open ENTRANCE

Illustrative case examples for the coordinated use of models

DELIVERABLE NO. 5.4

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

Deliverable No.	D5.4	Work Package No.	5
Suite of modeling tools			
Status	Final	Final	
Dissemination level		Public	
Due date deliverable	2022.09.30	Submission date	2022.09.27
Deliverable version	Version 1		

Deliverable Contributors:	Name	Organisation	Date
Deliverable Leader	Franziska Holz	DIW Berlin	2022.04.29
Work Package Leader	Luis Olmos	Comillas	
Contributing Author(s)	Sandrine Charousset	EDF	
	Daniel Huppmann	IIASA	
	Ingeborg Graabak	SINTEF Energy Research	
	Luis Olmos	Comillas	
Reviewer(s)	Sandrine Charousset	EDF	
	Luis Olmos	Comillas	
Final review and approval	Ingeborg Graabak	SINTEF Energy Research	2022.09.27

History of Change

Release	Date	Reason for Change	Status
Final	2022.09.27	Feedback from EC and reviewers incorporated	Final
Preliminary	2022.08.11	Feedback from EC incorporated	Preliminary
Preliminary	2022.05.01	Feedback from reviewers incorporated	Preliminary
Initial draft	2022.04.09		Draft

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

Executive Summary

Task 5.3 is part of WP5 ("A suite of modeling tools") and contributed to ensuring the functional characterization of models and model linkages, as well as to showing and providing proof of the coordinated use of the models. To this end, reduced case studies, so-called "case examples" were developed and tested. Model linking is carried out by exchange of input and output data of models. The data exchange is facilitated by the use of a common data format initially developed by the IAMC and a template (i.e., list of variables and regions) adopted from previous model comparison projects. In this report, we highlight the main features of the case examples and of the case example building process, with a particular focus on the model linking and the openENTRANCE variable template. We also report on the definitions of regions and variables in the IAMC/openENTRANCE template.

1. Introduction

The openENTRANCE project develops, uses and disseminates an open, transparent and integrated modeling platform for assessing low-carbon transition pathways of the European energy and transport system. The fully open platform is populated with a suite of modeling tools and datasets selected to cover the multiple dimensions of this transition process.[1] This shall facilitate and improve the dialogue between researchers, policy makers and industry when investigating key questions linked to this transition in the next decades, notably as far as the European energy and transport system is concerned.

This deliverable was developed in Task 5.3 which is part of WP5 ("A suite of modeling tools"). WP5 oversees the collection of numerical models used to build a consistent perspective of the energy system in the openENTRANCE model suite. Task 5.3 contributes to WP5's objective to ensure the coordination of the different models and research teams involved. More concretely, Task 5.3 contributed to ensuring the functional characterization of models and model linkages, as well as to showing and providing proof of the coordinated use of the models. To this end, reduced case studies, so-called "case examples" were developed and tested.

The openENTRANCE project includes nine case studies that investigate in detail some of the main challenges of the low-carbon energy transition for Europe. In these case studies, one or several models of the modeling suite are used and, thereby, provide proof of their functioning, either stand-alone or linked to other models. Indeed, several of the case studies in the project include linking of two or more models. Linking models with different foci allows to conduct analyses that combine the detailed perspectives of several fields, for example of different sectors such as electricity and heat. Moreover, this allows to improve consistency of single-model results which often take simplifying assumptions on related sectors or fields. Hence, model-linking has become state-of-the-art in European energy sector analyses.

For consistent results and an efficient linking process, a coordinated data exchange between models can be helpful. This data exchange was developed in the openENTRANCE project and described in a first step in Deliverable D5.2 "Definition of the interface between the models in the suite and the Common Database" (Crespo Del Granado et al., 2020). This report identifies and describes which data shall be exchanged between the models for a well-working model-linking, concretely for the models in the openENTRANCE model suite. Exchanging data requires a very

[1] https://openentrance.eu/modelling-tools/

accurate definition of each variable in the data. For this, a variable template was developed, which is described in this document.

The Open Platform also includes a Scenario Explorer, that is a database for storing, exchanging and making data searchable (also see openENTRANCE Deliverable 5.2 Crespo Del Granado et al., 2020). The objective of the openENTRANCE Scenario Explorer and the underlying database is to facilitate exchange of input assumptions and outputs between models as well as to support transparency and openness of scenario and case study results. The openENTRANCE Scenario Explorer can be accessed online at https://data.ene.iiasa.ac.at/openENTRANCE. It is open to any modeling team, including non-consortium members, to publish their data.

Data are up- and downloaded to the openENTRANCE Scenario Explorer using a common data format, derived from the Integrated Assessment Modelling Consortium (IAMC) data format, which has already been used for many years in several different modelling comparisons. The IAMC data format is the standard used to compile the data and/or results of numerical energy and climate models, for example in the scenario ensembles supporting the quantitative assessment in IPCC reports (IPCC AR6 WG3, 2022). The data format is described in openENTRANCE Deliverable 4.2 (Krey et al., 2019). This data format requires that all 'values' are associated to a model, a scenario, a region, a variable name, a unit, and a date. The openEntrance template mainly describes the list of regions and variables of the data which can be uploaded to the platform. An automatic validation process prevents users from uploading data which do not follow the format or list of allowed variables or regions, thus preventing errors in model runs and analyses, and ensuring that each data really is what the user thinks it is. The variable template and additional utility methods for scenario processing are available on Github (https://github.com/openENTRANCE/openentrance) under the open-source APACHE 2.0 license.

In addition to the list of variables used in the openENTRANCE project, an open-source Python package called "*nomenclature*" was developed to facilitate the validation of scenarios against the variable template and list of regions used in a particular project. The package also supports automated processing and aggregation of regions. The documentation on this package is available at https://nomenclature-iamc.readthedocs.io, and the package is available on GitHub (https://github.com/iamconsortium/nomenclature) under the open-source APACHE 2.0 license. This package now forms the backbone of the scenario processing infrastructure when submitting data to any Scenario Explorer instance hosted by IIASA, including the openENTRANCE Scenario Explorer.

2. The case study examples

For each of the nine case studies in openENTRANCE, a simplified case, named 'Case Example' was defined in order to check and validate the methodology of the case studies, and the workflows, especially for case studies using several linked models. We recall here that the models were implemented independently from openENTRANCE, in different not linked projects by different teams, and this is the first time some of the models are linked together (i.e., one model uses outputs of another model). As all case studies also use the openENTRANCE scenarios (from WP3), and the process of creating the quantitative scenarios and developing the case studies was done in parallel, it was also useful to demonstrate the case studies' workflows using incomplete, or artificial data, or data from the first scenario releases, so as to be ready to put the models to work together once the final quantitative scenarios were delivered. In this section, we describe the case studies, and the case study examples which were run.

Table 1. Overview of openENTRANCE case studies

Case study	Number of models included	Models in the case study
1) Demand response - behaviour of individuals	2	EMPIRE, plan4eu, Econometric database
2) Behaviour of communities of actors	1	FRESH:COM
3) Need for flexibility – storage	3	openTEPES, EMPS-W, GUSTO
4) Need for flexibility- sector coupling	2	SCOPE, plan4eu
5) Decentralisation	1	plan4eu
6) Innovative technologies	1	INTEGRATE (former eTransport)
7) Integration of electricity and heating sector	2	Frigg, plan4eu
8) The role of natural gas storage for flexibility	1	GENeSYS-MOD Turkey
9) Barriers to investment (WP7)	3	REMES, EMPIRE, GENeSYS-Mod

Description of case studies and case examples

The case studies in the openENTRANCE project are very distinct (see Table 1). Each of them was chosen so as to highlight and deep-dive into a specific aspect of the energy transition. The case study choice was topic-driven; the models were chosen among the project's model suite so as to optimally put them into practice. In practice, this meant that the models as well as the model linkages (if several models have worked together on one case study) first needed to be adapted to the case study. This was done during the case example work. Below is a brief overview of the case studies and their case examples. A more in-depth description of the case studies and their final results will be available in Deliverable 6.2.

Case study 1 "Demand response – behaviour of individuals" focuses on the electricity demand response potential by households. Statistical (empirical) data collected by Energieinstitut Linz was used to identify the household flexibility potential, distinguishing several appliance types (Electric Vehicles, Air Conditioning, Dryers, Washing Machines, Dish Washers, Water Heaters, Refrigerators and Freezers, Storage Heater, Heat Pumps, Circulation Pumps) Using the electricity system models EMPIRE and plan4EU, the impact on the integrated European electricity system cost, operation and investment needs of these household demand flexibilities is analysed. For this, it is necessary to include in both models the different appliance including their load profiles and flexibility (in terms of load shifting) which are taken from the empirical data.

> *For the case example, only a subset of appliances was included, Moreover the geographic scale was reduced in some runs with country or regional aggregations.*

Case study 2 "Behaviour of communities of actors" studied the shared energy management in different types of local energy communities, taking into account the individual preferences of the actors involved. This case study only included one model, FRESH:COM by TU Wien. For the case study, new sample communities representing different settlement patterns needed to be identified and parameterized.

> *The case example focused on settlements in Austria and model-runs with the new sample communities were performed. This prepared for the full-scale case study in which all different settlement patterns were modeled and investigated for all other European reference countries before generalizing for the EU level.*

Case study 3 "Need for flexibility – Storage" analysed the optimal trade-off between the deployment of new pumped-hydro generation (i.e., centralized electricity storage) on the one side and local energy communities (i.e, decentralized storage like small batteries) on the other side, as well as their effect on the development of the transmission grid. Storage and/or grid can provide the flexibility required to integrate variabe renewable generation in the electricity system. This case study was specially complex since it involved the use of three models, including two large-scale models of the EU electricity system (openTEPES and EMPS-W) and one local model representing local energy communities (GUSTO). Each model has different comparative advantages as well as technological and regional foci, such as a more disaggregated modeling of their respective home country (Spain, Norway, Austria) and the more detailed representation of the operation of hydro generation in EMPS-W vs. that of electricity transmission by openTEPES. This case study considers a detailed modeling of the Norwegian and Spanish electricity systems, including the deployment of local energy communities within both systems, and focuses on these two systems and the interactions between them and the neighboring ones.

Within the case example, the coupling of models was implemented considering as input some preliminary results computed for the Techno Friendly scenario. Besides, the results computed were preliminary. The full convergence of te results produced by the several models was not achieved.

Case study 4 "Cross-sector flexibility" focuses on the flexibility potential of sector coupling. It involves two very detailed EU-wide models, plan4EU (by EDF) and SCOPE (by Fraunhofer IEE). While plan4EU has a focus on the electricity sector, SCOPE includes other related sectors and their energy consumption, notably transport and heat. With this, the flexibility potential of sector coupling calculated by SCOPE can be further verified for its electro-technical feasibility by the plan4EU model.

In the case example, the flexibilities provided by electric vehicle owners in Germany and France to the EU electricity system in 2050 were investigated. In the case example, the linkage of SCOPE-SC and plan4EU was focused on the country level, and was performed with a first estimate of the flexibility potentials.

Case study 5 "Decentralisation" aims at comparing different levels of geographic coordination for investment decisions, both at regional and European level, focusing on the topic of decentralisation. A variant of the model plan4EU is used in this case study. This variant includes investment decisions in generation capacities.

For the case example, validation tests of the model linked to the GENeSYS-MOD data scenarios were performed considering aggregated regions within Europe.

Case study 6 "Innovative technologies – heat storage" is a single-model case study in which the model INTEGRATE (formerly eTransport) is used. In contrast to the other case studies, which have an EU-wide scope, this case study focuses on the application of the innovative technology underground rock heat storage for one case study region, namely the district Furuset in Oslo, Norway. The case study investigates how seasonal storage of heat may reduce the surplus in district heating production in the summer, while helping to supply peak demand in the winter. Such storage could potentially reduce the need for investment in additional (peak) heating capacities.

There was no proper case example (i.e. a prior zoom-in in the case study) because the regional case study scope was limited.

Case study 7 "Integration of electricity and heat" focuses on the flexibility potential of the integrated operation of district heating and electricity supply. It involves the newly developed model Frigg (by DTU) which is linked with the plan4EU model (by EDF). Frigg is a generic soft-linking framework to integrate demand flexibility in energy system models, while plan4EU is a very detailed electricity dispatch model for the EU. The regional scope of the case study is Denmark for which the flexibility potential of the integrated operation of district heating and electricity supply in 2050 is analysed.

For the case example, some of the complicating features of heat provision were ignored (e.g. heat storage, cooling) and a focus was put on operationalizing the link between the two models.

Case study 8 "Gas storage" investigates the role of natural gas storage in current and future energy systems in transitions. Today, natural gas-fired electricity generation provides flexibility in many European electricity systems. Inter-seasonal underground natural gas storage can further strengthen the availability of natural gas in the winter months and gas-fired power generation can contribute to shaving off the winter demand peaks. However, in the medium to long-run, the climate neutrality target will lead to a phase-out of fossil natural gas use. Some types of natural gas storage can be converted to be used by hydrogen, which is a different gaseous molecule that is expected to play a large role in the energy transition (salt caverns). This case study focuses on the EU accession country Turkey where the use of natural gas increased strongly in the last years and natural gas storage is currently being expanded, starting from a very low storage capacity level. In this case study, the Turkey variant of the GENeSYS-Mod model is put into practice (GENeSYS-MOD-Turkey).

For the case example, some new model features related to natural gas transport and storage, and hydrogen use and storage (e.g., blending) were incorporated in the model and validated

Case study 9 "Barriers to investments" aims at analysing the macro-economic impacts of different policies to foster the integration of renewables, including the role of subsidies, taxes and regulatory barriers. The CGE (Computable General Equlibrium) model REMES (by NTNU) is at the core of this case study. Two parallel model linking processes take place in this case study: i) linking to the energy system model GENeSYS-Mod, used in the case example; ii) linking to the electricity sector model EMPIRE for the full-fledged case study.

In the case example, the link between REMES and GENeSYS-Mod was implemented. Convergence between the model results was primarily seeked for the energy mix and the activity level of the economic sectors.

Linking to the openENTRANCE platform and model linking

All the case studies provide their final results on the openENTRANCE platform and use the platform for performing data exchanges between models, as described in Deliverable D5.2 (Crespo Del Granado et al., 2021). The openENTRANCE Scenario Explorer has been available to the consortium since April 2021. The variable template has been in continuous development over the course of the project.

Five of the nine case studies include several models that are being linked (Table 1). Two of these five include three models; however, only one of them includes linking of three models with each other (CS 3).[2] All the model links are newly developed within the framework of this project. Model linking in the openENTRANCE project is carried out as so-called soft-linking, where each model retains its full own characteristics, and data (usually results) are exchanged between the models. Linking models often requires the implementation of data conversion tools in order to feed the models in their natural data format. Soft-linking enables combining the sectoral expertise of each particular model and the in-depth representation of several sectors. This is opposed to hard-linking, or integration of models, where some or all the model features are integrated into one same model (Wene, 1996; Helgesen et al., 2017).

[2] CS 9 is the other case study with three models, but here one model (REMES) is linked with one other model in two different processes (with EMPIRE for the fully-fledged case study, with GENeSYS-MOD for the case example). The two energy models (EMPIRE; GENeSYS-MOD) are not linked with each other.

3. The openENTRANCE variable template and the nomenclature package

The openEntrance template is a shared list of variables, regions and units used across the entire project. The development of this common understanding of definitions has been conducted in an open, transparent and collaborative manner on GitHub (https://github.com/openENTRANCE/openentrance). This repository is released under an open-source license so that the wider community can engage and benefit from this work. This repository makes available the variable template used within the consortium and serves as a discussion platform for extending the lists of terms and their definitions. To facilitate the adoption of the common understanding across modelling teams, several Python utility tools are also available in the GitHub repository.

Following best-practice of (scientific) software development, after an initial phase of prototype development, the project-specific variable template (i.e., the list of variables, units and regions including their definitions) was cleanly separated from the Python package for validation of scenario data against the template. This Python package is now available on GitHub (https://github.com/iamconsortium/nomenclature) under the open-source APACHE 2.0 license, and the documentation including extensive user guides is hosted on ReadTheDocs (https://nomenclature-iamc.readthedocs.io/). The openENTRANCE variable template has recently been adopted and extended by the Horizon 2020 project "European Climate and Energy Modeling Forum (ECEMF, https://www.ecemf.eu).

The openENTRANCE repository on GitHub is comprised of

- A structured list of yam files describing all variables and regions. The file format was chosen so as to facilitate a good trade-off between readability of the variable template by humans and easy processability in automated scripts. Being completely text-based (compared to, e.g., xlsx files), the yaml files can be easily version-controlled on GitHub.
- An installable python package "*openentrance*", which includes several utility functions for scenario processing based on the code lists and region mappings.

In the following, we give more detail of the data formats chosen by the openENTRANCE project.

Definition of regions

The list of regions is grouped into several levels of spatial detail. The definitions of regions chosen for this project are guided by energy modelling conventions and pragmatism rather than political considerations.

Aggregate regions

This list covers groupings of several countries, like 'World', various definitions of Europe and the EU, and other groupings of several countries (e.g., EFTA).

Countries

Each country in this list is included with its ISO2 and ISO3 codes as attributes as well as a flag on EU membership and (optional) a list of synonyms. The list also includes the alternatives to the ISO 3166 as used by the European Commission for the United Kingdom and Greece.

The nomenclature python package allows for easy access to the list of countries, as well as for mapping between natural names and iso codes from a Python computing environment.

Sub-country areas following the 'Nomenclature of Territorial Units for Statistics' (NUTS)

One set of disaggregation of countries follows the NUTS 2021 classification[3] used by Eurostat:

- Major socio-economic regions: NUTS 1
- Basic regions for the application of regional policies: NUTS 2
- Small regions for specific diagnoses: NUTS 3

Each file includes the mapping of the NUTS-x code to the country name and the "parent" region(s) for NUTS 2 and NUTS 3 areas. The script to generate the codelist is available in the data folder in the openENTRANCE github repository.

The "*openentrance*" python package includes a recursive dictionary along the NUTS classification, i.e., easy access to the full hierarchy between countries, NUTS 1, NUTS 2 and NUTS 3 regions. The package also includes a `regions` dictionary with the names of all NUTS areas.

Other sub-national area classification

Other sub-national disaggregations can be defined, ideally described as (dis-) aggregations of NUTS 1, NUTS 2 or NUTS 3 regions.

[3] See the EU website for more details on the current NUTS classification: https://ec.europa.eu/eurostat/web/nuts/background

Among the sub-national regions included in the list of regions are in particular the *ehighway2050* clusters. *e-highway2050* was an EU-funded project (2012-2015), whose objective was to provide a modular and robust expansion plan for the Pan-European electricity transmission network from 2020 to 2050. It defined a model with regional clusters in the Pan-European transmission grid.[4] The cluster model is included in the definitions.

Other regions

Other classifications are also available or can be defined at later stages.

Directional data

Moreover, to represent data that refers to a flow or capacity between regions, any two regions' names can be combined using a ">" character (without spaces before/after that character). Bi-directional data must be declared separately for each direction using only the ">" character. No other characters (such as <>, =) are allowed to represent directional data.

The correct spelling is, for example: Norway>Germany, Germany>Norway

Definition of variables

The repository lists all the variable names which are included in the openENTRANCE template. Following the conventions established by the IAMC, the variables are described within a "semi-hierarchical" structure using the "|" character to indicate the *depth*. Semi-hierarchical means that a hierarchy can be imposed; however, this is not mandatory.

This repository contains a set of subfolders for classifying different kinds of variables and a series of files named "tag_*.yaml" which lists sets that are used to complement variable names : Variables are usually constructed with a top-level category/indicator (e.g, Primary Energy, Capacity) followed by a number of categories and specification (e.g., <Fuels>, <Sectors>). See the following examples:

- Tag_fuel_types: Fossil, Coal, Oil, Gas, Nuclear, Hydro, Solar, PV, Biomass,....
- Specifications: Offshore, Onshore, w/ CCS, w/o CCS, ...

Naming conventions are used for all variable names:

- A "|" (pipe) character indicates levels of hierarchy
- No spaces before and after the "|" character,
- Words separated by spaces (e.g., Primary Energy|Non-Biomass Renewables)
- All words are capitalised (except for "and", "w/", "w/o", etc.)

[4] Also see https://docs.entsoe.eu/baltic-conf/bites/www.e-highway2050.eu/e-highway2050/

- Abreviations are avoided (e.g, “PHEV”) unless strictly necessary
- Hierarchy levels are used where it might be useful
- No abbreviations of statistical operations are used (“min”, “max”, “avg”), words are fully spelled out
- Words like “Level” or “Quantity” should not be used as this should be clear from the context

The following sections provide an overview of the top-level categories or indicators of the variable dimension.

Energy

This category includes three top-level indicators related to the energy supply chain (also called reference energy system):

- **Primary Energy**: This group includes extraction of fossil resources and production/generation of energy/fuels from renewables.
- **Secondary Energy**: This group includes any fuel or energy carrier resulting from an intermediate conversion process (e.g., electricity generation, gasoline).
- **Final Energy**: This group includes any fuel or energy carrier at the point of consumption. The sub-categories of this group can be separated into a by-source (eg type of fuel), a by-sector dimension (sector= users, e.g., industry, commercial, residential) and a dimension by-uses (uses=transportation, heating, industrial process, etc.). Variables can be, for example, Final Energy|{Fuel}|{Specification}.

Technology

- **Technologies:** This file defines variables and indicators related to characteristics and specifications of (energy) technologies including power plants, transmission lines and pipelines. It includes in particular Installed Capacity, Capital Cost (i.e., cost of capital per installed MW) and Investment Expenditure.
- **Power-plant**: This file describes the characteristics of the different assets of an electricity system. It includes in particular fixed and variable costs, start-up and shut-down costs, maximum and minimum active power of a given asset of a given technology, ramping constraints, possible ancillary services provisions, maximum and minimum storage in case of an asset with storage, etc.
- **Electricity-grid:** This file contains variables referring to the description of an electricity grid, in particular length and capacity of interconnections, ancillary service requirements of a region, maximum/minimum flows of an interconnection, etc.
- **Electricity-operation:** This file contains variables that are usually results of a unit commitment model. It includes in particular variables describing the committed power per

technology, the commited ancillary services, the volumes of storages or the marginal costs per regions.
- **Electricity-expansion:** This file contains variables used to describe the results of an electricity capacity expansion model. In particular it includes commissioned / decommissioned capacities for power-plants, storages and interconnections.

Emissions

This section defines variables and indicators related to emissions, carbon sequestration and the impact of emissions on the climate (i.e., temperature). It includes in particular variables related to the emissions, as well as to the carbon sequestration, which can be classified into several subcategories:

- Carbon Capture & Storage/Sequestration (CCS): carbon dioxide captured at the point of emission (energy sector & industrial processes)
- Land Use: carbon dioxide sequestered through land-based sinks
- Other methods: Direct Air Capture, Enhanced Weathering

Economy

This section defines variables and indicators related to the economy and societal drivers such as population, Discount Rate, GDP, Consumption, Price, Policy Cost.

Units

Each variable is linked to a unit (or a list of possible units). For unit conversion as part of the pre- or postprocessing in the model workflow, the Python package "*pyam*" provides an intuitive and low-level interface (see https://pyam-iamc.readthedocs.io/en/stable/tutorials/unit_conversion.html), see Huppmann et al (2021).

4. Lessons learnt from case examples, model linking and template use

The openENTRANCE project introduced an innovative sequencing of the process of developing and putting into practice new model links. This task made the step of testing new model links with small-scale problems („case examples") explicit. The task preceded the full-scale case study runs and included the following steps:

- Test models with simpler data and evaluate needs for adaptation
- Implement conversion/formatting tools where necessary
- Fine tune list of necessary variables and extend openENTRANCE variable list if needed
- Validate workflows
- Test data exchanges between models and with the IIASA platform

The modeling teams have found this explicit task useful for several reasons. First, time and resources could be committed to the testing of new model links and case examples. This dedicated time period allowed for parallel work on both the ‚input' data and the test of the case studies' workflows with ‚simplified' data. Second, the regular monitoring was useful to effectively advance and regularly make progress. Third, the regular and open meetings allowed for regular interaction between the modeling teams. This included critical review by colleagues that were not part of the case study. Fourth, the modeling teams mutually benefitted from the data discussions during the meetings. In sum, the openENTRANCE project established a new good practice in case study management with this process.

Most case studies identified some need for adaptation during the case example phase. All these challenges have subsequently been tackled by the project team. These adaptation needs had different characteristics: i) model adaptation needs, in particular data adaptation (harmonization) needs in those case studies where several models are linked; ii) re-formulation of data input and, especially, data output in the openENTRANCE variable template; iii) the openENTRANCE platform needed to be adapted to very large databases (e.g. model output with high temporal and geographical resolution). iv) The variable template was refined and augmented based on the input by the modeling teams during their case example runs.

The case examples provided feedback to the core elements of the platform, in particular to augmenting the variable template. It is very difficult to accurately define the list of variables which will be exchanged by models before having done any trial runs. Thus, the process of working with the case examples and in parallel extending the variable template by adding new variables (or removing useless or inconsistently defined variables) proved very efficient, and should be included in the normal process of running a case study with the openENTRANCE platform.

In preparation for the submission to the openENTRANCE Scenario Explorer, all modelling teams had modified their relevant input and output data format and/or implemented conversion scripts to conform to the openENTRANCE variable template already during Task 5.2 (see Deliverable 5.2 Crespo Del Granado et al., 2020). Models may either use the openENTRANCE data format directly for their input and/or output, or use some *ex post* conversion of their data. There are several reasons for using *ex post* data conversion. First, the openENTRANCE project team was still in the process of updating the openENTRANCE variable template. While the case example process constantly informed the discussions and updates to the list of variables, it was not found necessary to upload intermediate data from test runs with preliminary openENTRANCE scenario data. Second, some models already have had input or output interfaces with something else than the openENTRANCE platform (e.g., graphic interfaces, other data sources), so the native input or output format had to be kept to keep the model running. Third, for some models it was far easier to implement *ex post* conversion to the IAMC format than change their model's input/output format.

Several case studies include two or more models that are linked. In this project, we use soft-linking of models for several reasons. First, (nearly) all models can be soft-linked and the sector-specific expertise of the model is kept. Second, keeping the original models in place allows to use model-specific tools such as visualisation (e.g., of results) without the need for re implementing them. Third, models usually have multiple users who may have already defined processes with some former data formats. Soft-linking allows to keep the data format and avoids creating different versions of the model which would prevent efficient maintenance and extensions of this model. For this reason, in the openENTRANCE project, we allowed model teams to chose between changing their data format and implementing conversion scripts and keeping their native data format. The openENTRANCE data format is easily understandable and readable, and it is based on the IAMC format which is widely used. However, the efficiency of the data formats depends on the context and some model teams may chose a format which is less „shareable" but more efficient in terms of speed, data base size or other.

In sum, the following conclusions can be drawn from the case example process. The progress in the case studies depended on a number of factors. First, the status of the model(s) at the moment of starting the case example (in development, heavy need of adaptation, complete database available yet) plays a crucial role in determining how quickly the case study flow could be carried out. The least developed models needed more time to advance on their model and data development and did not all fully work on a case example. Second, the level of complexity of the interaction within the case study played an important role in determing how fast a case study could advance. We confirm earlier experience that showed that when more models are involved, a case study becomes more ambitious and the progress slows done because of the larger mutual need of adaptation.

Lastly, the experience during the case examples confirmed the advantages of case studies with model linking that were anticipated. Multi-level case studies combine cross-sectoral expertise with an in-depth representation of several sectors. Modeling teams mutually improve their data and mutually check and proof their model's results in a case study. In sum, both the case studies as well as the case example process have proved useful to progress in the openENTRANCE project.

5. References

H. Auer, K. Löffler, K. Hainsch, T. Burandt, I. Graabak, S. Schmidt, A. Yucekaya, E. Celebi, G. Kirkil, S. Zwickl-Bernhard (2022): *Quantitative Scenarios for Low Carbon Futures of the European Energy System on Country, Region and Local Level.* openENTRANCE project, Deliverable 3.2. Available online at https://openentrance.eu/2022/07/06/quantitative-scenarios-for-low-carbon-futures-of-the-european-energy-system-oncountry-region-and-local-level/

P. Crespo Del Granado, G. Resch, F. Holz, M. Welisch, J. Geipel, M. Hartner, S. Forthuber, F. Sensfuss, L. Olmos, C. Bernath, S. Lumbreras, L. Kranzl, A. Müller, S. Heitel, A. Herbst, C. Wilson, A. Ramos (2020): Energy Transition Pathways to a Low-carbon Europe in 2050: the Degree of Cooperation and the Level of Decentralization. *Economics of Energy and Environmental Policy*, Vol. 9 (1), pp. 121-135.

P. Crespo Del Granado et al. (2020): Definition of the interface between the models in the suite and the Common Database. openENTRANCE project, Deliverable 5.2. Available online at https://openentrance.eu/2020/08/15/model-interface-common-database/

P.I. Helgesen, A. Lind, O. Ivanova, A. Tomasgard (2018): Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport. *Energy*, Vol. 156, pp. 196-212.

F. Holz, T. Scherwath, P. Crespo del Granado, C. Skar, L. Olmos, Q. Ploussard, A. Ramos, A. Herbst (2021): A 2050 perspective on the role for Carbon Capture and Storage in the European power system and industry sector. *Energy Economics*, Vol. 104, pp. 105631.

D. Huppmann, M.J. Gidden, Z. Nicholls, J. Hörsch, R. Lamboll, P.N. Kishimoto, T. Burandt, O. Fricko, E. Byers, J. Kikstra, M. Brinkerink, M. Budzinski, F. Maczek, S. Zwickl-Bernhard, L. Welder, E.F. Alvarez Quispe, C.J. Smith (2021): pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios [version 2; peer review: 3 approved]. *Open Research Europe*, Vol. 1, pp. 74 (https://doi.org/10.12688/openreseurope.13633.2)

IPCC (2022): *Climate Change 2022: Mitigation of Climate Change*. 6th Assessment Report. Intergovernmental Panel on Climate Change, Working Group III. Available online at https://www.ipcc.ch/report/ar6/wg3/

V. Krey, D. Huppmann, S. Charousset, L. Olmos Camacho, J. Cohen, A. Ramos Galán, P. Pisciella, H. Boonman, T. Perger, P. Haertel, I. Graabak (2019): Data exchange format and template. openENTRANCE project deliverable 4.2. Available online at https://openentrance.eu/2019/10/31/data-exchange-format-template/

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