e., [5]). On the other hand, the ESM will give these models a technology-rich approach for the energy sector (i.e., "system perspective") and understand how energy prices and mix will respond.

Models in linking group (b) will give a deeper analysis of how each sector inside of the energy system behaves for a specific planning structure provided by the ESM. In this case, ESM gains a detailed representation of one or more sector operational aspects. An example is linking to a PSM, which provides better electricity generation dispatch, and electricity market price, due to its hourly temporal and spatial resolutions. Therefore, these models give a "sectoral perspective" or

Table 8
Sample of format for the input/output assessment (green and yellow colors represent homogeneous and heterogeneous data, respectively).

G1					
Model 1		Model 2		Model 3	
Input	Output	Input	Output	Input	Output
Input 1	*Output 1*	*Input 3*	*Output 1*	*Input 1*	*Output 2*
Input 2	*Output 2*		*Output 4*	*Input 4*	*Output 3*
Input 4					

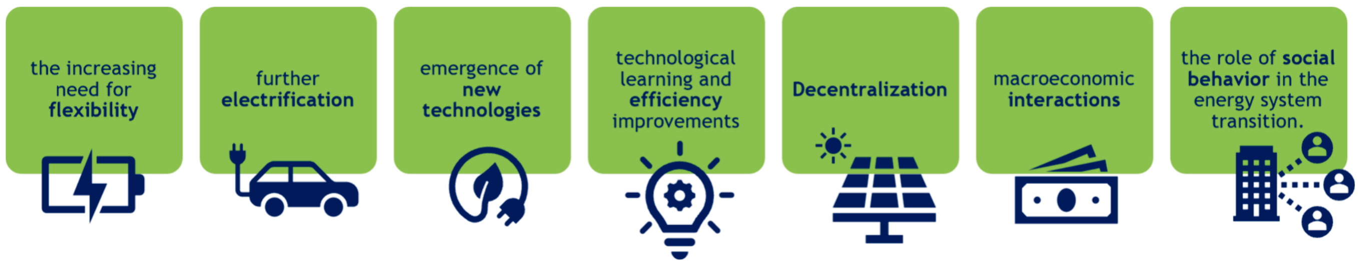


Fig. 11. Energy System Models challenges. Source: Based on [6].

Table 9
Energy System modeling gaps and suggestions. .

Current energy system modelling gaps	Suggestions
Lack of sectoral coupling technologies between electricity, heat, and transport sectors. Lack of new seasonal storage technology options such as TES and HES.	Developing a long-term planning optimization Energy System Model (ESM) that involves all energy sectors, hourly temporal resolution, regional spatial resolution, seasonal storage options, and technological learning
Lack of endogenous technological learning rates.	
Lack of hourly temporal resolution for capturing intermittent renewables and corresponding potentials.	
Lack of regional spatial resolution for analyzing energy flows between regions across a country.	Hard-linking ESM with a **Regional Energy System Model (RESM)** that involves resolved spatial resolution, land use analysis, and infrastructure analysis.
Lack of fine geographical resolution options such as GIS, fine mesh, and clustering for analyzing decentralized intermittent supply and infrastructure costs and benefits	
Lack of spatially resolved datasets such as infrastructure and local storage. Simplistic modelling of human behaviour in the current Agent-Based Modelling (ABM).	Developing an ABM simulation **SocioTechnical Energy Model (STESM)** that involves stakeholders' behaviour, local and neighbourhood effects, bounded rationality, and perceived environmental values.
The focus of current datasets is only on technological detail, rather than stakeholders' behaviour.	Hard-linking ESM with an international (or European) **Energy Market Model (EMM)** that involves an optimal dispatch electricity market, the gas and oil market, hourly temporal resolution, regional spatial resolution, and a detailed generation database.
High dependence of ESMs on consumer load profiles.	
Lack of national energy modelling consistency with a European (or an international) energy market.	
Lack of energy modelling consistency with macroeconomic indicators	Soft-linking ESM with a **Macroeconomic Model (MEM)** such as a Computable General Equilibrium (CGE) model that involves the whole economy

Source: Based on [6]

operational perspective to ESMs.

Linking techniques are divided into two main categories [1]: soft-linking and hard-linking. The soft-linking method uses the outputs from one model to produce information for the other model. Moreover, it takes advantage of both models' strengths and modeling capabilities. It can be subdivided into two categories: unidirectional and bi-directional. In unidirectional soft-linking, the information flows in one direction without automated feedback. For instance, the capacity investments outputs from an ESM are used as input capacities for a PSM (e.g., [10]). Although no automated feedback exists, the results are usually compared to determine critical discrepancies that can improve the models' formulations or inputs.

On the other hand, a bi-directional soft-linking applies feedback loops that use the differences between common outputs to achieve a certain convergence criterium. An example of bi-directional soft-linking is presented by Alimou et al. [13]. They evaluate the adequacy of an electricity generation portfolio determined by an ESM (TIMES) using a power system model (ANTARES). The convergence criterium applied was based on the capacity credit estimation and was achieved in seven iterations.

A third type of soft-linking is discussed in [11]. Here, we named it *"unidirectional soft-linking with updating checks."* In this case, the flow of information from the upstream model on the linking direction is done only once. After that, an updating algorithm is used to actualize the values until the convergence is reached. For instance, an ESM (upstream) provides the capacity sets to a power system model (downstream) that is coupled with an updating algorithm that actualizes the generation capacities set based on the output results for electricity prices and total costs. Fig. 12 show a visual representation of each soft-linking type defined.

Finally, the hard-linking approach is based on a deeper integration of the models, which are solved simultaneously, without any interactive

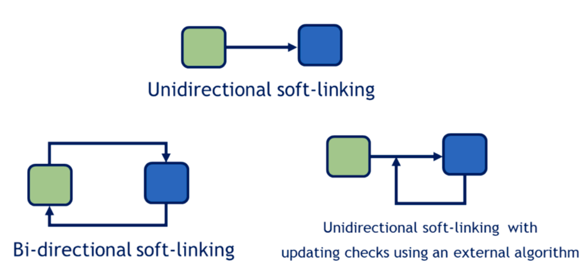


Fig. 12. Schematic view of each soft-linking type.

process (Fig. 13). Usually, this approach involves simplifying one or both models descriptions, as exemplified in [44]. However, technical limitations (e.g., inability to access the model code or computational capacity availability) can limit the implementation of hard links. Furthermore, it is also discussed that this type of linking can lead to a "black box" integration, where we do not clearly understand how the information exchanges are taking place, and the why of results are hard to explain [45].

A combination of soft-linking and hard-linking approaches is presented in [40], combining an ESM with a macroeconomic model. Their strategy allowed for using simple models to explore the economic issue of supply function in macroeconomic growth models and production and capital theory.

Krook et al. [5] state that hard-linking approaches are valuable when focusing on the global picture on which regional details depend. In comparison, soft-linking is more useful at a higher spatial detail (national scope), where there is a need for more detailed models. On the other hand, Chang et al. [46] discuss that the use of hard-linking or fully integrating models are very challenging in terms of computation effort to solve more complex mathematical structures and the complications of dealing with different data assumptions and model formulations that lead to heterogeneous outputs across the models.

Table 10 compares the limitations and strengths of the linking methodologies discussed here.

Lastly, we will present a second classification for coupling approaches, diving them into endogenously and exogenously relationships, as done in [12,42]. Thus, exogenous linking refers to the methods where each variable exchange between the models is determined independently from what happens internally in each model. For instance, let's consider a unidirectional soft-linking. How the model downstream (e.g., a PSM receiving the power capacities and determining the generation mix) in the linking direction process the information provided by the model upstream does not affect the behavior of the model upstream on the determination of the variables shared (e.g., an ESM determines the power capacities and generation mix independently of the electricity prices that the PSM will calculate). Soft and hard links methods are examples of exogenous approaches.

In contrast, endogenous linking incorporates the particularities of the sectorial dynamics directly as additional variables and constraints in the higher scope model. It should be noted that the difference between endogenous modeling and hard-linking is that in the former there is only one resulting all-encompassing model, while the latter still relies on two independent models that are directly linked by code and exchange information. An example of this approach is the hybrid ESMs focusing on specifics sectors representation. They incorporate more detailed characteristics of the sector model and improve their operational aspects in ESM or TD models. Some examples are presented by Welsch et al. [12], that examined an enhanced version of an open source energy system model (OSeMOSYS) incrementing the representation of operating reserves of the power sector, and Rodrigues [47], that built a hybrid model that incorporates a detailed representation of electricity operation aspects in a CGE (Fig. 14).

In the context of large ESMs currently used for national and global

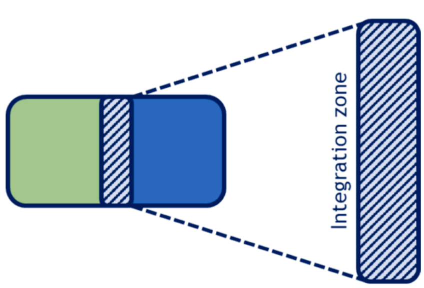


Fig. 13. Schematic representation of a hard-linking approach.

Table 10
Advantages and disadvantages of each linking approach with ESM.

Linking approach	Advantages	Disadvantages
Soft-linking	• More flexible and adaptable for a wide range of models (e.g., different mathematical structures or spatial and time resolutions), allowing for more system complexities to be represented. • Helpful to mitigate the error propagation between models, as the linking is relatively independent. • Less computationally intensive and straightforward to be conducted and replicate.	• Could lead to less consistent results across the linked models. • Requires an additional effort to develop and maintain the links once models can be updated or modified. • Does not guarantee a simultaneous convergence between the models and might need less rigid convergence criteria.
Hard-linking	• Provide a more robust approach to address complex problems. • More efficient exchange of data and information between the models. • Allows for the implementation of a more robust convergence criteria.	• High computational intensity and time-consuming. • Its implementation may require substantial effort as the linked models have different modeling frameworks. • Can create a "black box" effect, where the interactions are unclear and difficult to interpret as the information is transferred without any user judgment.

policy analysis, exogenous methodologies are generally data-intensive, and further assumptions might be necessary to develop the correlations between different time, units, and spatial scopes. Although, these methods are attractive when an appropriate model linking method is considered, helping modelers or users overcome computational limitations and avoid mathematical complexity compared to endogenous methods. Also, the exogenous approach is often used as a reliable way to consider short-term system operational aspects in ESMs [42].

However, if the assumptions necessary for improving the representation of specific sectors in ESMs are not so robust and higher computational capacity is available, an endogenous approach can be more reliable. Usually, there will be a trade-off between having a higher temporal and spatial resolution or incorporating various operational constraints in the model [42].

In summary, ESMs are necessary for describing a consistent pathway toward any future energy system. The need for capabilities such as hourly temporal resolution, grid representation, economic relationships, and operational aspects can be addressed through linking methodologies. Many models are available, and each has a different accuracy in terms of the technical or economic representation [6], where the compromise can be easily understood depending on the research question defined and the perspective taken as the essential one to answer this question. Therefore, there will always be a trade-off between the economic and engineering aspects represented in the ESM, which can be overcome by linking with other models to characterize these perspectives better (Fig. 15).

5.4.2.1. Literature visual mapping. Based on the classification provided

Fig. 14. Schematic representation of an endogenous approach.

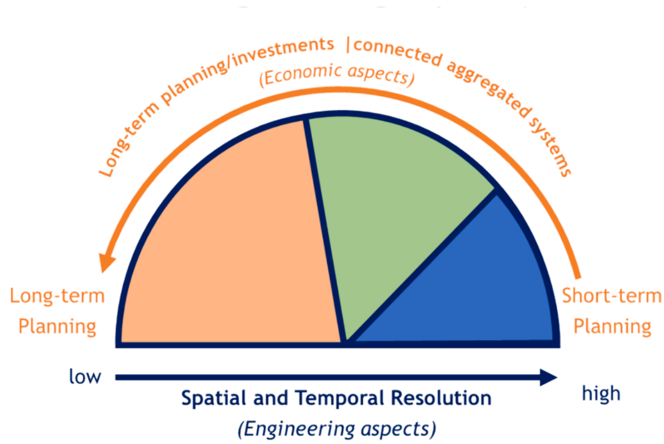


Fig. 15. The trade-off between engineering and economic aspects for the different perspectives on the energy system planning problem.

in section 0, a visual mapping was constructed to classify the different linking presented in the literature reviewed. For our analysis, the global cube (orange color) refers to macroeconomic models, the system cube (blue color) to the ESMs or IAMs, and the sectoral cube (green color) to power system models or sector models used with ESMs. The linking approaches are grouped into exogenous and endogenous links. The cubes represent the coupled models, and the arrows represent the direction of the link, i.e., the order of execution of the models. For the hard-linking scheme, the stripped area represents the equations and variables that connected the models. Meanwhile, for endogenous approaches, the cube inside of the big cube represents the integration of the downstream model (smaller cube) into the upstream model in the linking direction (bigger cube). The visual mapping is presented in Fig. 16.

Table 11 presents a literature review of the most common linking approaches with ESMs, focusing on power system models. They were classified according to the criteria given in section 0, and summarized in Fig. 16.

5.4.3. *Defining the linking direction*

Once we have identified the deficiencies in the models and determined the linking technique to be used, it is crucial to formulate a data sharing strategy that promotes efficient information exchange between these models. This entails considering the direction of information flow. Here, we adopt a soft-linking approach because there will be some cases where we will manipulate the information (i.e., aggregation/disaggregation process) from one model to another model.

Besides, we use the homogeneous data to identify the following cases for links classification based on the data shared:

- O/I: an output of model A coincides with an input of model B.
- O/O: an output of model A coincides with an output of model B.
- I/I: an input of model A coincides with the input of model B.

Case O/I marks an interaction between models (a true link), case O/O is a candidate variable to apply a convergence criterion, and case I/I indicates some shared input (i.e., the models could need the entry data in the same or different dimensional unit). Note that an input could be equal to an output: one variable could be one model's input but another one's output. Table 12 presents a sample classification of the variables and parameters that will guide the links characterization, where PAR X refers to the parameter X that can use information from variables VAR X from the outputs as inputs.

After characterizing model links, a graphic representation can be performed as presented in Fig. 17, where a dotted line represents a shared description of parameters or variables (e.g., electricity prices, hourly demand, etc).

Through the graphic representation shown, it is possible to note that there are two true links of information between models: a) from *output 4* to *input four* and b) from *output 3* to *input 3*. Note that the link from *output*

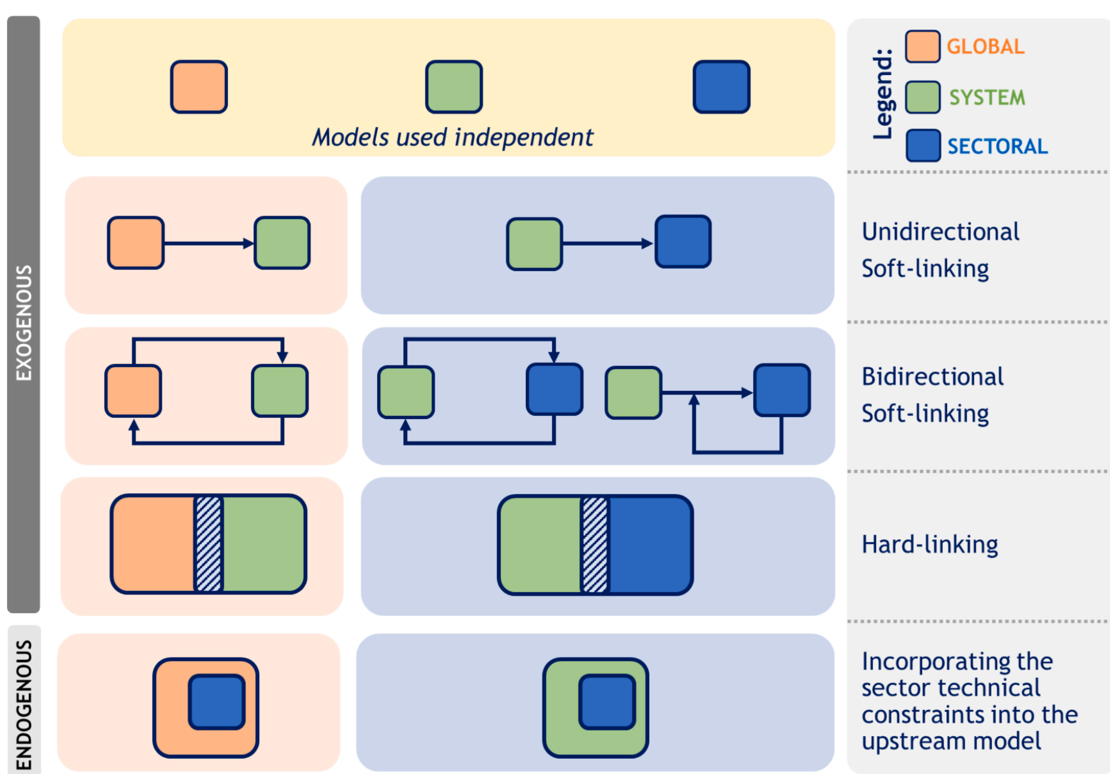
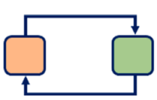
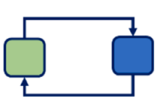
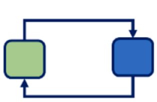


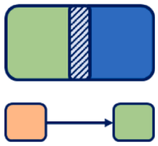
Fig. 16. Visual mapping for classification of the different linking approaches with ESMs.

Table 11
Overview of linking approaches with ESMs.

Reference	Linking Type	Description	Coupled Model	Spatial Dimension	Time Dimension	Mathematical Approach	Year Published
[38]		Describe a framework for linking a Macroeconomic model and an ESM and definition of common measuring points (CMP) as indicators of interaction points between models.	Macroeconomic Model	Regional (China and central planned Asia)	ESM and Coupled Model:1990——2050	ESM and Coupled model: Optimization	1996
[10]		Explore the impact of adding technical constraints to the electricity generation portfolio provide by the ESM model.	Power System Model	National (Ireland)	ESM model: 2005–2050 (12 time-slices resolution) Coupled Model: 2020 (Hourly resolution)	ESM and Coupled model: Optimization	2012
[12]		Utilize an open-source energy system model that can capture operating reserve constraints as an alternative approach to the soft-linking approach presented by Deane et al. [10]. The analysis was made for two specific years: 2020 and 2050.	Integrated power system model constraints	National (Ireland)	ESM model: 2020 | 2050 (12 time-slices resolution)	ESM model: Optimization	2014
[1]		Explore the insights into the electricity market prices when adding the transmission operational constraints for an ESM model analysis,	Power Sector Model	National (Italy)	ESM model: 2010–2030 (12 time-slices resolution) Coupled Model: 2030 (Half hourly resolution)	ESM and Coupled model: Optimization	2015
[39]		Develop a link approach between an ESM and general equilibrium models via a sequential or recursive dynamic process. The coupled run intervals are defined for every year, every two years, or every four years.	General Equilibrium Model (GCE)	National (South Africa)	ESM model: 2006–2040 (20 time-slices resolution) Coupled Model: 2010 and 2030	ESM and Coupled model: Optimization	2016
[5]		Introduce the definition of direction-specific connection points (DSCP) to identify the direction of how the information should be transferred in a soft-linking between a GCE and an ESM.	General Equilibrium Model (GCE)	National (Sweden)	ESM Model:2005–2050 (12 TS resolution) Coupled Model: 2008 and 2035[*]	ESM and Coupled model: Optimization	2017
[47]		Hybrid model that incorporates a detailed representation of electricity operation aspects in a CGE.[†]	Integrated power system model constraints	National (Spain)	Vary in a range from 6 up to 540 time-slices	Optimization	2017
[36]		Utilize an energy system model that focuses on district heating systems soft-linked with an operational heating model, with greater detail of the operational constraints, to address the energy flexibility of the district heating systems, minimizing the total system costs.	Operational Sector Model	Local (District Heating of Zagreb, Croatia)	ESM Model Two days (Hourly detailed level) Coupled model: Hourly Resolution	ESM and Coupled model: Optimization	2019
[13]		Automated linking between a standard long-term energy system planning and Power Sector models. Definition of a framework to analyze the adequacy of the generation portfolio defined by a TIMES model to assure the security of supply, for France Case.	Power System Model	National (France)	ESM model: 2013–2050 (12 time-slices resolution) Coupled Model: 2030 (Hourly resolution)	ESM model: Optimization Coupled Model: Simulation (Monte Carlo)	2020
[37]		Explore the needs of flexibility potential across different sectors (Heat, Hydro, and Transport) for the EU Power System.	Multi-sectoral Energy model	Regional (EU Zone, except for Matal and Cyprus, and including UK, Norway, and Switzerland)	ESM model: 2016–2050 (12 time-slices resolution) Coupled Model: 2050 (Hourly resolution)	ESM and Coupled model: Optimization	2020

(*continued on next page*)

Table 11 (*continued*)

Reference	Linking Type	Description	Coupled Model	Spatial Dimension	Time Dimension	Mathematical Approach	Year Published
[6]		Present critical criteria for analyzing ESMs and a conceptual modeling suite with two approaches: hard-linking ESM + Electricity Market Model and Soft-linking ESM + Macroeconomic model.	Macroeconomic Model and Regional Model	National	N/A	N/A	2020
[43]		Propose an open-source methodological framework for soft-linking a global ESM and power system model. The framework utilizes a standardized data format, making it applicable to a wide range of IAMs[‡]. This framework is also a first in the literature, specifically designed to link a global IAM with a global power system model.	Power System Model	Regional(World)	ESM model: 2015–2100 (126 time-slices resolution) Coupled Model: 2050 (Applied different temporal resolution)	ESM and Coupled model: Optimization	2022
[48]		Use a bi-directional soft-linking methodology between an ESM and a multi-sectoral unit commitment and power dispatch model (Dispa-SET). The convergence criterium used is system adequacy.	Multi-sectoral Model	National (Belgium)	ESM model: 2015–2035 (Varies between 6 and 20 typical days) Coupled Model: 2035 (Hourly resolution)	ESM and Coupled model: Optimization	2022

[*] One-step recursive dynamic (solved one period at a time).

[†] This study was included to present an example of endogenous approach incorporating a sector model (e.g., a PSM) in a global perspective model (e.g., a macroeconomic model).

[‡] They use the ESM model MESSAGEix, a linear programming (LP) energy engineering model with global coverage, linked to GLOBIOM (GLObal BIOsphere Model, cf. Section Land-use (GLOBIOM)). This approach makes the IIASA Integrated Assessment Model (IAM) framework, also referred to as MESSAGEix-GLOBIOM owing to the fact that the energy model MESSAGEix and the land use model GLOBIOM are its central components [16].

Table 12
Sample of format for the classification of links based on models' input and output variables.

G1					
Model 1		Model 2		Model 3	
Input	Output	Input	Output	Input	Output
PAR 1	*VAR 1*	*PAR 3*	*VAR 1*	*PAR 1*	*VAR 2*
PAR 2	*VAR 2*		*VAR 4*	*PAR 4*	*VAR 3*
PAR 4					

4 to *input 4* illustrates that one model can send information to several models. *Output 1* and *output two* can be used to establish a convergence criterion. This is one of the easiest cases for a convergence criterion: in the case that cycles exist, and there is no pair of outputs that coincide, then it is not possible to define a formal convergence criterion. This will lead to the results of the case study being less solid.

Last, *input 1* needs to be analyzed in order to be suitable for *Model* 1 and *Model 3*. In this way, we define the solution strategy for the proposed research question. This solution includes several classifications of models' data and their representation in tables and graphs. This should be carried out for the list of candidate model sets so that the most convenient can be selected.

6. Formulation of a model manipulation strategy for implementing the selected linking approach

Taking in account that the research question, the chosen model's characterization (i.e, dimension and technological scopes, the input and output data), and the potential links have already been defined. This section discusses the manipulation of a set of models to execute the proposed linking approach. The description of the manipulation strategy

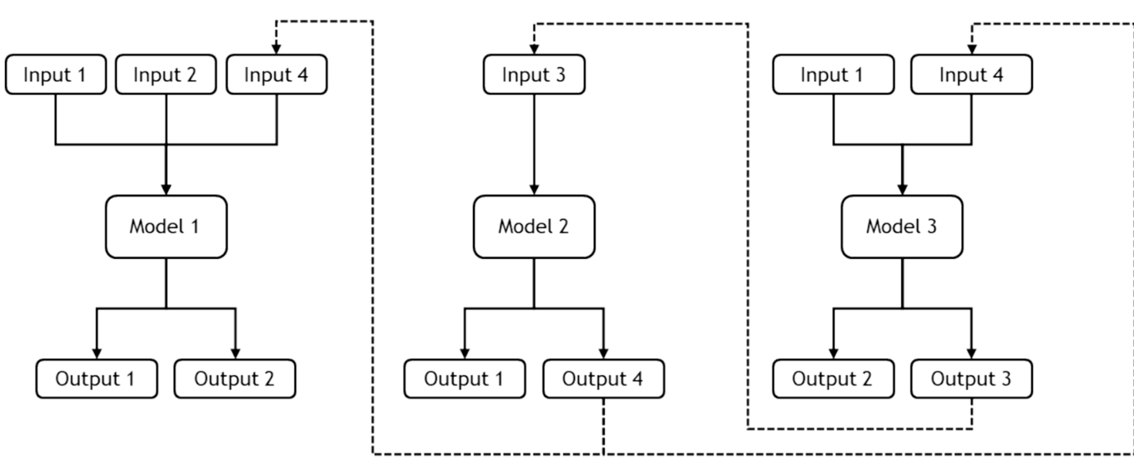


Fig. 17. Sample representation of models and links.

is divided into three steps:

- Identification of necessary conversions
- Definition of the order of execution
- Establishment of a convergence criterion

6.1. Identification of necessary conversions

Any model links should be subject to a dimensional unit evaluation in order to define the data correspondence and make the necessary conversions to ensure consistency. This includes:

- Unit adjustments (i.e., calories per hour to watt, MWh to GWh, or PJ to TWh).
- Aggregation/disaggregation (i.e., from regional demand to nodal values in a network).

This step, often overlooked, is, however, key to avoiding errors when using several models. This is particularly problematic when the scopes of the models are different.

6.2. Definition of the order of execution

The following guidelines are provided:

(a) If only BU models are linked:
The execution order is determined by granularity, starting from the coarse-grained models and moving to finer-grained ones.
(b) If only TD models are linked:
The order of execution starts from the model with the highest number of productive sectors and moves to lower numbers.
(c) If both BU and TD models are linked:
1. The TD model is the first to be executed.
2. If more than one TD model is considered, then the order of execution starts from the model with the highest number of productive sectors and moves to lower numbers.
3. The flow of inputs and outputs is followed until a BU model is encountered.
4. If more than one BU model appears at the same time, then the execution order is determined by granularity, starting from the coarse-grained models and moving to finer-grained ones.

6.3. Establishment of a convergence criterion

We have defined O/O variables as possible variables where convergence should be checked. We may be able to find several outputs of this type or none. Reasonable convergence thresholds should be established. Ideally, this should be fixed beforehand. However, often it is quite difficult to establish a criterion before having worked with the models concurrently in several case studies. In these situations, it may be advisable to start working and have an expert team decide after having worked on the case study.

In addition, a maximum number of iterations should be set, and it should be understood that under some circumstances, the models will not be able to reach convergence in a reasonable number of iterations. This can signal a particular weakness in the analysis, which should be considered when assessing the implications of the research question.

Now, two examples of the application of this methodology are provided, based on Case Study 3 and Case Study 4. It should be noted that some of the text has already been included in the deliverables that describe the case studies. Please refer to D6.1 for more detailed information on the case studies.

7. Application: Case study 3 in openENTRANCE, an analysis of alternatives for storage

This section provides an illustration of the developed methodology as applied in case study 3. The full application can be seen in the deliverables of the project.

7.1. Overall objective and case-study baseline

Electricity storage is one of the key supporting technologies of the energy transition, as it provides flexibility and thus is needed to facilitate the integration of renewables. Several technologies could be deployed in this context, including pumped-storage hydro and batteries. In addition, several strategies could be used to manage the new storage capacity, including profit maximization by single consumers, communities, or companies or several dumb or smart EV charging. The case study will focus on two regions where the possibilities of these technologies are particularly interesting: The Iberian Peninsula and the Nordic countries. Although these countries will be represented in more detail, the whole European area will be considered, albeit at an aggregate level.

7.2. Candidate model sets

The case study will be structured as a comparative analysis across two different dimensions: the level of deployment of storage in terms of MW and their operating strategy. Following the methodology proposed in section 5, the first step is to define the candidate model sets. For case study 3, three models that are used. EMPS-W will undertake the general definition of the hydrothermal systems studied, while GUSTO will deal with the deployment and optimal use of storage under several different strategies, and openTEPES will incorporate the impact of the transmission grid, which can enable the long-range use of resources across the European Union. The main data requirements for this case study are complete scenarios for demand, generation, and transmission.

The following step is to analyze the model's granularity and scope, which have already been provided in sections 3.4 and 3.5. Therefore,

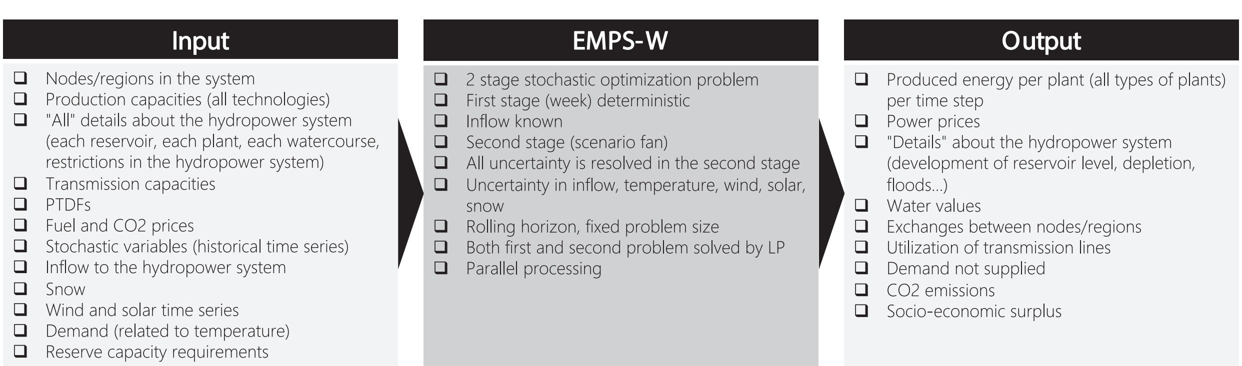


Fig. 18. Schematic overview of the EMPS-W modeling framework developed at SINTEF.

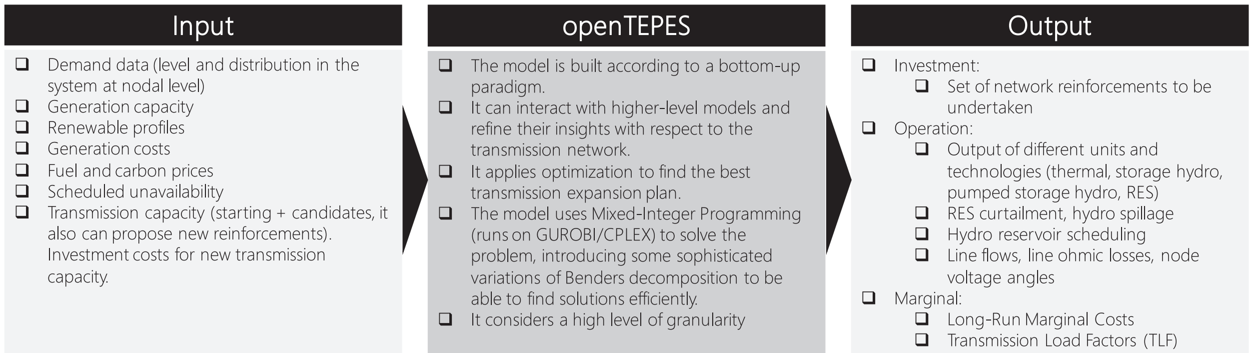


Fig. 19. Schematic overview of the openTEPES modeling framework developed at the Institute for Research in Technology – Comillas Pontifical University.

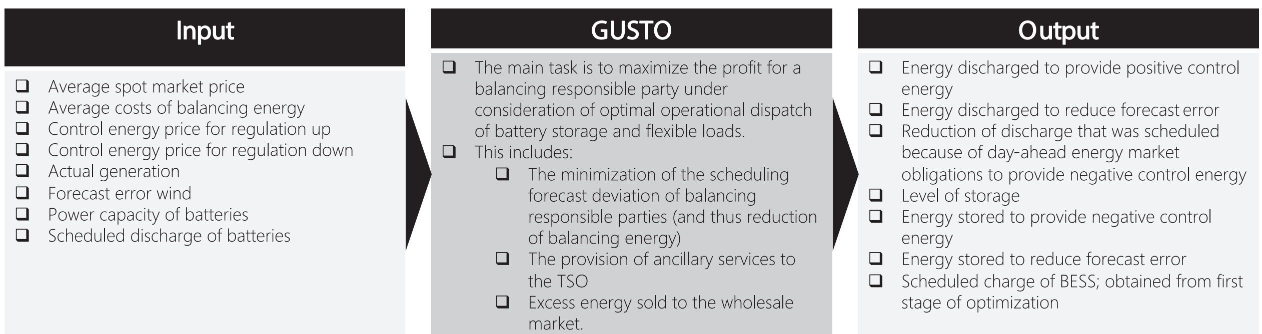


Fig. 20. Schematic overview of the GUSTO modeling framework developed at TU WIEN.

after defining the candidate model sets and understanding their main characteristics and granularities, the second step in the methodology is to identify the model's inputs and outputs.

7.2.1. Schematic overview of the model's input and output data

This section presents an overview of input and outputs within the defined model sets, as illustrated in Figs. 18, 19, 20, and 21. EMPS-W model requires detailed information about the hydropower system, as well as the production capacities of the reaming technologies and the reserve capacity requirements as inputs. At the same time, its outputs provide an overview of the electricity production, as electricity exchanges in the network and emissions, with more detailed information about the hydropower system operation and investment variables. On the other hand, openTEPES needs a more detailed set of variables as inputs regarding the power system operation and the grid representation, having as outputs a group of variables that provides an overview of the system operation and investment and the electricity price (short-term marginal cost). Finally, GUSTO inputs focus on gathering information about the distinct electricity prices (spot, costs, and regulation prices) and technologies productions to maximize the battery's dispatch. GUSTO outputs give detailed information about the battery's operation and the related costs.

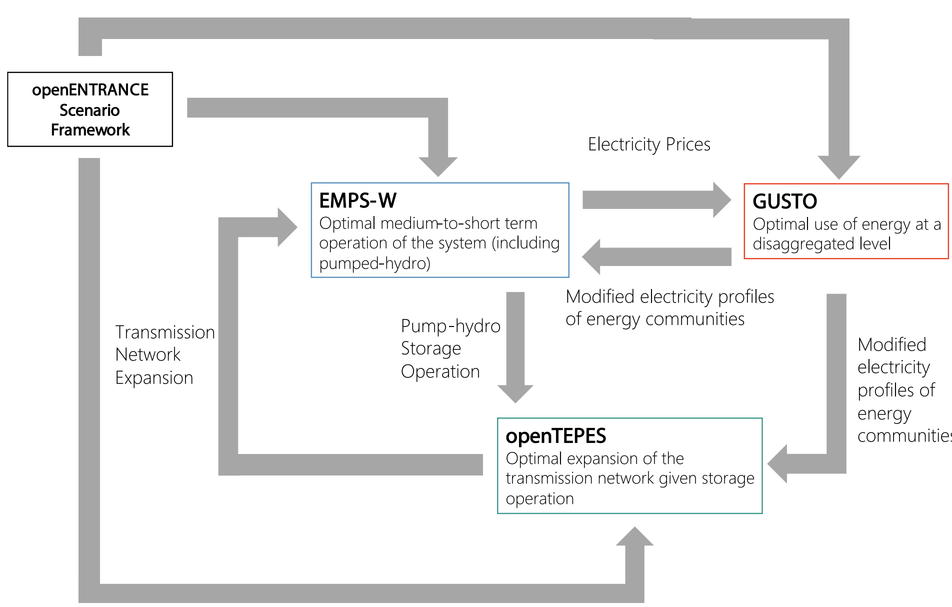


Fig. 21. CS3 high-level Workflow.

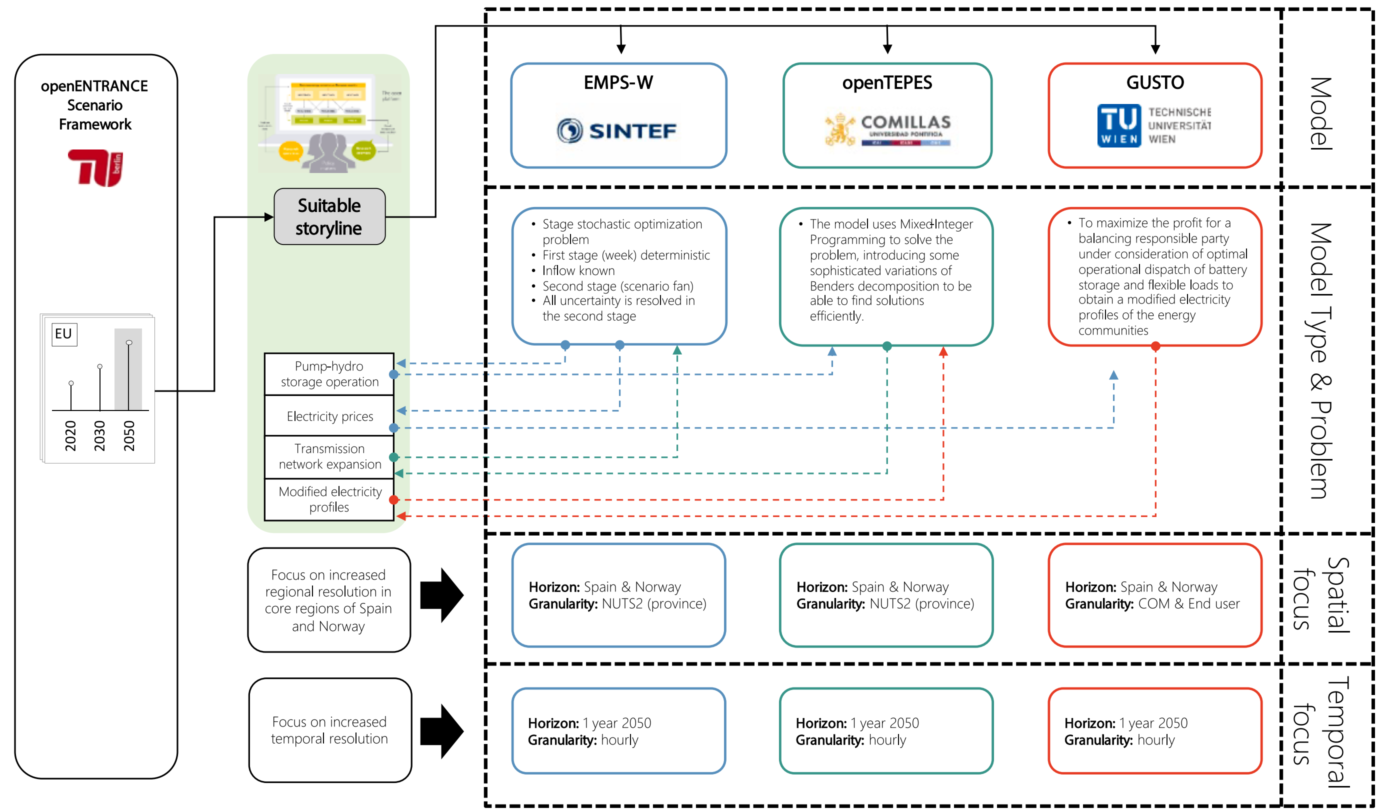


Fig. 22. A Schematic overview of case study 3 (methodology and model linkage).

By meticulously analyzing the information gathered in Figs. 19, 20, and 21, key insights into the performance and behaviour of the chosen models were unveiled, thereby contributing to a deeper understanding of their linking potentials explored in section 7.3.

7.3. Identification and characterization of potential links among models

With the information gathered in section 7.2, the potential links among the three models were identified. A wide perspective of the workflow is presented first in Fig. 21, followed by the specific data flow shown in Figs. 22 and 23. All the input information used comes from the openENTRANCE database. The link direction reflects the objective of the case study, being EMPS-W and GUSTO linked and used in parallel, followed by a link with openTEPES. The first two models provide a good overview of the storage technologies operation (hydro and battery), while openTEPES provides the transmission network expansion results. Soft-linking approaches were used for both links. For EMPS-W and GUSTO, a unidirectional soft-linking was applied. Then, a bidirectional soft-linking approach was used to link openTEPES and EMPS-W, while a unidirectional soft-linking was used with openTEPES and GUSTO.

Section 7.4 presents a detailed description of the strategies used to convert the exchange information among the models, while section 7.5 details the execution order.

7.4. Data-exchange tools

A list of the data-exchange tools that need to be implemented to perform the linkage of models is described in this section. These tools (or "translators"), to be developed by each model team, will include:

- Unit conversions, e.g., EJ to MWh, MWh to GWh (using the unit conversion available in the OE platform).
- Geographical aggregation or disaggregation (using aggregation/disaggregation functions available in the OE platform).
- Temporal aggregation or disaggregation (using aggregation/disaggregation functions available in the OE platform).
- Formatting: i.e., converting the excel format to the adequate format (columns, rows).

An example list is provided below:

T1 (OE-E&M)	Set of tools or methods to convert data from the Common data format to EMPS-W format
T2 (OE-oT)	Set of tools or methods to convert data from the **Common data format** to **openTEPES format**
T3 (OE-H&O)	Set of tools or methods to convert data from the **Common data format** to **GUSTO format**
T4 (E&M-OE)	Set of tools or methods to convert data from **EMPS-W output format** to **Common data format**
T5 (H&O-OE)	Set of tools or methods to convert data from **GUSTO output format** to **Common data format**
T6 (oT 2-OE)	Set of tools or methods to convert data from **openTEPES output format** to **Common data format**

7.5. Execution order

This section provides the stepwise plan to carry out the case study, specifying the data exchanged (with the relevant data-exchange tools if appropriate). Needs for convergence are highlighted, specifying the stopping criterion.

1. <u>**Extraction of data from openENTRANCE Database:**</u> First, Pack 1 is built by selecting the adequate variables. Pack1 is downloaded in a format that is as close as possible to Models formats (using the pyam functions as much as possible). It is transformed through T1, T2, and T3 into EMPS-W, openTEPES, and GUSTO data formats ID1b, ID2b, and ID3b.
2. <u>**Building Model 1 Input dataset and running EMPS-W:**</u> The EMPS-W's dataset is built out of EMPS-W own data (ID1a) and

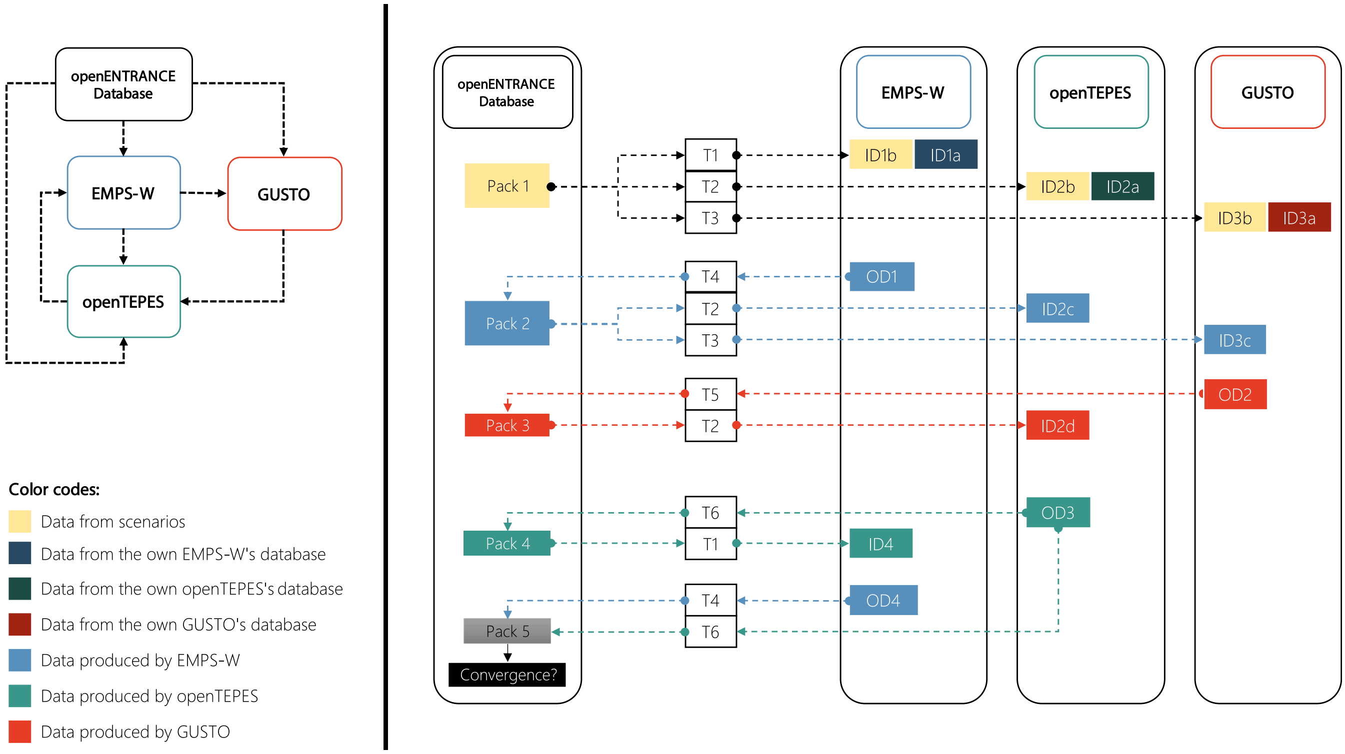


Fig. 23. Data workflow.

openENTRANCE Scenario data (ID1b). EMPS-W is executed and produces outputs. OD1 is the part of the outputs that can be shared, while other parts of the outputs will be kept as part of the results that will not continue the workflow or data that has to be kept in private. OD1 is converted to the Common data format using T4, which produces Pack2.

3. **Exchanging between EMPS-W and openTEPES:** Data from Pack2 (produced by EMPS-W) are downloaded and converted to openTEPES format using T2 $\Longrightarrow$ ID2c.
4. **Exchanging between EMPS-W and GUSTO:** Data from Pack2 (produced by EMPS-W) are downloaded and converted to GUSTO format using T3 $\Longrightarrow$ ID3c.
5. **Building GUSTO Input dataset and running GUSTO:** The GUSTO's dataset is built out of GUSTO own data (ID3a) and openENTRANCE database (ID3b and ID3c). GUSTO is executed and produces outputs. OD2 is the part of the outputs that can be shared, while other parts of the results will be kept as part of the results that will not continue the workflow or data that has to be kept in private. OD2 is converted to the Common data format using T5, which produces Pack3.
6. **Exchanging between GUSTO and openTEPES:** Data from Pack3 (produced by openTEPES) are downloaded and converted to openTEPES format using T2 $\Longrightarrow$ ID2d.
7. **Building openTEPES Input dataset and running openTEPES:** The openTEPES' dataset is built out of openTEPES own data (ID2a) and openENTRANCE database (ID2b, ID2c, and ID2d). openTEPES is executed and produces outputs. OD3 is the part of the outputs that can be shared, while other part of the outputs will be kept as part of the results that will not continue the workflow or data that has to be kept in private. OD3 is converted to the Common data format using T6, which produces Pack4.
8. **Updating EMPS-W dataset and running EMPS-W:** ID4 data from openTEPES is downloaded from Pack4 and used in order to update the EMPS-W dataset: ID4 is created by T1. EMPS-W is running again, which produces the new output OD4.
9. **Building Pack5:** OD3 is converted to the Common data format using T6. And OD4 is converted to the Common data format using T4. Both data (OD3 and OD4) produce Pack5.
10. Expert analysis of outputs will determine whether a new cycle is necessary.

8. Conclusions

This article presents a new methodology that advances from the already existing structured modeling framework to characterize, combine, and develop an execution strategy for using several energy models to solve particular research questions. We also identified and build a visual mapping for classifying the linking approaches available in the literature. This methodology particularizes structured modeling for energy modeling and lays out a comprehensive and research-question-oriented classification of models. In addition, it proposes a short series of steps that can be applied to solve any research question, choose the models that will be used, and design their interaction and convergence procedure. The framework has been articulated in several sections (shown in Fig. 1) through the next four distinct stages.

- Characterization of models.
- Definition of the research question.
- Discovery of solution strategies.
- Development of a model-manipulation strategy.

These stages have been illustrated with case studies taken from project openENTRANCE. The outputs from this work aims to fill this knowledge gap by developing a conceptual methodology and enhancing the design and current models' interactions to benefit the energy community as a whole and make the process of structuring case studies to solve policy questions more structured, easier, and quicker, and, above all, a sounder manner. Furthermore, categorizing and formalizing the connection between models contributes to establishing a strategy to answer a specific target research question, providing a better use of the current tools to policymakers and practitioners.

Our framework assumes that the macroeconomic aspects are taken into account earlier in the chain of models. The usual way that models are linked is from Integrated Assessment Models, which consider these macroeconomic aspects and climate modeling, to ESMs and then to Power System Models or other sector-specific models. In this work, our primary focus is the linking of ESMs to PSMs, which has become very relevant in recent years given the increase in intermittency (which demands a higher time resolution), distributed energy (which demands a higher spatial resolution) or the growth in storage technologies. This is our motivation to study further the link between ESMs and PSMs.

CRediT authorship contribution statement

Dilayne Santos Oliveira: Conceptualization, Methodology, Visualization, Writing – review & editing. **Sara Lumbreras:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Erik F. Alvarez:** Data curation, Software, Visualization, Writing – review & editing. **Andrés Ramos:** Methodology, Supervision, Writing – original draft. **Luis Olmos:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijepes.2024.110048.

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