D5.1: Analysis framework, functional specification of models, and conceptual assessment of the linkages among them defined in the Case Studies and Pathways

DELIVERABLE NO.D5.1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 835896

Deliverable No.	D5.1	Work Package No.	WP5
Work Package Title			
Status		Final	
Dissemination level		Public	
Due date deliverable	2022.04.30	Submission date	2022.04.29
Deliverable version			

Deliverable contributors

Deliverable Contributors:	Name	Organisation	Date
Deliverable Leader	Sara Lumbreras	Comillas	2022.04.10
Work Package Leader	Luis Olmos	Comillas	2022.04.10
Contributing Author(s)	Erik Quispe	Comillas	2022.04.10
	Andrés Ramos	Comillas	2022.04.10
Reviewer(s)	Sebastian Zwickl-Bernhard	TU Wien	
Final review and approval	Ingeborg Graabak	SINTEF Energy Research	2022.04.29

History of Change

Release	Date	Reason for Change	Status
Version 1	2022.04.29		Final

DISCLAIMER / ACKNOWLEDGMENT

The content of this deliverable only reflects the author's views. The European Commission / Innovation and Networks Executive Agency is not responsible for any use that may be made of the information it contains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 835896.

Table of Content

Contents

List of Tables

List of Figures

Executive Summary

The development and use of models as decision tools has increased steadily in the past few years. Given its complexity, the energy sector is one of the contexts where this trend can be seen more intensely. The fact that most energy models have been developed at different institutions with different scopes, structures or within different platforms creates a need for integrating them in order to generate a perspective on the entire implications of the energy transition. This document presents the framework for the connection of models that has been developed in the context of openENTRANCE.

This framework is one of the tasks of the European project openENTRANCE, which will develop, use and disseminate an open, transparent and integrated modelling platform for assessing low-carbon transition pathways in Europe. The platform has several committed energy models, and its main task will be to identify a suitable model or set of models for solving the relevant questions related to the project's objectives.

This task has developed a methodology that is based on *structured modelling*, a formal mathematical theory that was developed for conceiving, representing, and manipulating a wide variety of models. The framework has been articulated in several sections through four distinct stages:

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

.
These steps will be applied to **Case Study 3** and **Case Study 4 in the Open ENTRANCE project** as a real illustration of the framework so that its practical implementation can be demonstrated.

1. Introduction: Advancing the Structured Modelling Framework

The development and use of models as decision tools has increased steadily in the past few years. Given its complexity, the energy sector is one of the contexts where this trend can be seen more intensely. We can find different models that include sectoral models, macro-economic models, investment models, operation models or integrated assessment ones. These models have different scopes and granularities and have been developed at different institutions within different platforms. If the aim is to generate a perspective on the entire implications of the energy transition, it is necessary to use several of these models concurrently and in a consistent manner, that is, integrating them. This document presents the framework for the connection of models that has been developed in the context of openENTRANCE.

This framework is one of the tasks of the European project openENTRANCE, which will develop, use and disseminate an open, transparent and integrated modelling platform for assessing low-carbon transition pathways in Europe. The platform has several committed energy models, and its main task will be to identify a suitable model or set of models for solving the relevant questions related to the project's objectives.

The framework has the objective of characterizing, scheming and dealing with the linking of energy models to solve research questions could not be solved by a single model.

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 that normally are developed 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 the integration).

The framework is a general approach that is based on *structured modelling*, a formal mathematical theory that was developed for conceiving, representing, and manipulating a wide variety of models (Geoffrion, 1987). The framework has been articulated in several sections around four distinct stages.

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

These stages are discussed in the next sections. The **model characterization** stage is described together with the definition and characterization of each model to be used in the project. Next, the definition of the **research question** should be established in objective, scope and details. This question, together with the model characteristics, determines the available **solution strategies** that can be selected. Last, a specific procedure to communicate between the models and examine convergence is developed, defining the **model manipulation strategy**. These steps will be applied to **Case Study 3** and **Case Study 4** as a real illustration of the framework.

2. A characterisation of energy models

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

The classification of models is presented first. We have developed this classification as a comprehensive attempt to include all the relevant characteristics of the models that allow to:

1. Understand precisely 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 modelling exercises.
2. Design the interaction with other models with the specific aim of answer a policy question that cannot be tackled with a single model.

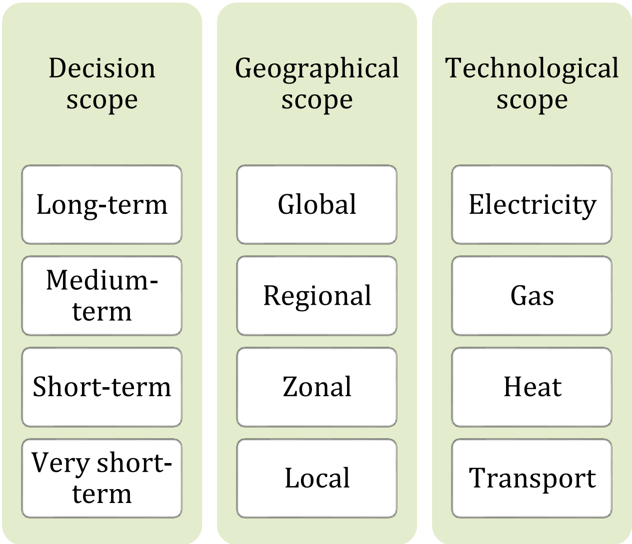
The classification is presented in the form of model maps, as this visual information is believed to be clearer for both modelers and policy makers. After this, we apply the model maps to the modeling suite in open- ENTRANCE, describing their features both comprehensively and succinctly.

Definitions

Several dimensions are considered when describing the models in a suite. We will classify these in three distinct groups: *decision space* (that is, the type of decisions that the model can consider), *geographical dimension* and *technological scope*, as shown in Figure 1. The decision scope refers to the 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).

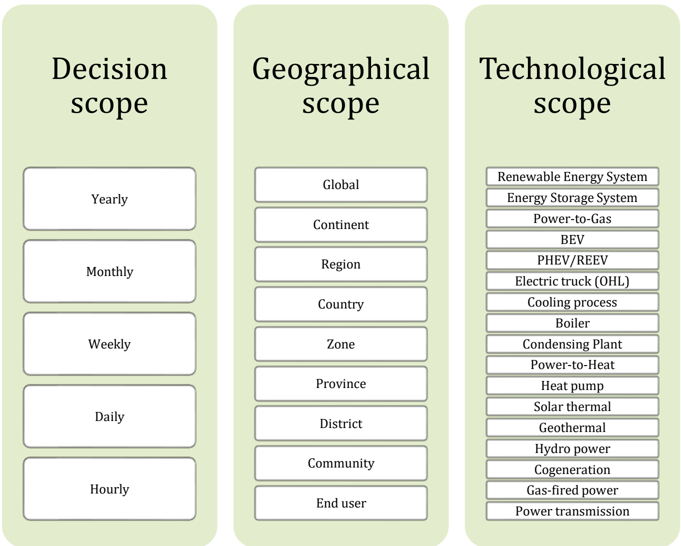
It is important to distinguish between time horizon (the furthest time considered in a model) and time resolution (the level of detail in the description of time). These two can be confused with each other and, to some degree, are related: limited computing power means that the longer the time horizon, 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 NUTS in the European context. The technological scope refers the technological sectors considered by the model such as electricity, gas, heat and transport. All the technologies considered in the models will be grouped into these sectors.



- **Long-term:** strategic investments
- **Medium-term:** tactical investments and system operation
- **Short-term:** day-ahead operation
- **Very short-term:** real-time operation
- **Time resolution:** one hour, one week, one year
- **Horizon:** 2030, 2040, 2050
- **Regional:** Continent (*e.g. Europe*), Region (*e.g.. Scandinavia*), Country (*e.g.. Spain*)
- **Zonal:** Zone (*e.g. Andalucía*), Province (*e.g. Sevilla*)
- **Local:** District, Community, group of end users

Figure 1. Dimensions of energy models



- **Note that there are granularities in technological scope that belongs to one or more dimensions, such as:**
- Electric Vehicle (EV)
  - **Consumption:** Electricity sector
  - **Production:** Transport sector
- Gas-fired power plant:
  - **Consumption:** Gas sector
  - **Production:** Electricity sector
- Electrochemical batteries (energy storage system)
  - **Consumption:** Electricity sector
  - **Production:** Electricity sector

Figure 2. Granularity of energy models

After that, the granularities are defined (from an agent's perspective) for each scope, as it is shown in Figure 2. 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, can be deemed to belong to the transport sector. Other devices, such as electrochemical batteries, just belong to one sector (by its 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 an 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 the short-term models. For instance, an energy system model can provide input to a power market model. The input is demand for power taking into consideration demands for charging of 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. In the technological scope, usually, this does not happen, i.e., the scope and granularities are independent.

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. OpenENTRANCE model suite. Many of these models are described in a series of academic references.

Table 1. OpenENTRANCE model suite.

MODEL	LEAD PARTNER	MAIN OBJECTIVE	SPECIAL CHARACTERISTICS	STATUS
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.	Finished
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.	Finished
EXIOMOD 2.0	TNO	Measure the environmental and economic impacts of policies	Thanks to its environmental extensions, see www.em-plus.eu, 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).	Finished
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.	Finished
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.	Under development
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-exising 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.	Finished

Plan4EU	EDF	i)Optimal capacity expansion, ii)Optimal operation of seasonal storage iii)Economic dispatch at European level	The plan4eu modelling 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 modelling of transmission and distribution networks.	Finished
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: 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).	Finished
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.	Finished
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.	Finished
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.	Finished

A visual tool to structure models

In Figure 3, 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.

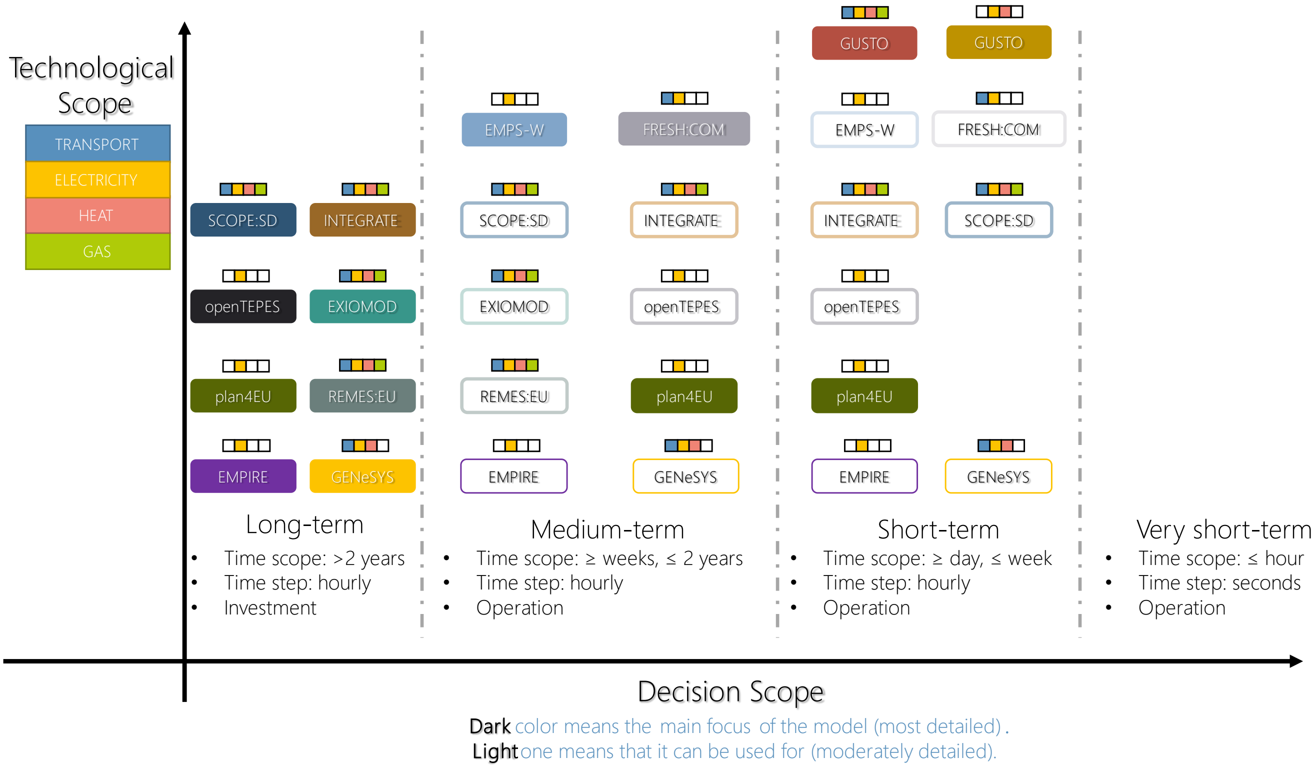


Figure 3. Model map: decision and technological scope

A mapping of the models according to their geographical and decision scopes is shown in Figure 4. As 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.

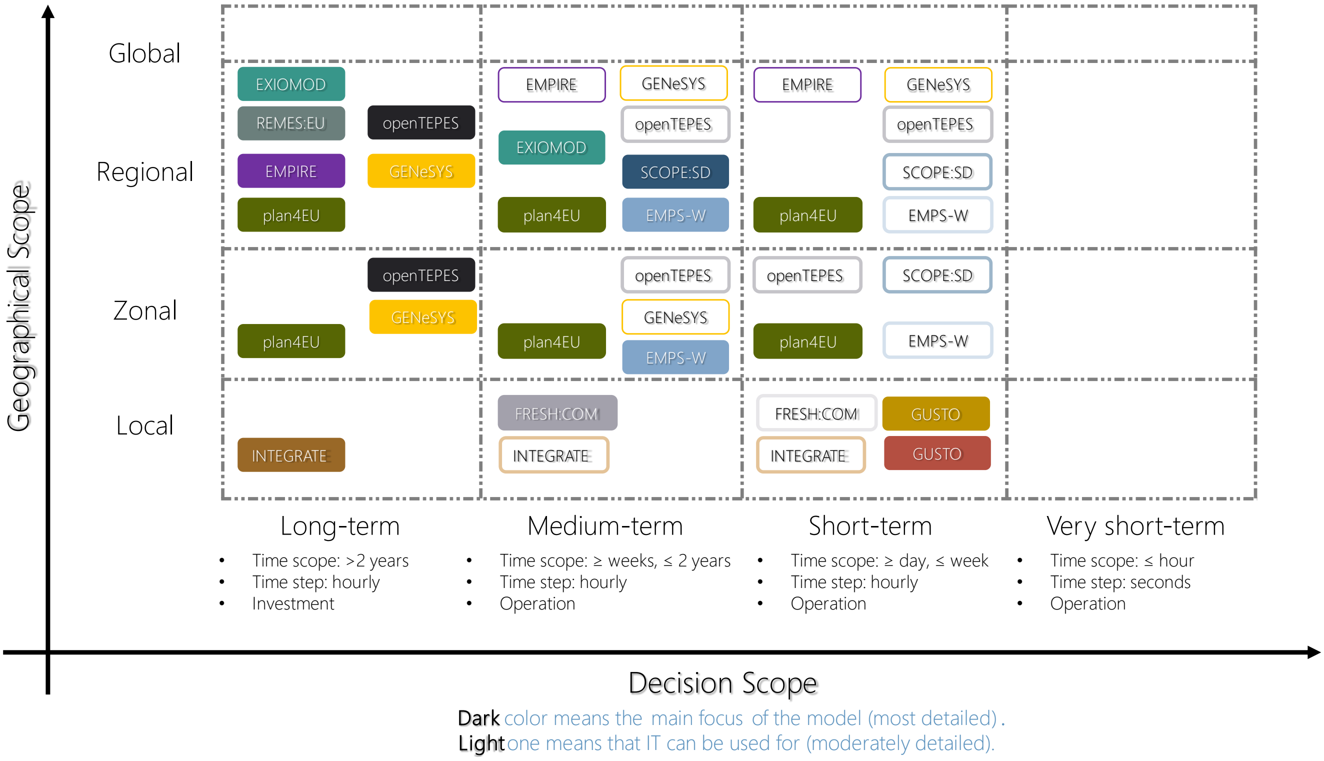


Figure 4. Model map: geographical and decision scopes

Granularity map

Figure 5 Figure 6, and Figure 7 together represent the granularities of the models with respect to the decision (time), 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 tradeoff was always present in the case studies in openENTRANCE.

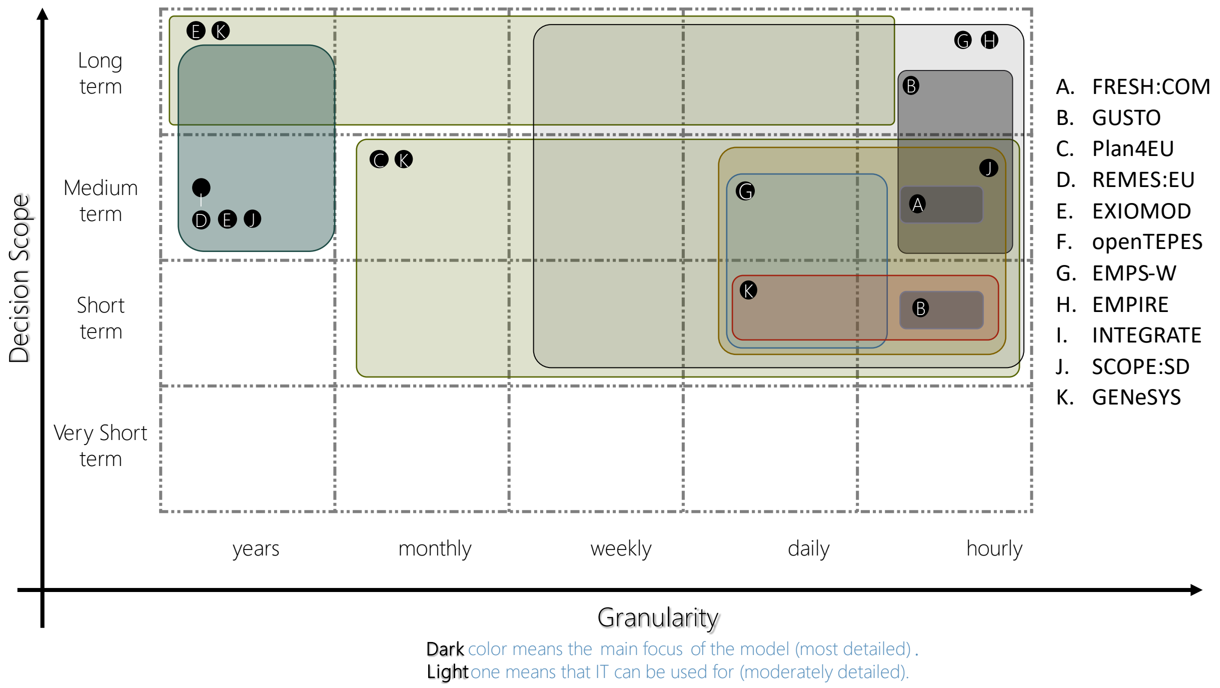


Figure 5. Granularity map: decision scope

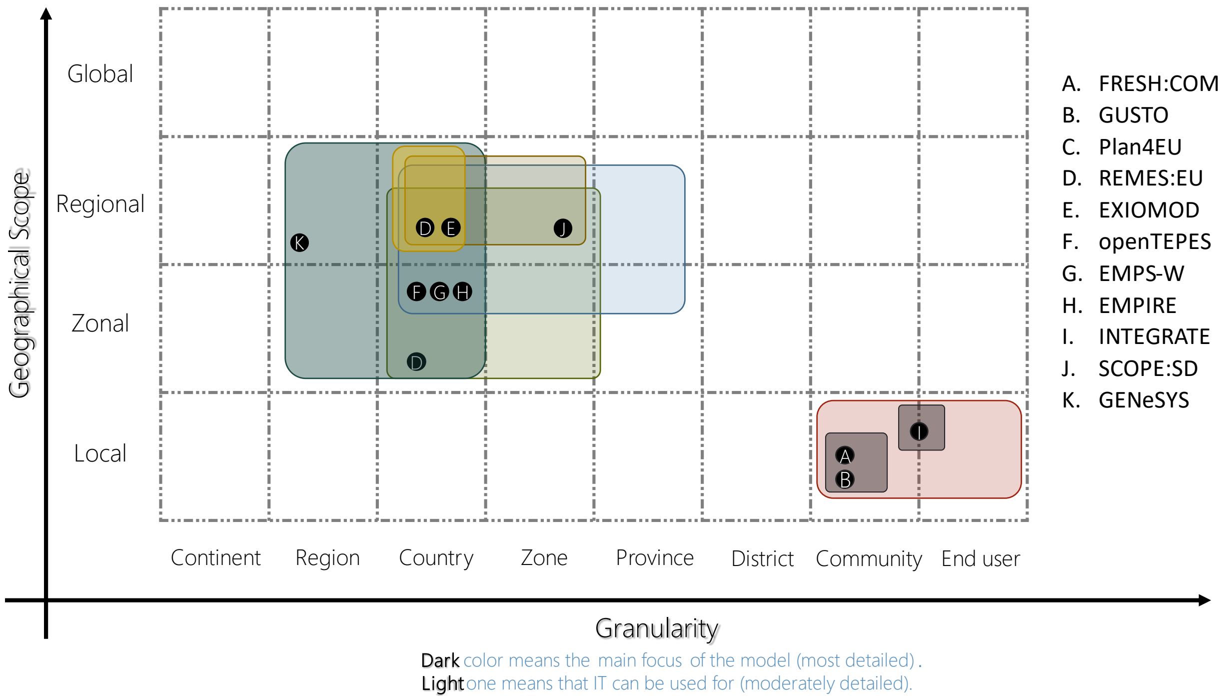


Figure 6. Granularity map: geographical scope

	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)	CompressedAir 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	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	✓	✓	✓				✓	✓			✓			✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓

Figure 7. Granularity map: technological scope

Characterization of input and output data

First, all data of the models are listed and classified into inputs and outputs following the next format:

Table 2. Sample of format for the characterization of data as an input

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

Table 3. Sample of format for the characterization of data as an output

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

In addition, inputs and outputs of each model can be represented by means of a graph as shown below:

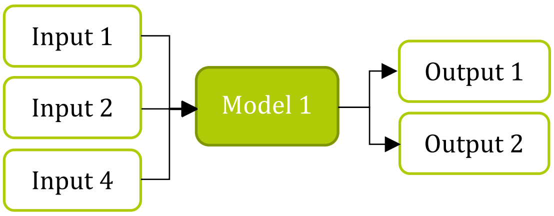


Figure 8. Sample of graph to represent the composition of a model

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.

3.How to define the research question

Introduction

The establishment of the research question is key to define what models should be used – and how. This is the center stage in structured modeling (Lee & Krishnan, 1990), 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.

Although structured modeling is arguably the most relevant framework in this context, other methodologies have been proposed for the integration of models, namely logic modelling (Geoffrion, 1987) and graph-grammars (Jones, 1990). We have chosen structured modelling as our base because of its simplicity and solid theoretical background.

Methodology: designing a policy-relevant sensitivity analysis

The definition of a *research question* should be framed as a *sensitivity analysis*. 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", 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 document. 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.

4. Discovery of solution strategies

Introduction

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 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

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 below.

Table 4. Sample of the format of characteristics required

	Decision scope	Geographical scope	Technological scope
Dimensions			
Granularity			

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 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 favored. 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, models can be classified into bottom-up (BU) and top-down (TD). In energy modeling, BU or fundamental models explicitly represent the functioning of specific technologies to assess their aggregate impact on the energy sector. Conversely, TD models represent the energy sector or the economy as a whole. They do not explicitly represent the technologies employed, but the economic activities and actors within the scope of the model and the interactions among them. TD models assess the impact of the policies considered on the economic activities and actors, and, by aggregation, on the economy, without providing information on their underlying processes. 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, which is known as *hybrid modelling*.

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 1:

Table 5. Sample of format for model or set of models found

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

Definition of input data

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

Classification

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

Table 6. 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

Table 7. 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	

Grouping

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

Table 8. Sample of format to identify each granularity on technological scope

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

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

Table 9. Sample of format to group each input/output into each granularity

<table>
<tr><th colspan="6">G1</th></tr>
<tr><th colspan="2">Model 1</th><th colspan="2">Model 2</th><th colspan="2">Model 3</th></tr>
<tr><th>Input</th><th>Output</th><th>Input</th><th>Output</th><th>Input</th><th>Output</th></tr>
<tr><td>Input 1</td><td>Output 1</td><td>Input 3</td><td>Output 1</td><td>Input 1</td><td>Output 2</td></tr>
<tr><td>Input 2</td><td>Output 2</td><td></td><td>Output 4</td><td>Input 4</td><td>Output 3</td></tr>
<tr><td>Input 4</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

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 have to be analyzed in terms of 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, from Table 9. Sample of format to group each input/output into each granularity *input 3* is equal to *output 3* and *input 4* is equal to *output 4*. It will be represented in the next table:

Table 10. Sample of format for the input/output assessment (green and yellow colours 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					

Characterization of model links

This work is inside of the hybrids modeling approach as it was mentioned before. The types of links found in hybrid modeling are soft-linking and hard linking as defined by Wene in (Wene, 1996). In hard-linking, the models are linked by code, making them part of a bigger composite model. In soft-linking, tools may be developed to be able to use them concurrently, but the models retain their functional independence. Several works, as (Deane, Chiodi, Gargiulo, & Gallachóir, 2012; Del Granado, Van Nieuwkoop, Kardakos, & Schaffner, 2018; Krook-Riekkola, Berg, Ahlgren, & Söderholm, 2017), adopt the terms soft-linking and hard-linking, where soft-linking is a manual transfer of information with possible data manipulations of a user, and hard-linking is like a formal link where there isn't any intervention of a user. The soft-linking is adopted in this work because there will 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:

- 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 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. The next table presents a sample classification of links:

Table 11. Sample of format for the classification of links (green, yellow and blue colours represent Case I, Case II and Case III, 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					

After characterizing model links, a graphic representation can be performed:

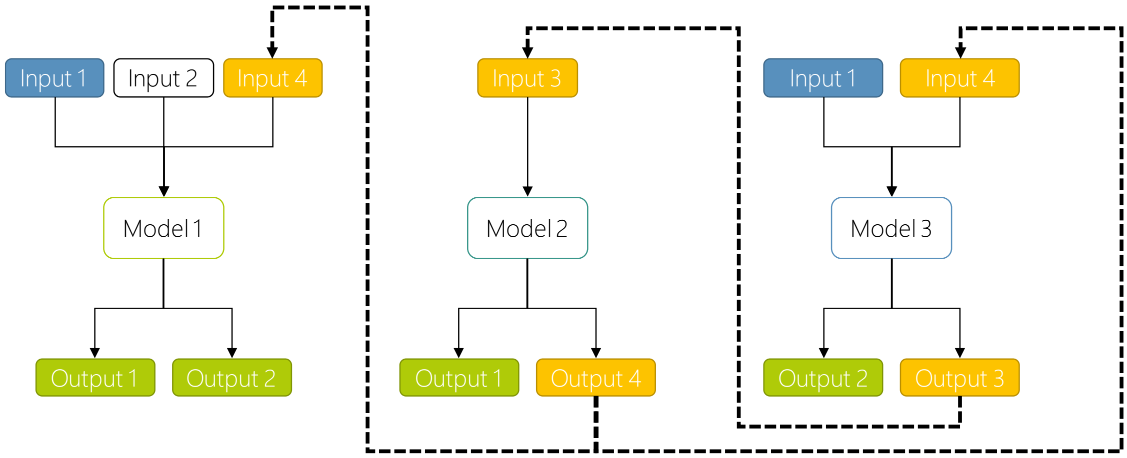


Figure 9. Sample representation of models and links

Through the graphic representation in Figure 9. Sample representation of models and links, it is possible to note that there are two true links of information between models: a) from *output 4* to *input 4*, and b) from *output 3* to *input 3*. Note that the link from *output 4* to *input 4* illustrates that one model can send information to several models. *Output 1* and *output 2* 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 analysed 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.

5. Development of a model manipulation strategy

Introduction

Having defined the research question, the input and output data and the potential links, this section discusses the manipulation of set of models. The description of the manipulation strategy is divided into three steps:

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

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 avoid errors when using several models. This is particularly problematic when the scopes of the models are different.

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.

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 for 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.

6. Application #1

This section provides an illustration of the developed methodology as applied in case study 3:

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. Pumped-storage hydro is a mature technology with low investment costs for relatively large sizes, but long and difficult (in some cases, impossible) installation of new capacity. However, although there are already significant hydro storage and pumped-hydro storage capacities installed in different regions across Europe, there is still potential to further invest and increase these capacities. In many cases, building new storage is not possible, but there is potential for upgrades (e.g. adding a pumping mode to HS plants). Some of these projects are already in the PCI list (Projects of Common Interest). The maximum stored energy in the present reservoirs in some European countries can be summarized as follows (all Numbers in TWh): Norway (85), Sweden (34), Spain (18.4), Switzerland (8.4), Austria (3.2) and France (9.8) (Lehner, Czisch, & Vassolo, 2001). Norway has hardly any pumping capacity in its present system. However, a recent study has shown that it is possible within present regulations (water-flows and levels in reservoirs) to install about 20 GW in the South-Western part of the country. The pumped-storage hydropower can contribute to balance variable wind and solar power production in UK and Germany/Benelux if the transmission capacities are increased.

At the other side of the spectrum, batteries could offer an alternative to complement hydro with smaller (often at the scale of a single consumer), decentralized storage, albeit at a higher current cost. In addition, the differing sizes of these technologies mean that they can be used at different time horizons and levels in the system: while pumping stations with large sizes in terms of energy content (capacities) could be used to shift loads over the weekend periods or even seasons, the smaller batteries could only be used for several hours. In addition, smaller batteries would not be completely controllable by the system operator and would rather respond to the needs and behavior of consumers.

As seen, both technologies represent different avenues for the use of storage. On the one hand, batteries have traditionally been associated to smoothing short-term fluctuations in demand or renewable generation. Their size is directly related to the scope of this smoothing: smaller batteries support a single consumer, while larger ones can minimize the local power excess or deficits of a community over longer time periods. Therefore, battery storage supports the relative independence of prosumers and is linked to the development of decentralized structures in energy markets. Large-scale pumped-hydro, on the other hand, can be used to balance renewables at the European level. These two alternative uses of storage and schemes of centralization/decentralization will lead to diverging needs for market integration, which will be reflected in transmission network needs.

Hence, the main objective of this case study is the analysis of the widespread deployment of pumped-hydro storage and batteries in terms of system operation costs and transmission network development. Several options for the upscaling of pumped-hydro storage will be considered in combination with the wide-scale adoption of small-scale batteries. For the latter, several operation strategies will be considered:

1) profit maximization by single consumers, communities, or companies

2) minimization of local excess-deficit by prosumers

3) dumb or smart EV charging

The analyses will contemplate different time scales (seasonal, weekly, daily), associated with different storage capacities.

The case study will focus on two regions where the possibilities of these technologies are particularly interesting: The Iberian Peninsula and the Nordic countries. However, the analyses will consider the impact of these developments at a European level. This means that, in order to keep the calculations manageable, the focus regions will be studied in detail, while the rest of Europe will be represented at an aggregate level.

Detailed methodology of the case study

The case study will be structured as a comparative analysis, across two different dimensions:

- Level of deployment of storage, which will consider several situations for the upscaling of hydro pumping and batteries. This will assess the flexibility they can provide for the system comparing their performance and evaluating their synergies.
- Operating strategy associated to the agent in charge of the operation of the batteries. This will include an analysis of the types of agents involved and their multiple utilization objectives: single consumers, communities (e.g. municipalities), or small companies operating storage for maximum profit and other entities that can take into account physical prosumer energy management (e.g. mitigation of local generation excess/deficit) or electric vehicle charging management. The different operating strategies will be translated into output curves (e.g. charging/discharging patterns and changing load profiles over time) that describe the use of storage.

The effectiveness of storage deployment and utilization will, in this case study, be measured as reduced needs for transmission network expansion and reduced overall system costs. Pumped hydro and batteries provide the same functionality at different levels in the system and we will observe the impact on transmission network expansion.

For each considered deployment possibility, the model EMPS-W will calculate the optimal medium-to-short-term operation of the system, which implies solving the hydrothermal coordination problem at the European level considering a detailed model for focus regions (that is, the Iberian Peninsula and Norway) and an aggregate perspective for the remaining countries. Then, the models GUSTO will be employed to compute the optimal operation of battery storage based on the electricity prices generated by EMPS-W. The operation of these battery storage devices will be represented through output curves. Then, the model openTEPES will take the operation of both pumped hydro and battery storage to determine the optimal expansion of the transmission network needed to provide additional flexibility in the form of an increase in the level of integration across markets. Subsequently, the new transmission network will be fed back to EMPS-W, which will adapt the operation of hydro storage and the system to take into account the new transmission lines. EMPS-W will produce new electricity prices to be considered by GUSTO to compute new battery operation output curves, to be considered by openTEPES together with the new operation of pumped hydro. The process will iterate among EMPS-W, GUSTO, and openTEPES to ensure the stability of results indicated as convergence.

Model set

The models involved in the development of the case study are listed in this section, detailing their lead partner and main functionality, as shown in the table below.

Table 12. Sample of format the set of models

Models	Lead Partner	Main Objective
EMPS-W	SINTEF	Long-to-medium term operation of hydrothermal power systems
openTEPES	COMILLAS	To determine the investments plans of new facilities for supplying the forecasted demand at minimum cost
GUSTO	TU WIEN	Optimal utilization of small battery storage systems at prosumer level

Summary

The table below presents a format for the summary of model requirements.

Table 13. Sample of format for the summary of models requirements

	Geography		Time		Technological scope
	Horizon	**Granularity**	**Horizon**	**Granularity**	
EMPS-W	Iberian Peninsula (ES + PT) & Norway	NUTS2 (Province)	1 year (2050)	Each 2 or 3 hours of Time Step. Hourly is possible (weekly for water values)	• Biomass • Coal • Cogeneration • Combined Cycle Gas Turbine (CCGT) • Demand Response • Energy Storage System (ESS) • Geothermal • Hydro Power • Lignite • Nuclear • Oil • Power Transmission • Pumped-Hydro Storage (PHS) • Solar PV Utility • Solar Thermal (CSP) • Wind Offshore • Wind Onshore
openTEPES	Iberian Peninsula (ES + PT) & Norway	NUTS2 (Province)	1 year (2050)	Hourly (weekly for water values)	• Biomass • Coal • Cogeneration • Combined Cycle Gas Turbine (CCGT) • Energy Storage System (ESS) • Geothermal • Hydro Power • Lignite • Nuclear • Oil • Power Transmission • Pumped-Hydro Storage (PHS)

					• Solar PV Utility • Solar Thermal (CSP) • Wind Offshore • Wind Onshore
GUSTO	Iberian Peninsula (ES + PT) & Norway	Community & End User	1 year (2050)	Hourly	• Energy Storage System (ESS) • Heat • Heat pump • Power-To-Gas (P2G) • Power-To-Heat (P2H) • Solar PV Rooftop • Solar PV Utility • Wind Onshore

The case study will pivot between several models that, together, will be able to provide the necessary details of system planning and operation. 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.

- <u>**EMPS-W**</u>: Computation of the **long-to-medium term operation of hydrothermal power systems**
    - Optimal dispatch considering stochastic weather-related variables: wind and solar gross output and inflows to hydropower reservoirs
    - Manages individual water reservoirs separately, computing individual water values
    - Considers aggregate power flow constraints (at corridor level)
- <u>**GUSTO**</u>: Optimal **utilization of small batteries and flexible loads** at prosumer level **under various operation strategies**
- <u>**openTEPES**</u>: Computation of the **optimal expansion of large electricity transmission grids**
    - Network model with detailed granularity
    - Full representation of Kirchhoff laws and network losses
    - Both long and short-term uncertainty can be represented
    - Suitable for the analysis of the impact of the implementation of specific energy policies on the development of the transmission network.

The main data requirements for this case study are complete scenarios for:

Generation, with capacities per technology per region and costs in the case of thermal generation. In the case of hydro, the definition of reservoir structure, capacities and inflow scenarios will be needed, as well as their operation constraints. Gross power production scenarios for intermittent generation will also be needed. The expansion of generation will be calculated within the scope of the project by models such as GENeSYS-MOD, SCOPE or EMPIRE.

Demand, which includes the data that are needed to model prosumer strategies in GUSTO.

Transmission, which should include the starting network in a detailed manner for the focus regions and aggregated for the rest of the European Union.

Storage, data on all the storage units, or the equivalent aggregate ones to be represented in the analyses, need to be provided as well, including their injection/withdrawal capacity in terms of power and energy, and their efficiency.

Input and output data

- *Input data*

A list of input variables, including: description, unit, spatial resolution, temporal resolution, flexibility to upgrade or downgrade resolution.

Model	Variable	Description	Unit	Spatial		Temporal	
				Granularity	Flexibility	Granularity	Flexibility
EMPS-W	Power Demand	Demand in Active Power, can be total demand for a region or split in sub-groups as below	MW	NUT2 (Province)	**From:** country **Until:** NUTS2	Hourly	Typically yearly demand plus weekly and season profile
EMPS-W	Gas power capacities	Installed capacity of gas	MW	Per plant	**From:** clustered technology **Until:** per plant		
EMPS-W	Wind energy resources	Wind power production. A profile hour-by-hour is given by WindResources below	TWh	Per plant	**From:** clustered technology **Until:** per plant	Hourly	**From:** yearly **Until:** hourly
openTEPES	Transmission capacity	Capacity of transmission lines	MW	Lines	**From:** Transfer capacity between regions **Until:** Lines		
openTEPES	Investment cost	Investment cost of transmission lines	MW	Lines	**From:** Transfer capacity (circuits) **Until:** Lines		
GUSTO	Electricity price	Average spot market price	EUR/MWh	NUTS3 (Districts)	**From:** NUTS3 **Until:** End user	Hourly	**From:** yearly **Until:** Hourly
GUSTO	Discharge of Batteries	Scheduled discharge of Battery Energy Storage Systems	MWh	NUTS3 (Districts)	**From:** NUTS2 **Until:** Lines	Hourly	**From:** yearly **Until:** Hourly

- *Output data*

A list of output variables, including: description, unit, spatial resolution, temporal resolution, flexibility to upgrade or downgrade resolution.

Model	Variable	Description	Unit	Spatial		Temporal	
				Granularity	Flexibility	Granularity	Flexibility
EMPS-W	Power Production	Produced energy per plant (all types of	MW	Per plant	**From:** clustered technology **Until:** per plant	Hourly	Per time step used in the specific project, typically 2-3

		plants) per time step					hours. Per hour is possible
EMPS-W	Reservoir level	Development of reservoir level	Mm3	Per reservoir	**From:** aggregated for all reservoirs in each region **Until:** per reservoir	Weekly	**From:** yearly **Until:** weekly
EMPS-W	Electricity price	Power price at spot market	Euro/MWh	NUTS2 (Province)	**From:** Country **Until:** NUTS2	Hourly	**From:** yearly **Until:** hourly
openTEPES	Power flow	Power transmitted on a line	MW	Lines	**From:** Transfer capacity between regions **Until:** Lines	Hourly	**From:** yearly **Until:** hourly
openTEPES	Investment in lines	Candidate line installed or not	{0,1}	Lines	**From:** Transfer capacity between regions **Until:** Lines		
GUSTO	Storage level of ESS	Storage level of Battery Energy Storage Systems	MWh	End user	**From:** Community **Until:** End user	Hourly	**From:** yearly **Until:** Hourly
GUSTO	Spillage of wind resources	Spillage of wind power units	MWh	End user	**From:** Community **Until:** End user	Hourly	**From:** yearly **Until:** Hourly

- ***Schematic overview of the model***

  The following figures are presented a schematic overview of the models.

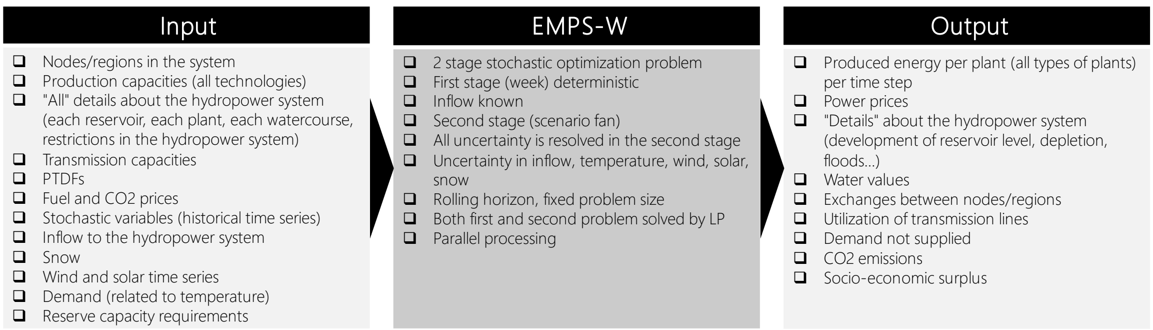


Figure 10: Schematic overview of the EMPS-W modelling framework developed at SINTEF.

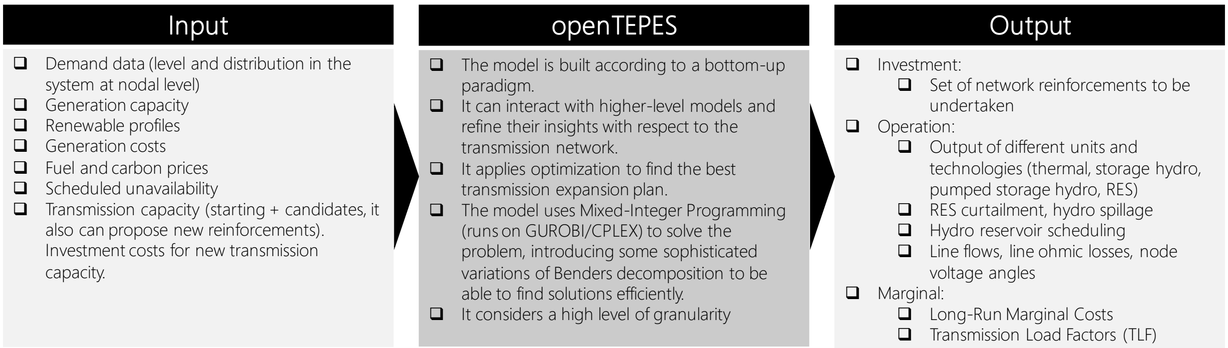


Figure 11: Schematic overview of the openTEPES modelling framework developed at Institute for Research in Technology - Comillas Pontifical University.

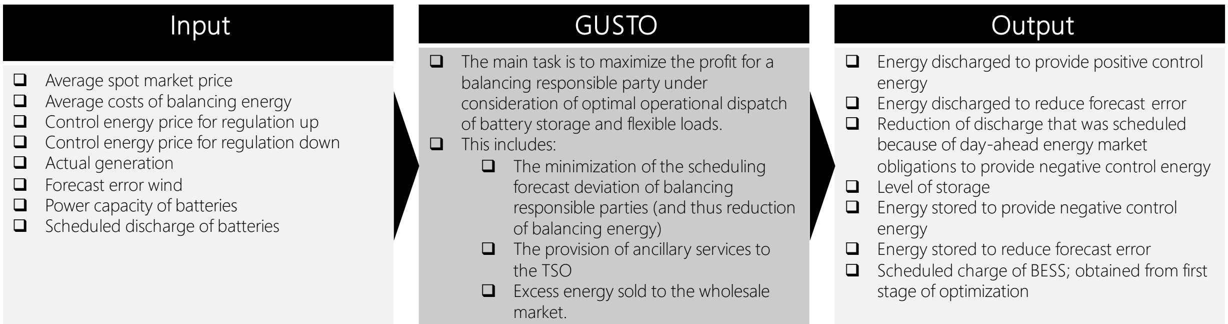


Figure 12: Schematic overview of the GUSTO modelling framework developed at TU WIEN.

A general list of data required is needed to be given in order to perform the case study. This list should be expanded immediately below and have a strict equivalence with the GitHub - openENTRANCE/nomenclature.

List of data that are or will be on the openentrance platform

All those data are either already on the openENTRANCE platform or are going to be uploaded to the platform during the project.

- **Data from openENTRANCE scenarios (for the chosen scenario) (performed in WP3).**

This information is provided by the openENTRANCE database using a common data format based on a template developed by the Integrated Assessment Modeling Consortium (IAMC). The data format is generic and suitable to be used for a wide range of applications, including energy-systems analysis or modelling of specific sectors like transport, industry or the building stock. The list below provides the needed information:

- Installed capacities per country per technology in 2050
- Energy demand per country per use in 2050
- Net electricity production from all sources of solar energy (e.g., pv and concentrating solar power)

- **Data coming from modelling teams own databases.**

This is data produced outside the suit of tools in openENTRANCE that is given to each model in an independent way. We have:

- Boundaries: electric power exchanges with not-accounted for neighbouring countries
- Other generation profiles (biomass for example)
- Electricity Demand profiles correlated to temperature time series

- Power technologies with their financial and technical parameters (Generation, Transmission & Distribution)
- Storage technologies
- Hydro technologies with their technical parameters (lakes, run of river, pumped storage)
- Demand response technologies and potentials
- Temperature

- **Data produced during the case study exercise (mainly outputs of models)**

This data will be exchanged between models as inputs for someones and output for others.

For example, we have:

- Transmission grid (capacities between nodes)
- Generation profiles for wind, PV, hydro correlated to meteorological time series
- Fuel prices and CO_2 emission price (or budget)
- Level of deployment of storage, which will consider several situations for the upscaling of hydro pumping and batteries.
- Operating strategy associated to the agent in charge of the operation of the batteries.
- A tactical transmission expansion plan for the regions focused.
- Different operating strategies will be translated into output curves (e.g. charging/discharging patterns and changing load profiles over time) that describe the use of storage.

Links among models

This section presents, in a clear and simple manner, the workflow of the case study.

General workflow

A wide perspective of the workflow is presented first.

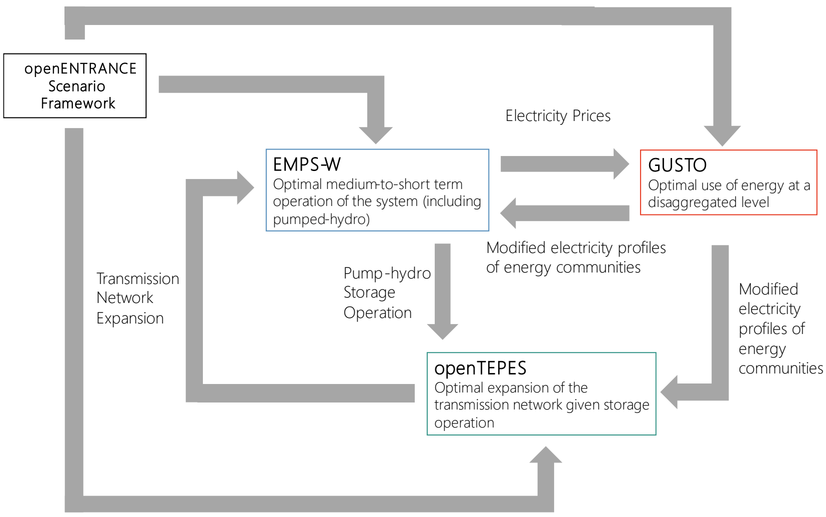


Figure 13: CS3 high-level Workflow

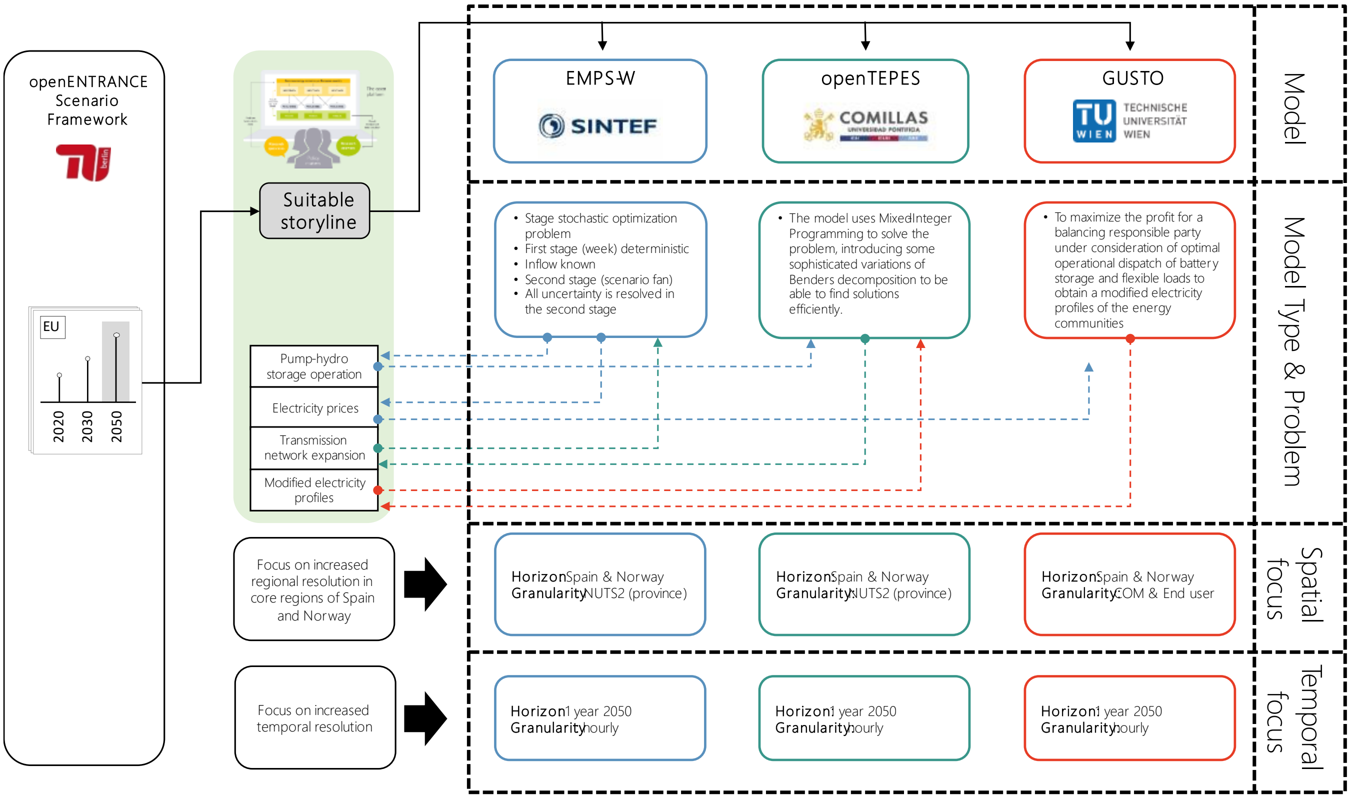


Figure 14: A Schematic overview of the case study 3 (methodology and model linkage).

The specificities of the data exchanged among models are presented in this section. The workflow of the case study is previously defined as it is presented in section 1.6. To illustrate the details of the workflow in a general and specific way, we use the example in Figure 7. This figure is composed of two parts: a) The left side corresponds to a general representation of the workflow; and b) The right side, which provides a detailed representation of the workflow.

Facts that are illustrated in the figure:

- The openENTRANCE database provides scenario information.
- There are three models that receive information from the database and outside the database
- Note that all the data that are exchanged among models are exchanged through the openENTRANCE database (thus using the **Common Data Format** from D4.2).
- There are tools to convert the data format that comes from each model to Common Data Format of the database and vice versa.
- Dashed lines represent the flow of information

It is considered two types of dataPacks:

- Whose content comes from openENTRANCE scenarios (**Pack1**)
- Whose content comes from mode's own database
- Whose content comes from models' output (**Pack2**, **Pack3**, **Pack4** and **Pack5**) and is used as input for other models

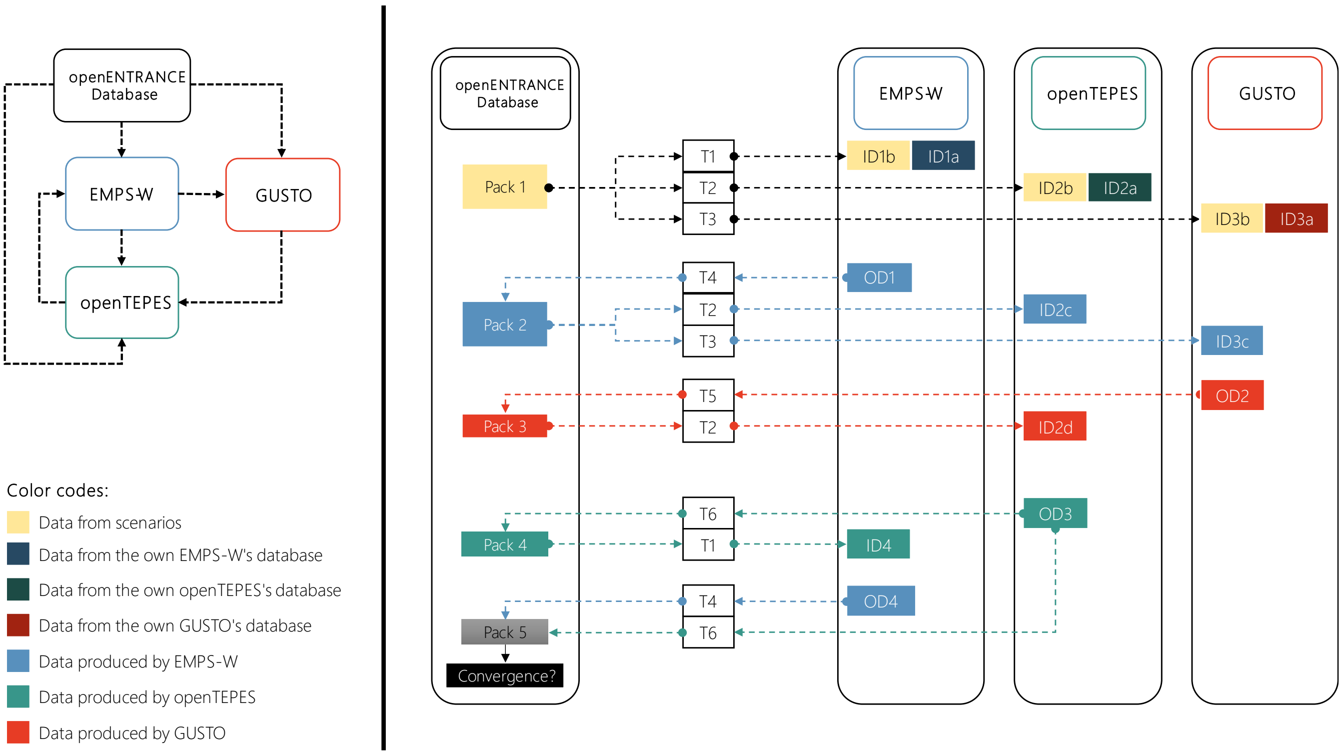


Figure 15: Data workflow

A list of specific dataPacks or sets should be introduced at this point, incorporating additional information to the data workflow.

dataPack	Data flow	Content
Pack 1	Input data from Scenarios, common between models	Fuels and CO2 prices Technology operation costs Energy demand per uses (power, heat, cooling, industry, transport) Installed capacities
Pack 2	Data exchanged between EMPS-W, openTEPES and GUSTO (from EMPS-W Output to openTEPES and GUSTO' input)	Generation production for wind, PV, hydro correlated to meteorological time series Other generation production (biomass for example) Water values Scheduled use of reservoirs Electricity price
Pack 3	Data exchanged between openTEPES and GUSTO (from GUSTO Output to openTEPES input)	Electricity Demand profiles correlated to temperature time series (including electric vehicle profile) Output curve for batteries Behavior profiles of electric vehicles
Pack 4	Data exchanged between EMPS-W and openTEPES (from openTEPES output to EMPS-W input)	Transmission expansion plan (capacities between "nodes") Generation production for wind, PV, hydro correlated to meteorological time series Other generation production (biomass for example) Transmission Load Factors (TLF)

Pack 5	Output data from EMPS-W and openTEPES	Use of each technology (hourly and aggregated) per node Costs of transmission expansion plan Energy not supplied Marginal costs Electricity prices per node

List of Datasets (using the models own formats):

ID1a	Input dataset **"part a"** that comes from the own **EMPS-W**'s database, *i.e., Reservoir topology*
ID1b	Input dataset **"part b"** that comes from the openENTRANCE database to EMPS-W, *i.e., energy resources, etc.*
ID2a	Input dataset **"part a"** that comes from the own **openTEPES**' database, *i.e., Investment costs, network topology*
ID2b	Input dataset **"part b"** that comes from the openENTRANCE database to **openTEPES**, *i.e., Demand, etc.*
ID3a	Input dataset **"part a"** that comes from the own **GUSTO**'s database, *i.e., Battery storage capacities*
ID3b	Input dataset **"part a"** that comes from the openENTRANCE database to **GUSTO**, *i.e., Demand, capacities, etc.*
OD1	Output dataset from **EMPS-W** to openENTRANCE database, *i.e., Electricity prices and storage hydro operation*
ID2c	Input dataset **"part c"** that comes from the openENTRANCE database to **openTEPES**, *i.e., storage hydro operation*
ID3c	Input dataset **"part c"** that comes from the openENTRANCE database to **GUSTO**, *i.e., Electricity prices*
OD2	Output dataset from **GUSTO** to openENTRANCE database, *i.e., Output curves for batteries, power production*
ID2d	Input dataset **"part d"** that comes from the openENTRANCE database to **openTEPES**, *i.e., Output curves for batteries*
OD3	Output dataset from **openTEPES** to openENTRANCE database, *i.e., Transmission network expansion*
ID4	Input dataset that comes from the openENTRANCE database to **EMPS-W**, *i.e., Aggregated power network*
OD4	Output dataset from **EMPS-W** to openENTRANCE database, *i.e., Power production*

Data-exchange tools

A list of the data-exchange tools that need to be implemented to perform the linkage of models should be 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 OE platform)
- Geographical aggregation or disaggregation (using aggregation/disaggregation functions available in OE platform)
- Temporal aggregation or disaggregation (using aggregation/disaggregation functions available in 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**

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.

Extraction of data from openENTRANCE Database: First, the **Pack 1** is built by selecting the adequate variables. **Pack1** is downloaded in a format which 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.**

1. **Building Model 1 Input dataset and running EMPS-W:** The EMPS-W's dataset is built out of EMPS-W own data (**ID1a**) and openENTRANCE Scenario data (**ID1b**). EMPS-W is executed and produces output**s. OD1** 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. **OD1** is converted to the **Common data format** using **T4**, which produces **Pack2.**
2. **Exchanging between EMPS-W and openTEPES**: Data from **Pack2** (produced by **EMPS-W**) are downloaded and converted to **openTEPES** format using **T2** => **ID2c.**
3. **Exchanging between EMPS-W and GUSTO**: Data from **Pack2** (produced by **EMPS-W**) are downloaded and converted to **GUSTO** format using **T3** => **ID3c.**
4. **Building GUSTO Input dataset and running GUSTO:** The GUSTO's dataset is built out of GUSTO own data (I**D3a**) 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 part 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**.
5. **Exchanging between GUSTO and openTEPES**: Data from **Pack3** (produced by **openTEPES**) are downloaded and converted to **openTEPES** format using **T2** => **ID2d.**
6. **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.**
7. **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 are running again, which produces the new output **OD4.**
8. **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.**
9. Expert analysis of outputs will determine whether a new cycle is necessary.

7.Application #2

This section provides an illustration of the developed methodology as applied in case study 4:

Overall Objective and Case study baseline

In this case study, simulation over the whole pan-European energy system will be run with the models SCOPE SD and Plan4EU. SCOPE SD model simulations will include a high sectoral and temporal resolution and a medium spatial (country level) while Plan4EU will focus on the electricity sector only but with a high temporal and spatial resolution (regions), including also a modelling of aggregated distribution constraints. SCOPE SD and Plan4EU will be linked together as to run Plan4EU simulations with inputs out of SCOPE SD.

General assumptions:

- Low-carbon energy systems in Europe need to be based on cross-sectoral integration to meet climate protection goals
- Cost-efficient coupling of the power with heat and transport sectors implies additional demands for renewable electricity but integrating technologies at the interfaces between those sectors may also provide a valuable source of flexibility
- Multiple studies have been carried out on a one-node-per-country level – but how does the integration of cross-sectoral technologies play out in the local but interconnected domain?
- Objective is to simulate the expansion and operation of the pan-European power system with a particular focus on transport sector technologies (i.e. (hybrid) electric vehicles, hybrid electric overhead-line highway trucks), while integrating all relevant flexibility assets, network costs and constraints on a local and decentralized level
- Flexibility considerations also focus on the consumer behaviour perspective, by investigating a different willingness to provide flexibility for electric vehicle owners
- Baseline is still to be defined but it should feature some cross-sectoral integration technologies including available (decentralised) flexibility

Model set

By linking the SCOPE SD (Fraunhofer IEE) and plan4EU (EDF) modelling frameworks, the case study combines a proprietary with an open-source modelling framework via the openENTRANCE platform.

Summary of the models

The following table details the geographical/time horizon and granularity as well as the technology scope of the models involved.

	Geographical scope		Time scope		Technological scope
	Horizon	**Granularity**	**Horizon**	**Granularity**	
SCOPE-SD [Ref]	EU27+NOR /CHE	Country, except for France and Germany : ehighway2050 clusters (defined in Nomenclature)	1 year (2050)	Hourly	• WindPower • PV • HydroPower • Condensing plant • Energy storage • Cogeneration • Power-to-heat • Power-to-gas • Cooling Process • BEV • Boiler

					• Solar Thermal • PHEV/REEV • Electric Truck • Geothermal
Plan4EU	EU27+NOR /CHE + UK	France and Germany : ehighway2050 clusters (defined in Nomenclature) Aggregated regions : Scandinavia, Balkans, Baltics, Spain+Portugal, Eastern Europe Countries, UK+Ireland The rest: countries	1 year (2050)	Hourly (weekly or monthly for water values)	• Electricity generation technologies • Electric vehicles (modelled as consumption with flexibility) • Electricity storages (batteries, hydro) • Electricity transmission

The SCOPE SD model is used to develop a long-term low-carbon energy system scenario [PH1] for Europe. By minimizing the generation, storage, and cross-sectoral consumer technology investment and system operation cost, this large-scale linear programming approach features representations for the traditional power system as well as all relevant bi- and multivalent technology combinations at the sectoral interfaces with the heat, industry, and transport sectors.

Model type and problem

SCOPE SD is used for cost-optimised target scenarios of future energy systems with energy and emission targets while capturing a wide range of technology combinations. The modelling framework can be characterised as follows:

- Static deterministic partial equilibrium techno-economic bottom-up [HP2] mathematical optimization model
- Cross-sectoral Capacity Expansion Planning (CEP)
- With/ without expansion decisions (pure system operation model/ or only sector-specific expansion)

Spatial scope and granularity

- EU27+NOR/CHE;
- One node per country

Temporal scope and granularity

- Full-year, i.e. historical (or potentially future) meteorological year
- Hourly resolution
- “Static planning”, i.e. only single scenario years and no pathway (“dynamic planning”)

Plan4EU modelling framework

CS4 will make use of the scenario valuation layer of Plan4EU. The Scenario valuation layer evaluates the investment decisions from the capacity expansion model by means of modelling the operation of the existing assets in the energy system. This layer contains two distinct models, the first model is referred to as the seasonal storage valuation (SSV) model and the second model is referred to as the European unit commitment (EUC) model.

- ***Seasonal storage valuation model (SSV)***

The objective of the seasonal storage valuation model is to provide an accurate account of “the value” that seasonal storage can bring to the system. Indeed, such seasonal storage (e.g., cascaded reservoir systems) can be used to store energy over large spans of time and use this “stored” energy when most needed. The actual use may in particular depend on adverse climatic situations (intense cold), but the ability to store the energy may in turn also depends on climatic conditions (e.g. draught). It is therefore clear that such a vision of value should be transferred in an appropriate way to shorter time span tools, such as the EUC model. In turn computing an accurate value intrinsically depends on the value of substitution, and thus ultimately on the EUC tool as well.

- ***European Unit Commitment (EUC)***

The EUC model computes an optimal (or near optimal) schedule for all the system assets on a typical period of one year, with a typical granularity of one hour in order to satisfy demand and ancillary services at the lowest cost. It ensures that the given system is « feasible » in the sense that at each hour of the year, including peak hours, it is able to fulfill the following constraints

    - power demand supply;
    - ancillary services supply;
    - minimal inertia in the system;
    - maximum transmission capacities between clusters;
    - technical constraints of all assets.

Input and Output data

General list of data

1- ***Data from OpenEntrance Scenarios (for the chosen scenario)***
    - Installed capacities per country per technology in 2050
    - Energy demand per country per use in 2050
    - Costs of technologies (variable costs including fuel cost)

2- ***Data from SCOPE-SD (for the chosen scenario)***
    - Updated Installed capacities per country per technology in 2050
    - Transmission grid (capacities between nodes)
    - Demand response (electric transport) technologies and potentials:

○

3- ***Additional data:***
    - Generation profiles for wind, PV, hydro correlated to meteorological time series
    - Electricity Demand profiles correlated to temperature time series (including electric vehicle profile)
    - Technical parameters of Power and storage technologies

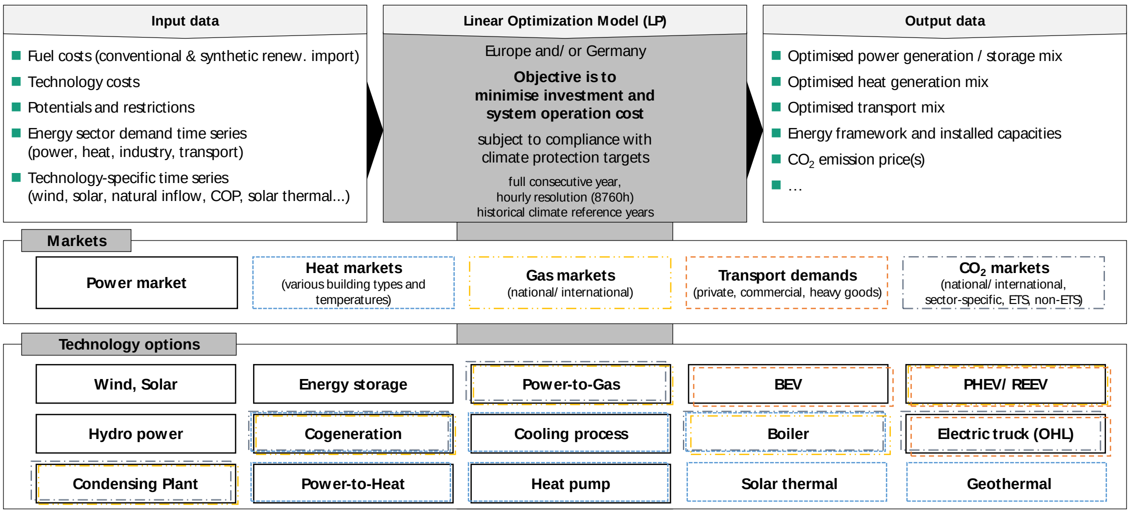


Figure 16: Schematic overview of the SCOPE SD modelling framework developed at Fraunhofer IEE.

Detailed methodology

First, pan-European reference scenarios will be implemented from WP3 in both model environments to determine further assumptions necessary for the detailed case study. Simulations will then be performed with SCOPE SD, including sensitivities regarding the share of flexible charging in all or selected European countries (i.e. uncontrolled versus system-friendly charging behaviour). Then, the flexibility information from SCOPE SD will be integrated into the plan4EU modelling framework to run more detailed simulations regarding the electricity sector.

The primary approach is to run the SCOPE SD model in a first step focussing on the national level and use these aggregate results as input for the Plan4EU model. In a second step, the Plan4EU model processes and disaggregates the country-specific input data to then perform the electricity market simulations in the more detailed regional domain.

An extension of this modelling chain is to already include a more detailed regional focus of Germany and France in the SCOPE SD model. By increasing the spatial resolution in terms of multiple bidding zones per country, some limitations regarding internal transmission grid effects could be alleviated. A more detailed spatial resolution allows for a more accurate aggregation (i.e. not to the national but only regional level) of the transport sector flexibility parameters. The Plan4EU model can use the new results from the SCOPE SD model with better assumptions on local potentials for flexibility in a second run. As a consequence, the two versions of running the models can be compared to provide insights into the impact of decentralised flexibility of electric vehicles on the grid and expansion planning.

Further aspects to investigate in optional analyses include a refined modelling approach of the power flow in the Plan4EU model, i.e. using a DC power flow approximation instead of a transport model (NTC). Another aspect focuses on the capacity limits between distribution and transmission network, which is particularly relevant since large shares of renewable power generation as well as electric vehicle charging is connected to the distribution grid level.

Links among models

The main links among models are presented in the Figure below. The EV Flexibility potentials as well as updated electricity capacities and demand are shared by SCOPE SD with plan4EU. Plan 4EU, in turn, shares the costs per variant with SCOPE SD.

General Workflow

The figure below shows a simplified workflow for the model.

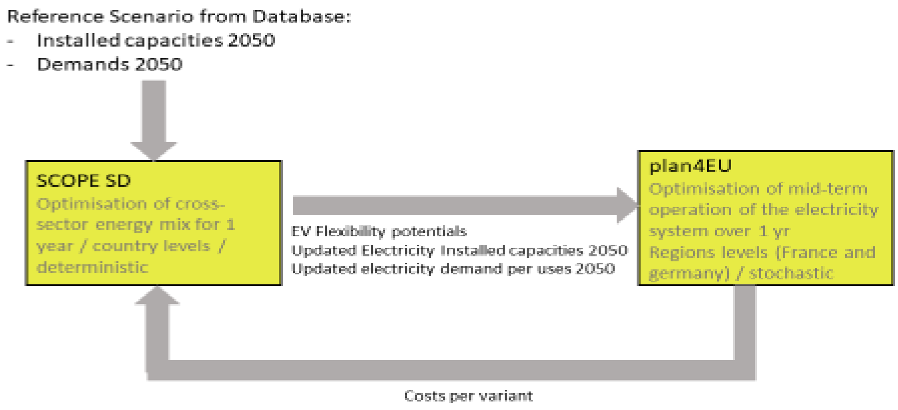


Figure 17: CS4 general Workflow

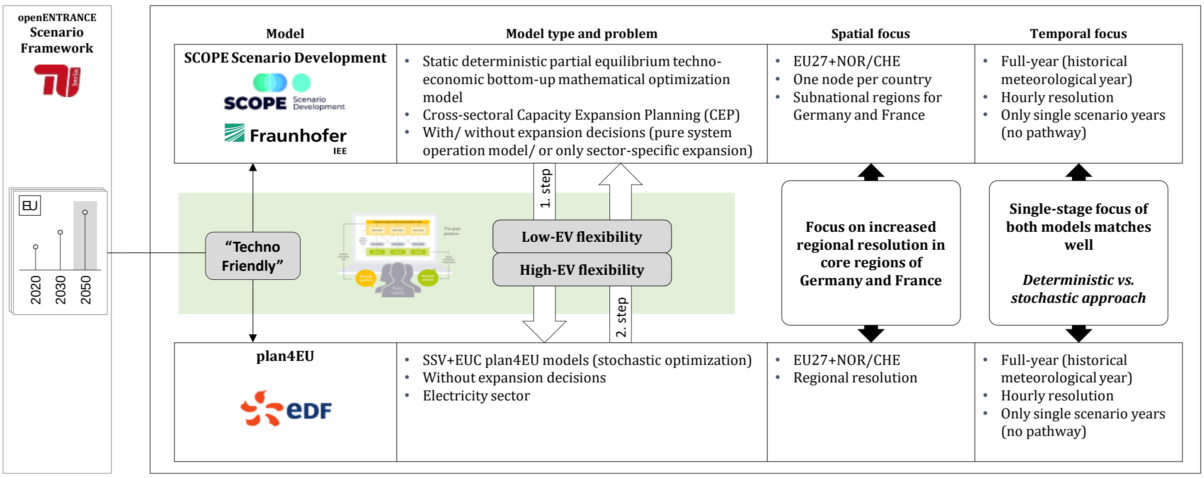


Figure 18: Schematic overview of the case study methodology and model linkage

Model manipulation strategy

The integration of the models in the case study is presented in the figures below. In summary, the main workflows that relate the models involved, represented by the black dashed lines, are the following:

- SCOPE-SD provides EV load and flexibility to plan4EU
- Plan4EU provides the cost/benefit of integrating this flexibility in the system to SCOPE-SD

- Using that additional knowledge, parameters in SCOPE-SD are adapted so a new run can be done

Data Workflow

The principle is that all data that are exchanged among models are exchanges through the OpenEntrance database (thus using OpenEntrance Data Format from D4.2).

List of dataPacks seen from the OpenEntrance database (of course using OpenEntrance Data Format):

Pack 1	Input data from Scenarios, common between models	Fuels and CO2 prices Technology operation costs Energy demand per uses (power, heat, cooling, industry, transport) Installed capacities
Pack 2	Data from plan4EU database (input data)	Generation profiles for wind, PV, hydro correlated to meteorological time series Electricity Demand profiles correlated to temperature time series (including electric vehicle profile) Power technologies with their technical parameters
Pack 3	Data exchanged between SCOPE-SD and plan4EU (from SCOPE Output to plan4EU input)	load profiles of electric vehicles nodes EV Flexibility (upper and lower deviation allowed around load profile) Updated installed capacities and transmission grid
Pack 4	Outputs from plan4EU	Mean use of each technology (hourly and aggregated) per node Costs of each technology Mean non supplied energy Marginal costs Mean use and costs of each flexibility

List of Datasets (using the models own formats):

ID1a	SCOPE-SD Input dataset part a that comes from the own SCOPE-SD database (SCOPE-SD Format)
ID1b	SCOPE-SD Input data part b that comes from the OpenENtrance database, converted to SCOPE-SD Format
OD1a	SCOPE-SD Output (SCOPE Format), will not be shared nor exchanged
OD1b	SCOPE-SD Output (SCOPE Format), will be converted to OpenEntrance Format, and shared
ID2a	Plan4EU Input data part a that comes from the own plan4EU database (plan4EU format)
ID2b	Plan4EU Input data part b that comes from the OpenENtrance database, converted to plan4EU Format
ID2c	Plan4EU Input data coming from SCOPE-SD
OD2	Plan4EU Output data
OD2a	Extract of Plan4EU Output data sent for analysis to SCOPE-SD team
ID3a	New SCOPE-SD Input Data updated using the outputs OD2a of plan4EU
OD3b	SCOPE-SD Output (SCOPE Format), will be converted to OpenEntrance Format, and shared
OD3a	SCOPE-SD Output (SCOPE Format), will be converted to OpenEntrance Format, and shared

List of tools and/or methodologies to be implemented by modelling teams:

T1 (OE-SCOPE)	Set of tools or methods to convert data between SCOPE-SD and OPenEntrance Format
T2 (OE-plan4EU)	Set of tools or methods to convert data between plan4EU and OPenEntrance Format
T3 (SCOPE-SD)	Set of tools or methods to build new SCOPE-SD input data using the results of plan4EU

These tools (or methodologies), to be developed by each model team will include:

- Unit conversions (eg. EJ to MWh, MWh to GWh).

- Geographical Aggregation or disaggregation: in particular, OpenEntrance Scenarios are at country level while plan4EU has a different geographical scope with smaller or larger regions. The values coming from OpenEntrance have, for France and Germany, to be 'disaggregated' by using the plan4EU weights of each sub-country region, or adding the values for the plan4EU aggregated regions.
- Formatting: ie converting the excel format to the adequate format. (columns, rows…)

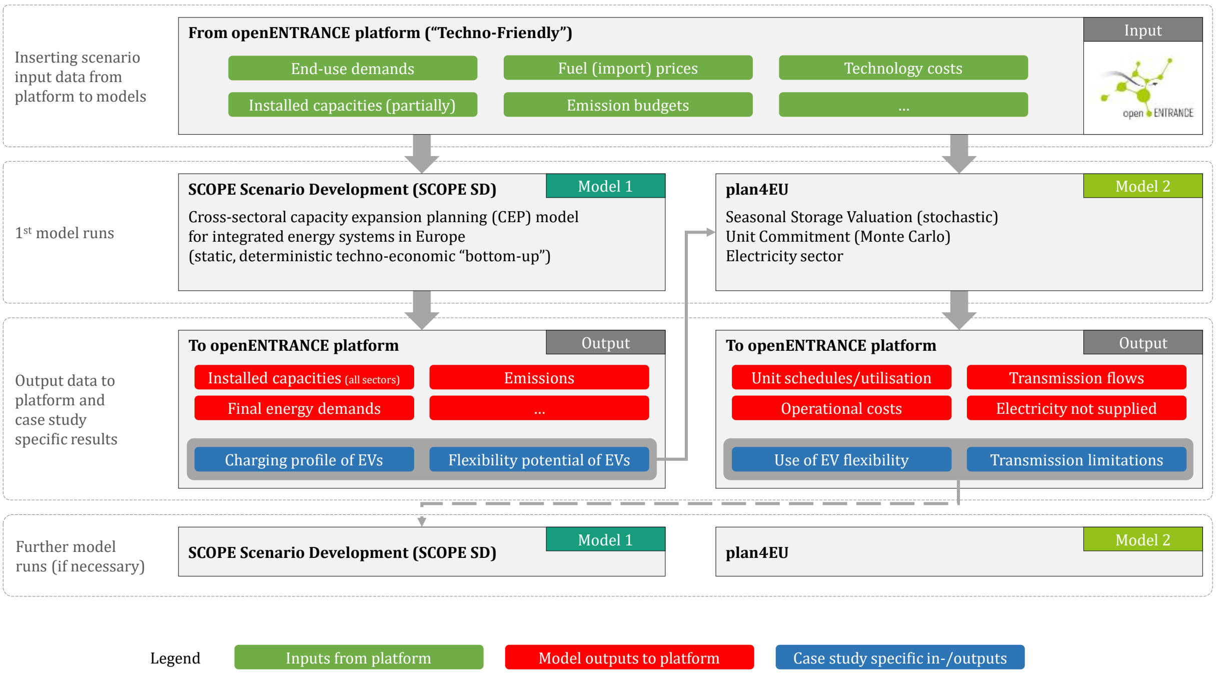


Figure 19: Overview of detailed workflow in case study 4.

Execution order

1. **<u>Extraction of data from OpenEntrance Database:</u>** First, the Pack 1 is built by selecting the adequate variables. Pack1 is downloaded in a format which is as close as possible to Models formats (using the pyam functions as much as possible). It is transformed through T1 and T2 into SCOPE-SD / plan4EU data formats ID1b and ID2b
2. **<u>Building SCOPE-SD Input dataset and running SCOPE-SD:</u>** The SCOPE-SD dataset is built out of SCOPE-SD own data (ID1a) and OpenEntrance Scenario data (ID1b). SCOPE-SD is ran, which produces the Output OD3a + OD3b. OD3a is the part of the output that can be shared, while OD3b is the part that cannot be shared and will be kept private by the SCOPE team. OD3a is converted to the OpenEntrance Format using T1, which produces Pack3.
3. **<u>Exchanging between SCOPE-SD and plan4EU</u>**: data from Pack3 (produced by SCOPE-SD) are donwloaded and converted to plan4EU format using T2 => ID4a.
4. **<u>Building plan4EU Input dataset and running plan4EU</u>**: The plan4EU dataset is built out of plan4EU own data (ID2a), OpenEntrance Scenario data (ID2b), and SCOPE-SD Outputs (ID4a). ID2a can be transformed into OpenEntrance Data format using T2 and uploaded to OpenEntrance database, producing Pack 2. Plan4EU is ran, which produces the Output OD5a + OD5b. OD5a is the part of the output which will be used by SCOPE while OD5b will not. Meanwhile, both OD5a and OD5b can be converted to OPenEntrance format by T2 and uploaded to OpenEntrance Platform, producing Pack4.

5. **Updating SCOPE-SD dataset and running SCOPE-SD**: OD5a data from plan4EU is downloaded from Pack4 and used in order to update the SCOPE-SD dataset: ID6a is created by T3. SCOPE-SD is ran using ID1b+ID6a, which produces the new outputs OD7b and OD7a.
6. Expert analyses of outputs will determine whether a new cycle is necessary.

8.Conclusions and lessons learnt

In this deliverable, openENTRANCE has provided a new methodology that advances from the already existing structured modelling framework to characterizing, scheming and dealing with the linking of energy models to solve particular research questions. This methodology particularizes structured modelling for energy modeling, 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, to choose the models that will be used and to design their interaction and a convergence procedure.

This is a useful addition to the results of the openENTRANCE project which can be applied in the very wide context of energy modeling.The framework is a general approach that is based on *structured modelling*, a formal mathematical theory that was developed for conceiving, representing, and manipulating a wide variety of models. The framework has been articulated in several sections (shown in Figure 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 two examples based on case studies 3 and 4, which clarify their application and their usefulness for case study design. In the rest of this section, several insights shared by the modelers participating in the case study have been selected based on their usefulness and generality.

The development of convergence criteria is problematic in many instances. In particular, when the model input/output graph is acyclic, it is possible to run the models sequentially and obtain a result. If there are indeed cycles in the models, it is necessary to establish a convergence criterion that is based on the coincidence of the outputs of two or several models. The difficulty in convergence criteria is shown in the example of case study 3, which involves two top-down energy models.

In addition, the experience in developing both case studies has shown the difficulty in sharing data among models that are focused on different technologies and aspects of energy planning, such as EMPS-W and openTEPES.

The work that was carried out in open-ENTRANCE also highlighted the difficulty of defining Europe-wide scenarios that strike an appropriate balance between the consistency of the scenario with European policy and the idiosyncrasies of the national systems involved. This is essential to be able to consider the developed scenario as something credible, realistic, and to have a certain capacity to influence the energy debate.

The work has also shown the essential role played by communication. Good and continuous contact between the modelers doing the work needs to be establish early, especially between modelling groups that have no experience working together, so that any issues can be addressed quickly to ensure an efficient workflow. Periodic meetings were found to be very useful and were adopted in most case studies. This importance of communication is in line with one of the key objectives of open-ENTRANCE, which is to build a community of modelers.

Previous experience did indeed make a difference. In the case studies where models had already been used concurrently, issues were considerably fewer and got resolved much quicker.

In addition, it is important to note that while conceptualisation is important, it should be directly coupled to concrete action in order to identify challenges early: many issues only arise at the moment when the model execution is taking place.

It is good practice to include very specific conversations about data early in the process. If this is not done, it is possible to easily miss compatibility issues. For example, although two models may consider hydro inflows, do they do so in terms of physical water storage or in energy terms? This sort of details can complicate model communication and should be addressed as early as possible in the process.

Most case studies identified some need for adaptation during the case example phase. These adaptation needs could have different characteristics: i) model adaptation needs, in particular data adaptation (harmonization) needs in those case studies when several models are linked; ii) re-formulation of data input and, especially, data output in the openENTRANCE nomenclature (IAMC format); iii) the openENTRANCE platform needed to be adapted to very large databases (e.g. model output high temporal and geographical resolution). All these challenges have subsequently been tackled by the modelling teams in the case studies.

We expect the work that has been carried out will benefit the energy community as a whole and make the process of structuring case studies to solve policy questions more structured, easier and quicker.

9.References

Deane, J., Chiodi, A., Gargiulo, M., & Gallachóir, B. P. Ó. (2012). Soft-linking of a power systems model to an energy systems model. *Energy, 42*(1), 303-312.

Del Granado, P. C., Van Nieuwkoop, R. H., Kardakos, E. G., & Schaffner, C. (2018). Modelling the energy transition: A nexus of energy system and economic models. *Energy Strategy Reviews, 20*, 229-235.

Geoffrion, A. M. (1987). An introduction to structured modeling. *Management Science, 33*(5), 547-588.

Jones, C. V. (1990). An introduction to graph-based modeling systems, part I: Overview. *ORSA Journal on Computing, 2*(2), 136-151.

Krook-Riekkola, A., Berg, C., Ahlgren, E. O., & Söderholm, P. (2017). Challenges in top-down and bottom-up soft-linking: Lessons from linking a swedish energy system model with a CGE model. *Energy, 141*, 803-817.

Lee, R. M., & Krishnan, R. (1990). Logic as an integrated modeling framework. *Computer Science in Economics and Management, 3*(1), 107-136.

Lehner, B., Czisch, G., & Vassolo, S. (2001). Europe’s hydropower potential today and in the future. *EuroWasser: Model-Based Assessment of European Water Resources and Hydrology in the Face of Global Change.Chapter8, Kassel,*

Wene, C. (1996). Energy-economy analysis: Linking the macroeconomic and systems engineering approaches. *Energy, 21*(9), 809-824.