Synergistic Approach of Multi-Energy Models for an European Optimal Energy System Management Tool

Deliverable D4.5

Public Dataset and document 'how this dataset was built'

Deliverable No.	D4.5	Work Package No.	WP4	Task/s No.	Task 4.1/4.2/4.4/4.5
Work Package Title	Providing Data Sets				
Linked Task/s Title	TASK 4.1 Data Identification TASK 4.2 Data Acquisition TASK 4.4 Scenario Generation TASK 4.5 Data Transformation and Construction				

Status	FINAL	(Draft/Draft Final/Final)	
Dissemination level	PU	(PU-Public, CO-Confidential)	
Due date deliverable	2020-04-30	Submission date	2020-04-30
Deliverable version	D4.5-Public-Dataset-V4.2		

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History of Changes

Release	Date	Reason for Change	Status
1	14.02.2020	Setup of document template	Draft
2	01.04.2020	New structure	Draft
3	17.04.2020	Intermediate structure	Draft
4	26.04.2020	Complete version	Draft
4.2	30.04.2020	Formal corrections	Final

DISCLAIMER / ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773897

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List of acronyms used in this document

aFFR	automatic Frequency Regulation Reserve
C3S	Copernicus Climate Change Service
CCS	Carbon capture and storage
CCGT	Combined Cycle gas Turbine
CDS	Climate Data Store
COP21	21th United Nation's climate change conference, Paris 30.11 – 12.12.2015
COP	Coefficient of performance (e.g. of heat pumps)
CSP	Concentration Solar Plant
CTS	Commercial, Trade Service (sector)
CS	Case Study
CSV	Comma Separated Values
CWE	Central Western Europe
EEX	European Energy Exchange
eH2050	e-Highway2050 European project (data source)
ENTSO-E	Coordination and cooperation of the TSOs (Electric Transmission Grid)
ENTSO-G	Coordination and cooperation of the national gas transmission system operators (TSOs) across Europe (Gas Transport Network)
ETS	The EU emissions trading system
EU	European Union
EU REF 16	EU Reference Scenario 2016
EUC	European Unit Commitment Model
FCR	Frequency Containment Reserve
HRE4	Heat Road Map 4 Project
MIM	Multimodal Investment Model (used in plan4res case study 1)
OCGT	Open Cycle Gas Turbine

RoR	Run of River
PSP	Pumped Storage Plant
PV	PhotoVoltaic
RES	Renewable Energy Source
SSV	Seasonal Storage Valuation
TYNDP	Ten-Year Network Development Plan
UTC	Coordinated Universal Time
WEMC	World Energy Meteorology council
WP	Work Package

Glossary of terms used in this document

- Sector coupling

Sector coupling means that the energy system is composed of coupled energy carriers such as gas and energy vectors such as electricity and heating. The consequence of the sector coupling is multi-modality of energy systems.

- Multi-modality (Definition transferred from communication to energy systems):

A multi-modal system processes input and delivers output in several modalities. In an energy system this means the (parallel) use of different energy modes resp. carriers usable to serve the same purpose, such as electricity and heating etc..

Example from transportation: In principle it is easy for many town dwellers to make use of multimodal transport, or in other words to make each journey with the most suitable transportation method - bus, rail or individual transport by car or bike.

Executive Summary

The general objective of plan4res is to fill the gaps between the increasing complexity of the future energy system planning and operational problems and the currently available system analysis tools. Enhanced end-to-end planning and operational tools dealing with technological and market uncertainty, emerging technologies and increased sector coupling of multi-energy vectors such as heat, cold and transport will be assembled in a synergistic approach to support European system planners, operators, decision makers, regulators. The framework is divided into investment models, operation simulation models and analysis models. Having separate models allows using the most promising techniques regarding mathematical formulation and solving methods for each specific model, thus increasing the computational efficiency.

The plan4res models will be hosted on an IT platform which will provide seamless access to data and high-performance computing resources, catering for flexible models and workflows.

Therefore, a database of public data will be constructed, and three exemplary case studies will be performed to highlight the tool's adequacy and relevance.

The objective of WP4 is to provide the needed input data to the Plan4Res tool. Datasets will be needed for the following uses: (i) perform the case studies defined in WP2; and (ii) provide a public data set within the format of the Plan4Res tool.

The present deliverable describes the public repository used to store public data as well as the data format, the transformations used in each case study, and the full process we applied to obtain the public data from the raw data.

1 Introduction

This Deliverable starts by presenting the plan4res framework (Chapter 2) which consists of three types of models: investment models, operation simulation models and analysis models. The separation between models allows to increase the computational efficiency of the solution methods that are applied to each specific model. Then, the next Chapter 3, describes the public repository and the public data stored in it, for each of the models developed in the three case studies. Finally Chapter 4, reports on the data sources used, and gives details on the overall process that we implemented to obtain the public datasets.

2 The models

In order to obtain a holistic assessment of the energy system, all relevant aspects have to be taken into account, e.g. investment & operation, grid & market, central & distributed, sector coupling. Since the modelling of these requires customized approaches, the concept of the H2020 plan4res project is to develop a framework separating individual components of the energy system into individual model blocks.

The framework is divided into investment models, operation simulation models and analysis models. The goal of investment models is to determine the optimal investment decisions for the future energy system. Different investment models are defined that are tailored towards the needs of different potential users. The core of the operation simulation model is the European Unit Commitment Model, which optimizes the operation of all assets (generation, storage, …). A Lagrangian relaxation approach enables to decouple assets and define sub-models. This modular approach also allows to only take the sub-models into consideration that are important for the respective user. Supplemental models are needed to either build or transform input data or to perform ex-post analysis e.g. transmission/gas grid calculations.

Having separate models allows using the most promising techniques regarding mathematical formulation and solving methods for each specific model, thus increasing the computational efficiency.

Figure 1 gives an overview of the plan4res model framework build within plan4res. Further details and a complete description of each model can be found in plan4res deliverable D3.1.

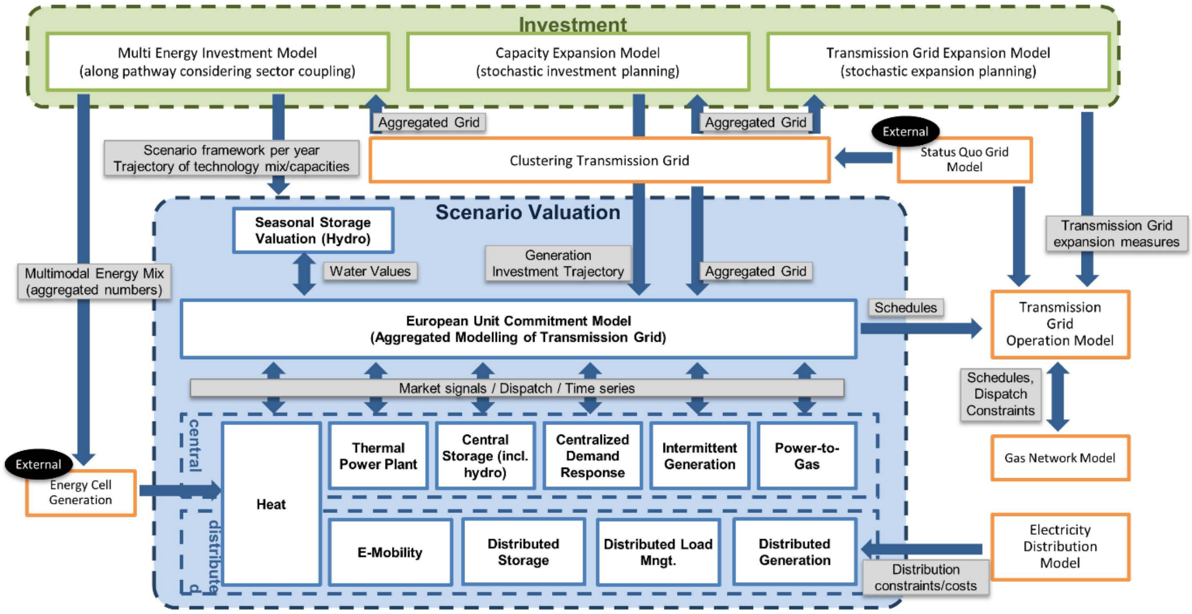


Figure 1: the plan4res model framework

Figure 2 describes a potential workflow that could be designed with the plan4res models:

- First the MultiModal Investment model (MIM) is run and produces a pathway from 2020 to 2050 for the energy system. The output is mainly composed of:
  - Installed capacity per technology/region/year (e.g. the installed capacity of PV in GWh per year and country);
  - Demand per energy/use/region/year (e.g. the electricity demand for heating in GWh per year and per country).

Then two different workflows can be branched:

Branch 1:

- Based on the results of the MIM, a disaggregation of electric and thermal generation units is done. Within a European market simulation, the optimal operation of the energy system is determined for one specific year. The resulting operation schedules are further analysed by means of a detailed European electricity grid model to study the impact of future energy systems on the electricity grid. D4.5 Public Dataset and document “how this dataset was built’ Deliverable D4.5 Public Dataset and document 'how this dataset was built' 17 / 140

- Within the multi-modal investment modelling (MIM) a cross-sectoral pathways analysis for 2020 to 2050 is done for a coupled pan-European energy system. Technology mix and investment decisions are optimized for the sectors electricity, heating & cooling, and mobility, while considering all energy vectors relevant for these sectors and demands from central (e.g. industry, CTS) and decentral (e.g. residential) prosumers.
- Gas Grid model is used to analyse whether the results from the cost-optimal operation and the projected technology mix from the MIM are feasible subject to the existing gas network infrastructure and amount of supplied gas from main gas sources of Europe such as Russia and Norway.

Branch2:

- A transmission planning model (TPM) takes the outputs of the MIM and adapts the transmission grid for the period 2020-2050. Its outputs are the exchange capacities between regions per year.
- The outputs of the MIM and of the transmission planning are used as inputs by the Seasonal Storage Valuation (SSV) and European Unit Commitment Model (EUC) which focus on the electricity system in the year 2050, with more detail (including representation of assets and accounting for uncertainties). These models will assess the feasibility and cost of the scenario built by MIM/TPM.
- Finally the Electricity Grid Model can be ran on the outputs of the EUC to evaluate the feasibility from the point of view of the electricity grid operation

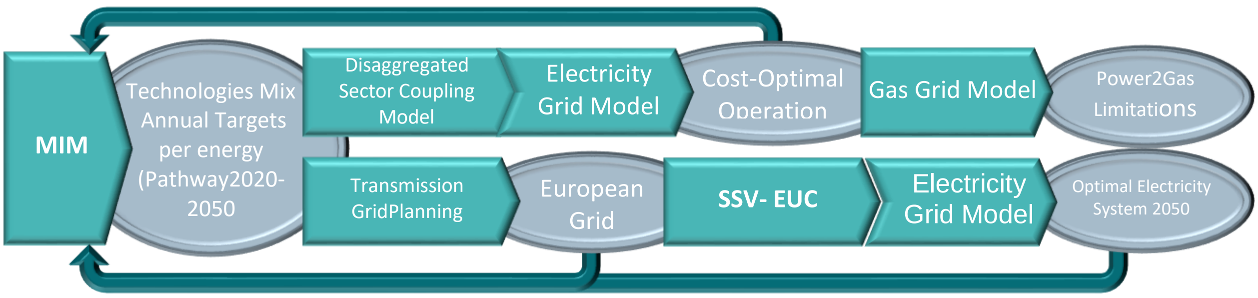


Figure 2: plan4res Models Workflow

2.1 Multimodal Investment Model

The multi-modal investment model (MIM) is used to determine optimal investment decisions along the pathway from today to a chosen horizon of interest. Along the pathway in equal intervals, for each interval the annual early retirements, new capacity and infrastructure installations, and the hourly generation/load schedules are simulated for each implemented technology. Additional results are marginal price levels and the carbon footprint for every modelled energy carrier (commodity) and an estimated tonnage for annual CO_2 emissions. A graphical overview is given in figure 3.

The technological scope includes all energy-related generation and demands, relevant for the electricity, mobility, heating and cooling sectors, and covering innovative technologies like power-to-gas, too. Additionally, energy-relevant demands – and where applicable generation – from the consumer clusters industry, commercial/trade/service (CTS) and residential are considered. For modelling these are sub-clustered in 'central' prosumers (e.g. industry & large CTS) and 'decentral' prosumers (representing residential and distributed CTS).

A linear optimization model is used, comprising a set of conversion processes $cp \in CP$, which describe the implemented technologies by a generic "input-conversion-output" scheme in a simplified way and using a regionally resolved technology fleet approach. To enable modelling of somewhat more complex processes, a conversion process cp can comprise a set of sub-conversion processes cs reflecting all relevant energy modes involved. Necessary constraints (e.g. efficiency, energy conservations, power limitations, efficiency and temporal consistency of storage levels) are also formulated using these abstractions. The objective function considers minimization of total investment C^{capex} and operation C^{opex}:

$$min(C^{capex} + C^{opex}) \qquad (2\text{-}1)$$

For evaluating investment decisions, costs are aggregated over several simulated years $y \in Y$ and discounted to a net present value in today's terms. Operational costs comprise all variable costs of all conversion processes $cp \in CS$, years $y \in Y$ and countries $co \in CO$, including fuel, CO_2 emission and O&M costs which are linked to each conversion process. As side constraint the CO_2 emissions are minimized.

The investment and operation decisions for all time steps and all regions are determined in one single optimization run in order to achieve optimal intertemporal allocation. Several planning steps are considered (e.g. 5 years intervals) to optimize the system development until the target year of the planning horizon (e.g. 2050). In each of these planning steps the hourly operation for the entire year or representative weeks is considered including operational constraints of power plants and storages.

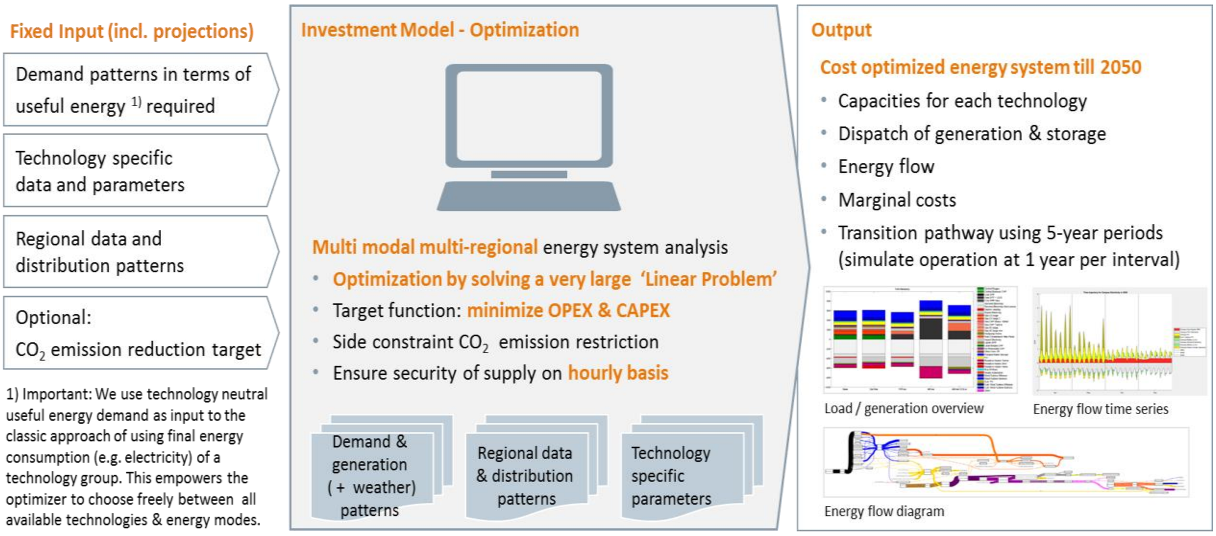


Figure 3: Overview of the multimodal energy investment model

2.2 European Market and electricity grid simulation

The European market simulation uses a sophisticated operation optimization to give a detailed view on the electricity-, heat- and electric mobility sectors, using a single year approach. The results of the MIM are therefore used for building the input data for this model. Besides the installed generation capacities for the year under investigation, the energy mix data are used as input. The concept of energy cells is used to enable a detailed modeling of distributed heating technologies. The use of detailed socio-economic data enables the construction of registers for households, commercial/trade/service (CTS) and industry within central western Europe (CWE; Austria, Belgium, France, Germany, Netherlands, Switzerland). These registers model buildings and businesses on a spatial level in these countries. For every single entry (e.g. a special household or a special business location) the registers include a predefined heat demand (warm water, space heating, process heating) with a hourly temporal resolution. Furthermore, the registers contain heat generation and storage technologies assigned to every single building/business based on the predefined energy-mix scenario generated by the MIM. The heat generation units might also have an interaction to the electricity sector (e.g. heat-pumps as additional electricity loads or combined heat and power (CHP) units as electricity generators), thus providing flexibility to the energy system. Within the process of building the input data these registers are aggregated to so called "energy cells". These energy cells define a regionally connected part of each country. Each energy cell contains a matrix of aggregated heat demands (as hourly timeseries) per occurring technology combination (e.g. CHP unit + gas boiler + heat storage unit) within this energy cell. Each heat demand profile is assigned an ID that clearly links this demand time series with the connected generation and storage units (e.g. generation units with ID 1,2,3 have to meet the heat demand with ID A).

For each generator within the energy cells a variety of information is provided, e.g. the heat-ID that links this unit to the heat demand profile it should supply, the power-to-heat ratio, the efficiency, the energy cell ID and more (see the powerplant database described in section 4.1). The hourly operation of those technologies has to meet the heat demand, while maximizing its profits on the electricity market and minimizing the generation costs for electricity and heat. Not only distributed generation technologies are supplying the heat demands, but also conventional power plants are used to generate heat and supply buildings by district heating or industrial companies by process heating. That means that also conventional power plants can have a corresponding heat demand ID, and thus are not solely optimized regarding the energy price.

2.3 Transmission expansion planning

The second Case Study (CS2) is " Strategic development of a pan-European network considering long-term uncertainties ".

The overall objective of this case study is the identification of the optimal investment decisions that a network planner needs to make over the course of many decades so as to achieve safe electric power system operation under the presence of various sources of uncertainty. The case study is conducted for the European electricity transmission system in a future world with high shares of renewable energy sources that are deployed in the system in an uncertain manner.

The associated input data will include the following.

- Investment costs associated with the deployment of electric energy storage (lithium) units at different areas of the grid;
- Investment costs associated with the upgrade of the thermal capacity of existing transmission interconnectors;
- Operational costs associated with the generation cost (i.e. fuel cost) of the thermal generation units as well as storage operation.

- The impact of sources of uncertainty.

In order to model the uncertainty, a scenario tree needs to be defined. This tree will consist of nodes distributed over a number of scenarios across a number of epochs. Each node will contain a particular value of the uncertain parameter (e.g. installed capacity of solar and wind generation, level of demand).

The case study models the electric power system operation over a long period of many decades and yields the optimal investment decisions. The results provide insight into how the presence of uncertainty at investment timescale affects the long-term investment strategy. Note that investments are triggered by the growth in demand and/or growth in the installed capacity of renewables, given the objective of investment and operational cost minimization.

Specifically, the focus is placed on electric energy storage as well as on network investments, when the deployment pattern of solar and wind installed capacity is uncertain and demand growth takes place under uncertainty as well. In this context, the contribution of electric energy storage is identified by studying the results of the case study in presence and in absence of this technology. Under the presence of uncertainty, this comparison will allow for the estimation of the option value of investing in electric energy storage. Note that option value of a smart technology is characterized as the net economic benefit that the specific technology brings to the system when uncertainty is taken into account.

Additionally, the case study allows for comprehending the impact of the uncertainty on the investment strategy. For this purpose, a deterministic model with perfect future foresight (i.e. no uncertainty) is solved and its results are compared and contrasted against those of a fully stochastic optimization model (i.e. with uncertainty sources included in the modelling). This comparison will lead to observations about how uncertainty may affect investment decisions.

The case study is particularly useful to stakeholders with interest in how investment decisions are affected by sources of uncertainty as well as by the availability of smart technologies.

Specifically, such stakeholders can include national and European regulatory authorities, transmission system operators (TSOs), electric energy storage investors, entities related to renewable energy development and deployment and distribution system operators (DSOs).

As mentioned, the electric power systems are expected to be radically impacted by the increasing share of variable and decentralised intermittent renewable energy sources as well as by the global effort towards greater levels of decarbonization. This global decarbonization effort undoubtedly shifts the focus of policy makers on how to ensure reliable and safe future power system operation by addressing the key challenges associated with future electric power system operation and investment.

In this context, obtaining the optimal investment solution constitutes a challenging task given the longterm study horizon, which for this case study covers the period 2020-2059. In this long timeframe it is important to accurately model the electric power system operation across all major aspects, such as power flow, generation – demand power balance, limits posed by the capacity of the transmission corridors etc., while also representing the different types of technologies in a realistic manner.

The key associated modelling challenge is therefore to achieve convergence of the model within a reasonable / acceptable amount of time. Doing so requires development of advanced decomposition methodologies for stochastic optimization.

The model will yield the following results:

- Optimal investment decisions in terms of timing (i.e. when the investments will take place), magnitude (i.e. how much investment will be made), location (i.e. which system areas will be equipped with a specific investment) and type. The latter can be of the following categories:
    - Electric energy storage;
    - Capacity upgrade/addition for electric power transmission corridors;
- Value of flexibility (option value) of investing in electric energy storage. This value is associated with the economic benefit that this smart technology brings to the system. This value is called ‘option value’ because investment in electric energy storage is an option which is exercised only when the total expected net benefit is greater than the associated expected cost. Hence, the network planner will decide to exercise this option only if it is economically beneficial to the system economics. The term ‘option value’ stems from the financial options theory where the holder of an option has the right – but not the obligation – to exercise it when the value from exercising it is greater than the associated cost;
- Operational characteristics of deployed technologies. The analysis will also present the operation of the deployed technologies e.g. how it may affect power flows at selected transmission corridors and how it operates to achieve this.

The scope of case study 2 is restricted by the following assumptions:

- Modelling of electricity only; the modelling of other energy vectors is not included in the problem formulation;
- Modelling of the horizon, for the stochastic model, through a number of scenarios in the form of a scenario tree where uncertainty is resolved via the passage of time (i.e. the

scenarios get distinguished as time progresses). Note that the deterministic version of the problem contains a single scenario so that the above scenarios will be studied in separation from each other. In addition, note that there are no sources of endogenous / decision-dependent uncertainty involved.

- Modelling only of the European electric power transmission system; the interconnections with Eurasia/Africa and other neighbouring areas are not modelled in the case study;
- Multi-dimensional uncertainty: Sources of uncertainty include solar and wind installed capacities as well as demand; other parameters of the system (e.g. fuel cost, thermal capacity of the corridors) are assumed unchanged across the horizon. However, the model is flexible enough to accommodate more sources of uncertainty should this be deemed necessary;
- Modelling of each country is represented by a single node.
- Modelling of the thirty-year span of the horizon through a number of stages (also known as epochs);
- Modelling of the electric power transmission system power flows via DC–PF (DC power flow). The assumption of DC-PF modelling for transmission system operation has been established in the literature as a norm;
- Modelling of the investment decision making in a centralized manner; specifically, each planner is considered the sole source of decision making in the model;
- Modelling of generation in a concentrated manner; essentially, each country is associated with a number of generating-unit types, and their total installed capacity is considered in the model.

Case study 2 deals with the electricity sector and specifically focuses on the following investment technologies.

- Electric energy storage (lithium battery).

  We model its operation which is to charge with energy at certain periods of the year and discharge it at other periods. This operation is characteristic of energy storage of any type of technology and is performed basically for the purpose of accommodating power flows in a safe and reliable manner.

For instance, when the power flows are close to the static thermal rating of a corridor, electric energy storage can discharge and, as a result, feed local loads, thereby alleviating the need for supplying them with power from a distance generating unit. Such operation can help defer conventional network reinforcement;

- Conventional network investment.

  This investment refers to adding new capacity in the electrical interconnection between two countries. Technical characteristics are considered including the associated cable reactance as well as length (km).

The methodological approach for conducting case study 2 involves the following formulations:

- Stochastic optimization formulation where both technologies are available for investment: energy storage and conventional network investment. Stochastic optimization allows for the consideration of uncertainty, which can be uni or multi dimensional. When considering both technologies the formulation requires the modelling of the operation of both technologies and their effect that they can have on system operation.
- Stochastic optimization formulation where only conventional network investment is available for investment: In this case, the formulation models the investment decision problem only from the perspective of conventional network reinforcement.
- Deterministic optimization formulation where both technologies are available for investment: In this formulation, all sources of uncertainty are ignored. Therefore, the planner decides on the basis of perfect future foresight.

The evaluation of the option value will be determined by comparing the first two formulations. The effect of using stochastic optimization will be determined by comparing the first / second and third formulations.

2.4 Seasonal Storage Valuation Model and European Unit Commitment

Those 2 models cannot be described independently as the Seasonal Storage Valuation Model itself uses the European Unit Commitment Model for solving its inner transition problem.

This means that SSV cannot be ran without EUC, while EUC can be ran alone.

Both models share the exact same set of data.

2.4.1 Seasonal Storage Model

The Seasonal Storage Model solves a mid-term problem, where mid-terms stands usually for annual. This problem consists in evaluating an approximation of the expected operation cost, $C^{opex}(\kappa, \eta)$, for a given vector of installed capacity, κ, under the assumption of the meta-scenario η.

The mid-term horizon is a set of stages $S = \{s_0, s_1, \dots s_n\}$ (eg. weeks), subdividing the typical period (eg 1 year) on which operation costs are evaluated. Each stage is divided in time steps $\{t_0, t_1, \dots t_n\}$ (eg. Hours).

Note that uncertainties (such as reservoir inflows, demand, outages or intermittent generation) are impacting operation decisions which are made dynamically along the mid-term horizon, while those uncertainties are progressively revealed and the forecasts are accordingly updated. Hence, the SSV model consists of a multi-stage stochastic optimization problem, aiming at minimizing the sum of operation costs on each stage s:

$$C^{opex}(\kappa) = \min_{x \in X} E\left[\sum_{s \in S} C_s^{opex}(x_s)\right]$$

Where:

• x = $(x_s)_{s \in S}$ is the sequence of operation decisions taken at the beginning of each stage. These decisions are supposed to be non-anticipative, in the sense that decisions x_s made at stage s should only depend on the past realizations of uncertainties.

X is the feasible set associated with operation decisions. In particular, it includes the already invoked non-anticipativity constraint relating decisions to observed uncertainties. We also emphasize the presence of dynamical constraints (relating reservoir levels between two stages, ramping rates or any other conditions that involves linking adjacent time steps). This prevents us from taking decisions independently between two stages.

• C_s^{opex}represents the operational cost on the stage s as a function of decisions x_s. Notice that C_s^{opex}depends implicitly on the installed capacity κ and on uncertainties revealed at stage s (demand, inflows, intermittent generation) so that the expectation appearing in (6) is related to the probability distribution of those implicit uncertainties. Furthermore, the expectation is not to be taken over the set of meta-scenarios U, since these are assumed to be given without a (probability) distribution: they represent plausible futures against which we want to hedge, but which cannot be reasonably equipped with a distribution.

This problem is solved by time decomposition using stochastic dynamic programming. At each stage s, a transition problem is solved, involving operational cost of stage s C_s^{opex} and the cost-to go function giving the minimum future operational expected cost. The transition cost is evaluated by the EUC Model (see below).

2.4.2 European Unit Commitment Model

The European unit commitment problem (EUC) solves the short-term horizon problem (short-term meaning daily or weekly), where operational decisions are provided at one stage s ∈ S, in a deterministic setting, taking into account the "value" that seasonal storage units can bring to the system via the cost-to-go function. The EUC occurs in two ways.

(a) The EUC optimization mode solves the transition problem of SSV with a convexification of the operational constraints. In fact, it is intended to provide cutting plane approximations of cost-2-go functions. Notice that the associated operational decisions may be infeasible since non-convex technical constraints have been convexified. The advantage is that the EUC optimization mode should run reasonably fast.

(b) The EUC simulation mode solves the transition problem, without any convexification of technical constraints. This mode is intended to provide a feasible generation dispatch, on a given sub-period. It uses the cutting plane approximations of the cost-2-go functions provided by SSV and is based on a feasible recovery heuristic ensuring the feasibility of operation decisions. The computing time required to run the EUC simulation mode could be significantly greater than that to run the EUC optimization mode.

However, in simulation mode, both investment capacities κ and approximations of the cost-to-go functions remain fixed. Therefore in total, likely, the simulation model will be faster than the optimization mode.

To compute the expected cost, $C^{opex}(\kappa)$ post-optimization, it is more relevant to rely on feasible decisions and consequently to use the EUC simulation mode implemented sequentially for each stage s ∈ S and averaged over Monte Carlo simulations of the random vector ξ. In this fashion we can compute a stochastic upper bound on the actual optimal cost of operation for the current investment capacity κ.

Various kinds of flexibilities involving both generation, storage and consumption are dealt with:

- Dynamic operation constraints of power plants (ramping constraints, minimum shut-down duration, …)
- Dynamic operation of storage (including battery-like storages and complex hydro-valleys modelling)
- Demand-Response (including eg. household dynamic consumption load-shifting or load curtailment)

The EUC can also account for both transmission and distribution networks:

- Transmission Network representation: from a copper plate approach to a 'clustered' approach with limited transport capacities.
- Electricity distribution limited capacities and reinforcement costs

2.5 Gas Network Optimization Model

In this project, the connection of the electricity sector with the gas sector by power-to-gas (P2G) and gas-to-power (G2P) is of particular interest as the gas grid allows the storage and transport of energy. This connection adds flexibility to the energy system as a whole.

The gas network model verifies the gas transport requests, which result from the electricity grid operation, subject to the existing gas transport network infrastructure. These gas transport requests include the demand of G2Ps and the amount of gas injected to the network by P2G. Besides, the model is used to compute the limits implied by the physical properties of the gas network to the application of P2G and G2P. These limits represent the input to the European market simulation.

For the verification of the gas transport requests, we need to know whether a feasible configuration exists for the given gas network to route the amount of demanded gas. In the gas network operational context, energy transport demands are called nomination. Whether a network allows a feasible operation for a given nomination is computed in a "NOmination VAlidation" model, or NOVA [1].

NOVA is a physical-flow based gas network model that includes pipelines and active components of the gas network such as compressor stations and control valves. The gas flow in the arcs by a pressure difference between the end nodes. A quadratic constraint in the model implies this relation. Active components such as compressor stations and control valves control the flow of gas by controlling the node pressure. They disable a particular arc when they are in bypass. The states of the active components are modeled as integer variables, while the node pressures and the gas flow on arcs are continuous. NOVA represents a Mixed Integer Nonlinear Problem [14-16]. It also includes constraints for compressor station models [1] [2] [3]. It also includes constraints for compressor station models [3] [4].

NOVA is a feasibility problem that returns either a feasible gas flow for a given nomination vector or infeasibility. The output of NOVA includes flow values through pipelines, configurations of the active network devices such as compressors, and the pressure distribution in the network.

The NOVA assumes a stationary gas network model, i.e., it does not consider the dynamic effects of gas transport. One consequence is that the gas inflow and gas extraction has to be in balance for any feasible nomination vector.

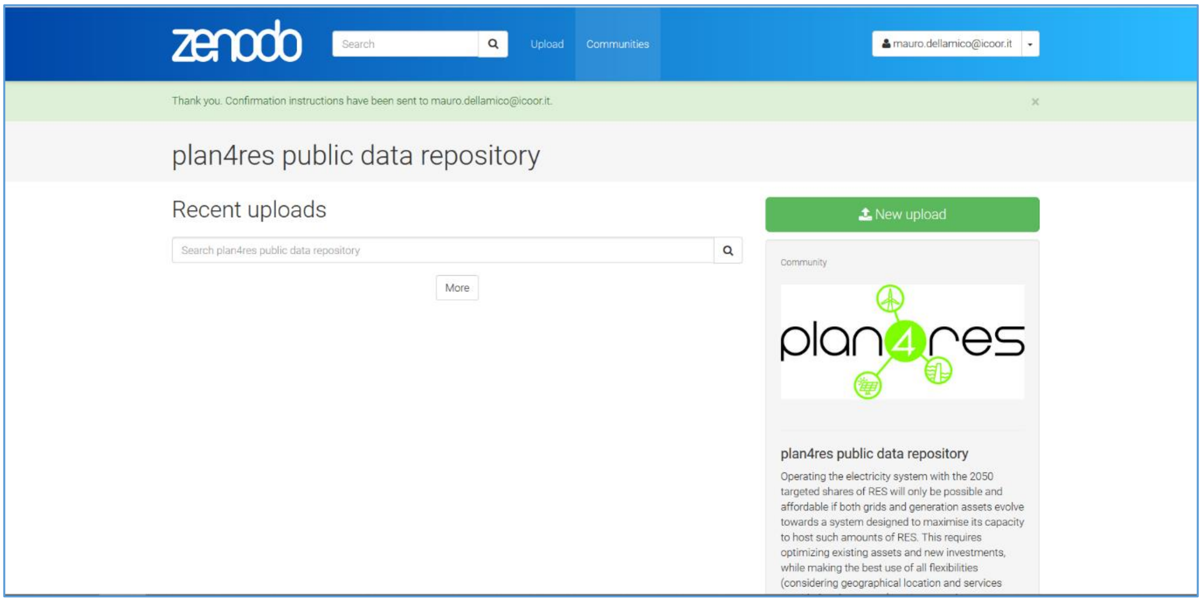
The inputs of NOVA are network topology data defining the physical network, and a demand profile in terms of in- and outflows of gas. This demand profile includes the main gas sources for Europe such as Norway and Russia, and demand of consumers of gas as well as the output of European market and electricity grid simulation. The consumers of gas include household and industry consumers, and output of European and electricity grid simulation constitutes the amount of gas required by G2P and injected to the network by P2G.

3 The plan4res public repository

This chapter presents the repository used to store the public dataset and the conventions deployed to name the files, the format they should have when saving it, and the main transformations. Model by model the chapter describes the relevant files and their format.

The public repository is hosted by Zenodo : a general-purpose open-access repository developed under the European OpenAIRE program and operated by CERN. In particular the plan4res data are available at the following web page

https://zenodo.org/communities/plan4res/



Each file is stored using the Zenodo policies and facilities which allow to accompany the data with a set of information on the author, the format, the licence of use etc. Each file is given a DOI (Digital Object Identifier) which is a worldwide unique identifier.

The Zenodo web pages allow to apply a wide set of filters to list the files and select the required data from the repository.

3.1 The common plan4res data Format

All the input files are given as CSV or Excel files. CSV files can be grouped as sheets in one Excel file.

All data files are named according to the plan4res File Name convention, and their format is following the prescriptions of the plan4res data format.

3.1.1 File naming Convention:

PROVIDERID__DATASETID__DATADATE__DOWNLOADDATE[__SERIAL][__SLICEID][.FT]

- PROVIDERID is the name of the source provider (eg. “Eurostat”, “EDF”, …)
- DATASETID is a data-curator-defined name like “Power-demands_DE_2010-2015”
- DATADATE is an ISO 8601/RFC3339 timestamp
- DOWNLOADDATE is an ISO 8601/RFC3339 timestamp

- SERIAL is an (optional) data curator defined serial identifier like v0001, or another timestamp, or a string
- SLICEID is an (optional) numeric index, possibly with padding zeros to allow alphabetic concatenation by globbing/wildcarding ('cat X__Y__D1__D2__*.FT')
- FT is an (optional) file type designator : .csv, .nc4, …

All strings cannot use '__' (double-underscore)

3.1.2 Format

The general format of sheets/CSV files is as follows:

1. One Optional row(s) with identification information
2. One optional row with units of all data
3. One row containing column labels
4. Serie of Rows containing the data (consistent with column labels)

Columns that are not used may be skipped.

3.1.3 Description of geography

Each dataset is linked to a geographical area that may be partitioned. Different partitions may be used for dealing with different levels of constraints or computations.

Those partitions are described in files or sheets named ZoneHierarchy or ZonePartition, that follow the same rules:

The first column 'Level1' lists the lowest level partition. The partition 'level2' is a higher level partition, meaning that the regions in Level2 are larger than the regions in level1, and each region in level2 is composed of a list of regions in level1. Level3 partitions again are bigger than level2. At each level we may have different partitions obtained by regrouping regions differently (here we have 2 different ways of grouping the regions of level2: level3part1 and level3part2).

- Level1 = identifier of the first level zone (e.g., datazone) - string
- Level2= identifier of the second level zone (e.g., cluster) - string
- Level3Part1 = identifier of the third level zone (e.g., region), in a first partition – string
- Level3Part2 = identifier of the third level zone (e.g., region), in a second partition – string
- Etc.

A row with values L1, L2, L31, L32 … means that zone L1 belongs to second level zone L2, and this zone belongs to third level zones L31 and L32, …; Each L1 belongs to a unique L2; Each L2 belongs to a unique L3 for the first partition, and to a unique L3 – that can be different- for the second partition, etc…

The Figure 4 below illustrates this.

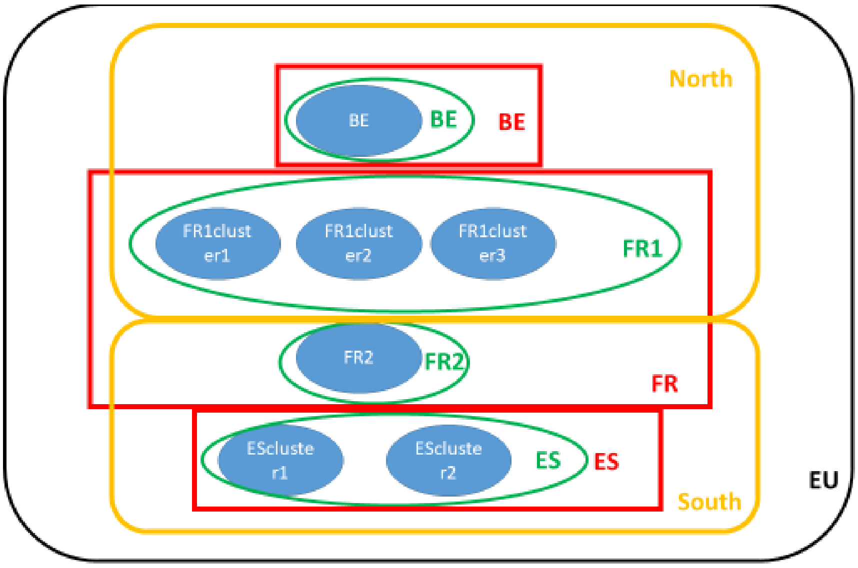


Figure 4: partitions

In Blue: Level1; in Green: level2, in red and orange: level3 (partition1 and partition2), and in black level4. Here there are 7 zones in level1, that are aggregated in 4 level 2 clusters: BE, FR1, FR2 and ES. Each level1 zone belongs to a unique level2 cluster. At level3 there are 2 partitions: Level3part1 partitions the 4 clusters as North=BE+FR1, South=FR2+ES while Level3part2 partitions the same 4 clusters as BE=BE, FR=FR1+FR2 and ES=ES.

Specificities: When used for transforming the data by using aggregation/disaggregation, different partitions for 1 level cannot be used. They are used only for dataset for running the models.

3.1.4 Description of data linked to partitioned zones

Labels:

- **Type**, **Name** and **ID** are optional columns that are used as identifiers. Type may be used to identify the source, use or sector for energy (e.g. heating, cooling, etc.); Name is used when names can be associated to data and ID is a unique identifier of the row (string)
- **Zone** = Name or identifier of the zone (string)
- **Datazone_ID =** optional identifier

- **Value** = numeric value
- **minValue** = numeric min value, to be specified (optional)
- **maxValue** = numeric max value, to be specified (optional)
- **Profile_TimeSerie** = label of the timeseries (string or csv file) associated with the row (optional)
- **Unit** = unit of energy values (string) (optional)
- **Year** = numeric year: the aggregation is done for the given year (optional)
- **Scenarios =** number of the scenario (optional)

3.1.5 Timeseries

Timeseries are described in CSV files or Excel sheets.

`Time Series Format:`

Headers:

- **1 line of identifiers of the data included in the file**
- **1 (optional) line identifyiong the scenarios**

Labels:

- **Timestamp [UTC]** is the first label: reports the timestamps of the time series in UTC format
- **next labels** are the "names" of the timeseries (one for each column) – in that case these names correspond to the field **Profile_Timeserie** in ZoneValues, or the identifiers of the scenarios (for scenarised timeseries). In that case the field in ZoneValues is the name of the csv file (toto.csv).

3.1.6 Interconnections

Labels: Link_Name, Link_Type, Direction, Link_Origin, Link_Destination, MaxFlow, Impedance

- **Link_Name / Name** = name of the link (string)
- **Link_Type / Type**= identifier (string) : describes if line is AC, DC…..
- **Direction** = Bidirectional/ Unidirectional
- **Link_Origin / StartLine** = starting Zone for the link (string, as in ZoneHierarchy)
- **Link_Destination / EndLine** = ending Zone for the link (string, as in ZoneHierarchy)
- **MaxFlow / MaxPowerFlow** = maximum capacity of the link

- **MinFlow / MinPowerFlow** = minimum capacity of the link (for unidirectional should be 0, for bidirectional should be –capacity in the other direction)
- **Impedance** = impedance of the link (may be NULL)
- **Year =** numeric year: the aggregation is done for the given year

3.2 Multimodal Investment Model - Files

This section describes the data used in the multi-modal investment model (MIM) whose aim is to determine optimal investment decisions along the pathway from today to a chosen horizon of interest.

3.2.1 MIM Geographical Scope

- Geographical scope for modelling potential pathway for a future multimodal energy system is Europe. Due to computational limitations geographical resolution has been limited to country level. This includes the EU-27 states, excerpt the islands Malta and Cypress, plus Switzerland, Norway, UK and the Balkan regions. Lichtenstein, Monaco, Vatican City are excluded, since these countries are responsible for only a very small share of the energy demand and generation of Europe.

Definition of modelling clusters / cell for MIM modelling:

- Kosovo and Serbia are modelled as SERBIA to improve (historical) data quality and availability
- There are no extra-European cells included. Energy resp. commodity imports and exports are modelled as ‘virtual conversion technology installed’ at the regions, where the imports are required.
- The north sea and the baltic sea provide excellent wind conditions for future energy harvesting from offshore wind power. To include modelling of these opportunities three additonal regions have been created, which cannot be connected an individual state, but to Europe itself.
- Format Zone Hierarchy Data
    - Level_1 describes the regional energy cell (here country level)
    - Level_2 describes the regional cluster, aggregating many cells of Level_1

      For countries level_1 and Level_1 are the same on the geographical level currently used for MIM modelling, but e.g. the two North Sea cells NSA and NSB can be combined to a cluster NorthSea.
    - Level_3 describes the supra regional cluster, here Europe, consisting of regional clusters of Level_2

Level_1	Level_2	Level_3
Data Zone	Cluster	Region
AL	AL	EU33
AT	AT	EU33
BA	BA	EU33
BE	BE	EU33
BG	BG	EU33
CH	CH	EU33
CZ	CZ	EU33
DE	DE	EU33
DK	DK	EU33
EE	EE	EU33
EL	EL	EU33
ES	ES	EU33
FI	FI	EU33
FR	FR	EU33
HR	HR	EU33
HU	HU	EU33
IE	IE	EU33
IT	IT	EU33
LT	LT	EU33
LU	LU	EU33
LV	LV	EU33
ME	ME	EU33
MK	MK	EU33
NL	NL	EU33
NO	NO	EU33
PL	PL	EU33
PT	PT	EU33
RO	RO	EU33
RS	RS	EU33
SE	SE	EU33
SI	SI	EU33
SK	SK	EU33
UK	UK	EU33
NSA	NorthSea	EU33
NSB	NorthSea	EU33
BSA	BalticSea	EU33

Table 1: Format Example Zone Hierachy MIM_EU33

- (Regional) Curing Rules in MIM

When combining data sets from different data sources often issues with missing data pop up. These data 'gaps' have to be cured in an appropriate way. It must be distinguished between regional gaps (data from some regions available, but some are missing) and temporal gaps (data is missing or of bad quality along the timeline).

The external data sets, used to construct the input data sets for MIM modelling, provide data with good temporal quality at hourly resolutions for the reference year 2015. Thus, no temporal curing of the data was necessary.

Some (external) data sets do not always include data for all regions requested for modelling. Data for some countries are missing. For regional curing two curing rules have been defined:

- Curing rule 'weighted mean from socio-economic analogous' countries (short 'weighted mean'):

  $$Data_{gapcountry}^{cured} = mean\left(\frac{Data_{neighborcountry,i}}{KPI_{neighborcountry,i}}\right) * KPI_{gapcountry} \quad (3\text{-}2)$$

  Curing by 'weighted mean' will be chosen whenever the data type to be cured is dependent on socio-economic KPIs, e.g. population or GDP.

  Examples are transport demand of freight (KPI: GDP) or persons (KPI: population), or the process heating demand of large industries, which can be correlated in 1st order estimation to the GDP of a country with 'socio-economic analogous' status.

  'Socio-economic analogous' countries are chosen in a way that, e.g. they have a similar level of wealth, earnings, energy consumption per capita or GDP if compared with the region the data is missing.

- Curing rule mean of 'neighbouring countries (with similar weather conditions)' (short 'mean of neighbours'):

  $$Data_{gapcountry}^{cured} = mean\left(Data_{neighborcountry,i}\right) \quad (3\text{-}3)$$

Curing by ‘neighbours’ is chosen whenever the data to be cured is independent on socio-economic KPIs, but on geography or weather conditions. Examples are temporal PV, Wind Onshore or space heating demand.

Sets of ‘socio-economic analogous’ countries or ‘neighbour’ country’ used for curing are listed in table below:

‘gap‘ country	‘socio-economic analogeous’ country
Norway	SE, FI
Switzerland	DE, AT
Albania	RO
Bosnia Herzegowina	RO
Serbia (incl. Kosovo)	RO
Montenegro	HU, RO
North Macedonia	EL, RO

Table 2 Allocation table for data curing by rule ‘weighted mean from socio-economic analogous’ countries

‘gap‘ country	‘neighbour’ country
Norway	SE, FI, DK
Switzerland	AT
Albania	HR, BG, EL
Bosnia Herzegowina	HR, HU, RS
Serbia (incl. Kosovo)	RO, BG, HU
Montenegro	HR, RS, BA
North Macedonia	RS, BG

Table 3 Allocation table for data curing by rule ‘mean of neighbour’

3.2.2 MIM Technical Scope

Multi-modal investment modelling requires a huge bunch of flower basket generation and demand relevant to the energy consuming sectors Industry, CTS, Residential and Mobility, and their relevant energy carriers, including, e.g. electricity, thermal energy in terms of heat & cold, transport amount used for Mobility needs, liquid/gaseous fuels, and chemicals.

Additionally, balancing of energy-related CO_2-emissions from the above-mentioned technologies and carriers is implemented. Although, non-energy related emissions, e.g. from agriculture or chemical processes, are excluded.

El. Generation Utility & Industry
- SPP Coal/Gas/Oil/Lignite
- SC GT PP Oil / Gas
- CC GT PP Oil / Gas
- Nuclear PP (ex, plus future EPR)
- CHP Engine (L >MW class)

Renewables
- Hydro Run-of-River
- Hydro Lake w/ reservoir
- Solar PV (L, farms)
- Wind Onshore
- Wind Offshore
- Waste
- Biomass SPP
- Biogas CHP
- Solar thermal (L)

Generation - decentral
- Rooftop PV (S)
- Micro CHP (S, <MW class)
- Solar Heat (S, roof-top size)

Grids
- Electric Interconnection Grid (NTC)
- H2 cross-border (Tank Trailer)

Heating – temperature levels
- LT <100 °C
- MT 100°C – 150°C
- HT 150°C– 500°C
- VHT >500°C

Heating - decentral
- Small Boiler (S)
- Small Electric (S)
- Micro CHP (SI)
- Heat Pumps (Air / Ground)
- District Heating (decentral)

Heating - central
- Boiler Large
- Heater electric LT / MT / MT
- Arc Furnace (electric) VHT
- Furnace VHT
- Heat Pump (LT, MT)
- District Heating (LT, single point per region)

Cooling – temperature levels
- Freezing <0 °C
- Cooling 0°C – 15°C

Cooling - central / decentral
- Compression Chiller
- Compression Chiller HVAC
- Absorption Chiller (L)
- District Cooling (single point per region)

Mobility
- Classic Mobility (Rail / Road / Ship / Air)
- Public Bus / Coaches
- Fuel Cell Cars / Rail / Bus
- E-Mobility
  - eCar, eBus, eCoach
  - eTruck heavy & light, eHighway
  - eAircraft [1)]

Mobility Demand (short/long distance)
- Passenger in p*km
- Freight in t*km (light, heavy)

Storage
- Pumped Hydro
- Batteries ('Li-Ion')
- Carnot Battery
- Heat Storage HT (S, L)
- Heat Storage MT (S, L)
- Heat Storage LT (S, L)
- Cold Storage H_2O (S, L)
- Cold Storage Ice (S, L)
- e-powered Pit Storage

Power to Chem
- Electrolyseur (H_2)
- Power2Gas (CH_4)
- Power2Synfuel (CH_3OH)
- eAmmonia Synthesis (NH_3)

Industry generation & demand (simplified, focus correlation to P2G)
- Simplified Steam Methane Reforming
- Simplified Refineries & H_2 Demand
- Synthesis Ammonia & Demand
- Synthesis Methanol & Demand
- Coke-off Gas from Industry

Table 4 Multi-Modal Investment Model – list of implemented sector coupling technologies

In order to simplify the linear problem to be solved, technologies are represented as simplified conversion process CP, consisting of tuple of sets of sub-conversion processes (CS, CO_{In}, CO_{Out}), where CS characterizes a sub-conversion process consuming input energy carrier CO_{In} and generating output commodities CO_{Out}, typical with limited efficiency. Whenever possible, CP names are constructed by predefined parts in order to increase readability of the description.

To facilitate a) consideration of the 'historically grown' existing technology mix and already installed capacity base and b) testing of public policies while MIM modelling, conversion process or technologies can be further distinguished in sub-types:

- existing units — suffix 'ex'
- planned installations from public policy — suffix 'plan' or 'planYEAR'
- planned / forced retirements from public policy — suffix 'deco' or 'decoYEAR'
- planned / forced continuation from public policy — suffix 'conti'

For presentation of results these sub-types are aggregated to one technology representation.

3.2.3 MIM Temporal Distribution and Temporal Regional Distributions

The MIM model uses time dependent data to include given load and or temporal generation patterns for a representative year of usually 8760h. This is necessary, e.g. when simulating volatile generation from renewable energy sources, or dealing with heating and cooling demand, which are highly dependent on regional weather conditions.

Often these characteristic temporal patterns differ from region to region. Then a time profile for each energy cell must be provided. These sets of time profiles are merged into a temporal regional distribution (short TRD).

If regional discrepancies are low a simplified approach by using only one temporal distribution (TD) for all regions can be used. Usage of TD for all regions improves solving speed dramatically and should be considered wherever possible.

To ensure consistent modelling, all temporal demand or generation profiles must be based on the same reference year within one model run, here 2015.

- Pre-Processing 'normalisation' of temporal profiles

To facilitate fast solving times all temporal profiles are normalised before using them within MIM modelling. For TD as well as for TRD profiles two types of normalized representations must be distinguished:

- TRD_CAP / TD_CAP
  A time profile normalized in a way that the maximum available power =! 1 by dividing all hourly values by their max value (suffix CAP) within a region.

  The integration of such a profile results in the nominal full load hours (FLH) per region.

The multiplication of this profile type with the installed base results in the absolute hourly generation or consumption by this technology.

- TRD_OUT / TD_OUT A time profile normalized in a way that the integration over one year =! 1 by dividing all hourly values by the sum of the whole year within a region.

- Format Time Profile Data (TD/TRD)

Timestamp [UTC]	TRD_OUT__Heat_Ind__HRE__AL	TRD_OUT__Heat_Ind__HRE__AT	TRD_OUT__Heat_Ind__HRET__BA	TRD_OUT__Heat_Ind__HRE__BE	...
01.01.2015 00:00	0.00508	0.00900	0.00962	0.00864	
01.01.2015 01:00	0.00256	0.00450	0.00484	0.00437	
01.01.2015 02:00	0.00128	0.00220	0.00242	0.00215	
01.01.2015 03:00	0.00104	0.00180	0.00194	0.00172	
01.01.2015 04:00	0.43980	0.47010	0.43526	0.42284	
01.01.2015 05:00	0.44565	0.47530	0.44240	0.43057	
01.01.2015 06:00	0.46403	0.50340	0.47384	0.45942	
01.01.2015 07:00	0.48163	0.53880	0.51079	0.49669	
01.01.2015 08:00	0.44754	0.51560	0.47862	0.48660	
01.01.2015 09:00	0.39494	0.47270	0.42835	0.45287	
01.01.2015 10:00	0.34507	0.43650	0.38933	0.41984	
01.01.2015 11:00	0.29812	0.39800	0.35500	0.38739	

Table 5: Format example TRD / TD

  - Colum 1: Timestamp [UTC]
    - Row 2 to …

      A UTC conform time stamp code, listed here for data of the reference year 2015 resulting in 8760 data rows for hourly resolution

  - Columns: 2 to …
    - Row 1: (case TD_CAP / TD_OUT) TD name of the temporal distributions name without region name as prefix. In case of several columns with different names, every column represents an individual TD profile
    - Row 1: (case TRD_CAP / TRD_OUT) TRD name with a suffix representing the corresponding region name separated by '__', resulting in X data column per TRD with X equal to number of all regions to be modelled
    - Example (format style: "TRDname__REGIONname") Regional temporal distribution for individual heating demand (fraction of energy demand in every hour related to a global energy demand → OUT)
      - TRD_OUT_HeatInd_2015_HRE __AL .. for Region AL

- TRD_OUT_HeatInd_2015_HRE __AT .. for Region AT
- TRD_OUT_HeatInd_2015_HRE_OUT__BE .. for Region BE

and so …

NOTE: If no TRDname token is given in the string headlines of columns 2 and following, but only a zone or region indicator, then the TRDName is indicated in the data filename.

- UNITS: Within MIM modelling every TRD or TD used as input data has arbitrary unit and has been normalized as indicated by the TD/TRD name suffix (→ 'OUT' or 'CAP' – definition see above)

Created TD Datasets:

- Generic uniform time profiles: TD_OUT_Uniform and TD_CAP__AllOne

  These time profiles are created to enable enforcement of

  - uniformly spread power by setting in all time steps the value = 1 (AllOne) indicating max power for every 8760 hours (results in 8760 FLH)
  - uniformly spread energy consumption or generation of the annual energy demand by setting in all time steps the value = 1/8760 (Uniform) resulting in 1.

- Industrial process heat demand patterns

  The TD profiles listed here have been implemented to enable simulation of typical industrial process heating demand patterns. They have been created from the [HOTMAPS] by using transformation rules, as stated in the data set, set to create typical generic process heating demand patterns for the reference year 2015.

  From the provided data for every temperature level industry sub-types can be identified, which dominate the time profile shape of process heat demand on the particular temperature levels most. These are:

  - Chemical industry: → TD_OUT__CHEM and is applied as dominant player to the corresponding heat demand on temperature levels VHT and LT.
  - Iron & Steel industry: → TD_OUT__IRON and is applied as dominant player to the corresponding heat demand on temperature levels VHT.

   - Pulp & Paper industry: → TD_OUT__PAPER and is applied as dominant player to the corresponding heat demand on temperature levels HT and LT.
   - Food & Beverage industry: → TD_OUT_FOOD and is applied to the corresponding heat demand on temperature levels MT, HT and LT.
- Individual Road Transport Demand: TD_CAP__RoadCar

  This time profile has been created to consider temporal transport patterns in Mobility. They have been created from the [HRE4] dataset and are normalized to 'CAP' style.
- Individual Road Transport Demand - Parking: TD_CAP__CarPark

  This time profile has been created to enforec the fact that eCars can't be charged if the vehicle is moving.

  It was created by simply subtracting TD_ CAP__RoadCar from the max value 1, indicating limitations of charging of eCar batteries when the car is driving.

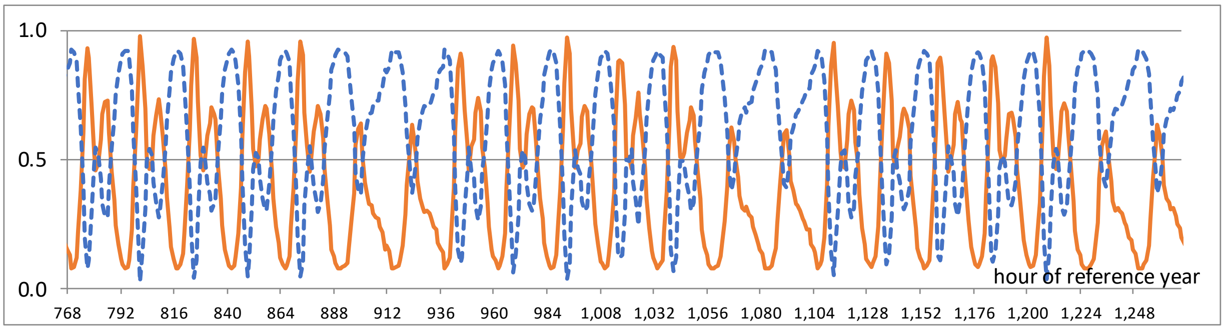


Figure 5 Transport demand pattern in Mobility for individual road transport (solid, TD_ CAP_RoadCar) and charging power limiting parking profile (dashed, TD_ CAP_CarPark)

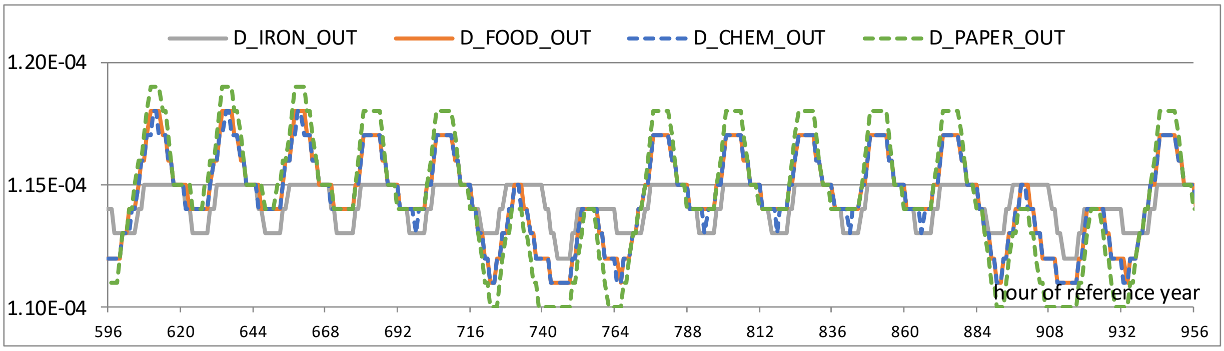


Figure 6 Generic process heat pattern from various industrial demands

Created TRD Datasets:

- PV generation: TRD_CAP__PV_2015_NINJA

  Simulated generation data from dataset [NINJA], curing has been done for countries AL, BA, ME, RS using rule 'mean of neighbours'.

- Wind Onshore generation: TRD_CAP__WindON_2015_NINJA

  Simulated generation data from dataset [NINJA], curing has been done for the Balkan countries AL, BA, ME, RS using rule 'mean of neighbours'.

- Wind Offshore generation: TRD_CAP__WindOFF_2015_NINJA

  Simulated generation data from dataset [NINJA], curing has been done for EL, HR, SI and PL using rule 'mean of neighbours' from neighbours with wind offshore potential.

  Note: The following countries show no (no access to sea) or only very low potential for Wind Offshore Power. Thus, regions SK, RS, MK, HU, CZ, CH, AT, LU, and BA, AL, ME and are set to zero (→ no 'usage' of offshore wind power considered in modelling allowed)

  The wind offshore generation profiles for the open sea cells of NS-A, NS-B, BS-A have been created as mean of their coastal states.

- Hydro In-Flow: TRD_OUT__HydroRoRa_HRE4

  Historical generation data from data set [HRE4] was used, curing has been done for NO, CH, AL, BA, MK, ME using rule 'mean of neighbours' of neighbours.

- Solar thermal generation: TRD_OUT__SolarThermal_HRE4

Historical generation data from dataset [HRE4], curing has been done for NO, CH, AL, BA, MK, ME using rule ‘mean of neighbours’ of neighbours with wind offshore potential.

- Individual (Space) Heating Demand: TRD_OUT__HeatInd_2015_HRE4

  Historical demand data from data set [HRE4], curing has been done for NO, CH, AL, BA, MK, ME using ‘weighted mean’ countries.

- Individual (Space) Cooling Demand: TRD_OUT__Cool_2015_HRE4

  Historical demand data from data set [HRE4] was used, curing has been done for NO, CH, AL, BA, MK, ME using ‘weighted mean’ countries

- Exogenous Electricity Demand: TRD_OUT_ElectricityExo

  Historical consumption data of total electricity demand can be downloaded from several sources. For MIM modelling purposes this time profile cannot be used directly. Instead a regional time profile cleared from the electricity demand contributions of heating, cooling and mobility must be used.

  Thus an ‘exogenous electricity demand’ is defined, which describes the residual electricity demand without contribution of the modelled sectors and technologies representing all left - and not modelled - energy consuming technologies, e.g. from lighting, television, washing machines etc.

  Construction TRD_OUT_ElectricityExo

  With knowledge of particular electricity demand in the references year this ‘cleared’ exogeneous electricity demand profile the ‘exogeneous electricity demand’ reginal temporal profile is created by subtracting from the total electricity consumption profile reference year 2015 (available from source ENTSO-E Power Statistics the particular regional hourly electricity demands from space cooling, space heating and industrial process heating, as well as the electricity demands for mobility, calculated with known TRD and annual electricity demand $D_{el,x,i}$ for electricity consuming technologies i of these sectors in every region x.

$$D_{el,x}^{ExoElectricity} \cdot TRD_{t,x}^{ExoElectricity} = D_{el,x}^{TotalElectricity} \cdot TRD_{t,x}^{TotalElectricity} - \sum_i D_{el,x,,i}^{SHeat} \cdot TRD_{t,x,i}^{SHeat} - \sum_i D_{el,x,,i}^{PHeat} \cdot TD_{t,i}^{PHeat} - \sum_i D_{el,x,,i}^{Cooling} \cdot TRD_{t,x,i}^{Cooling} \sum_i D_{el,x,,i}^{Mobility} \cdot TD_{t,i}^{Mobility}$$

Note: Final energy demand electricity can be found in [HRE4] and [EU REF16], too.

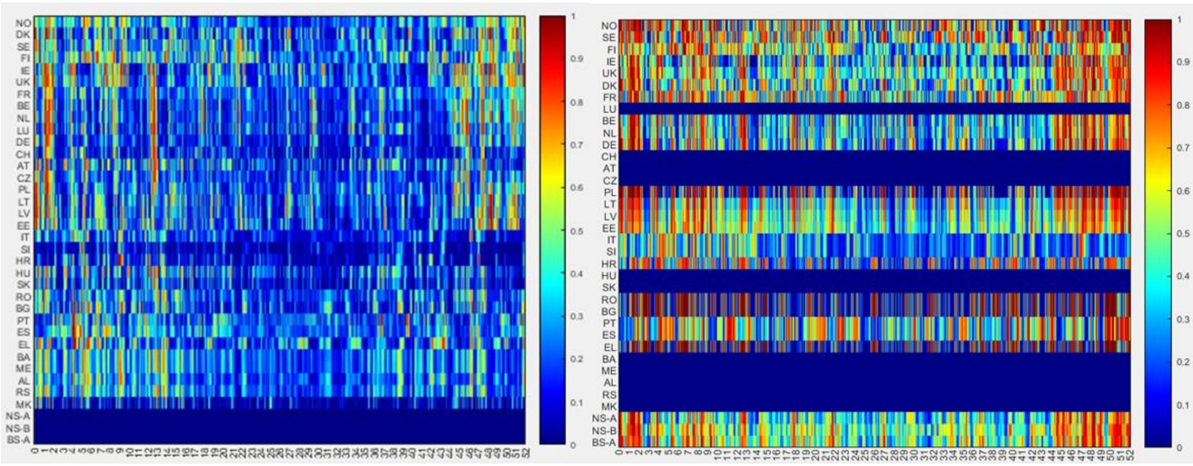


Figure 7 Temporal regional distribution for reference year 2015 of left: electric generation by wind onshore power; right: electric generation by wind offshore power (y-axis: regions; x-axis: reference year [week])

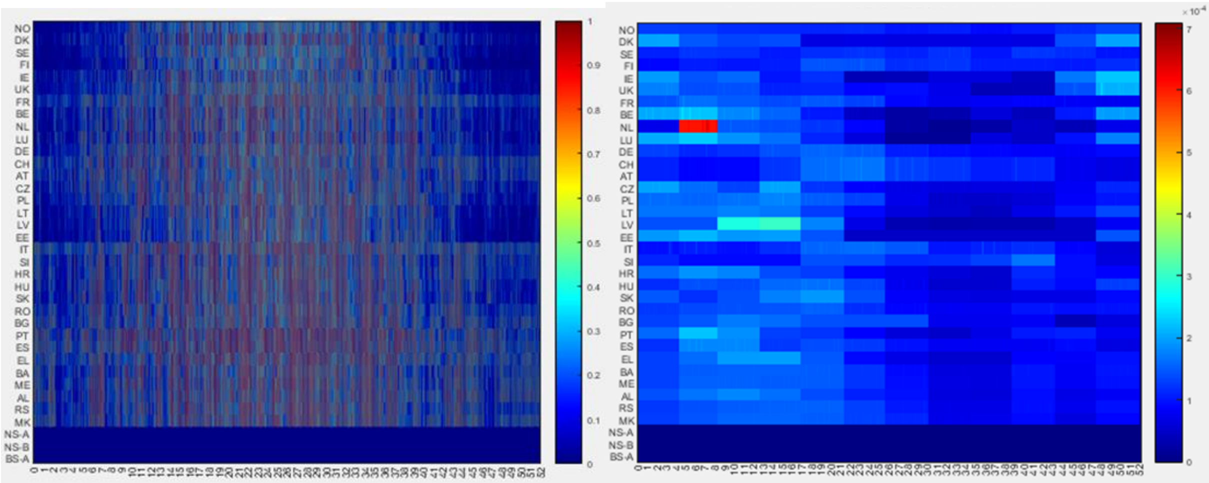


Figure 8 Normalized temporal regional distribution for reference year 2015 of left: electric generation by photovoltaic; right: electric generation from run of river hydro power (y-axis: regions; x-axis: reference year [week])

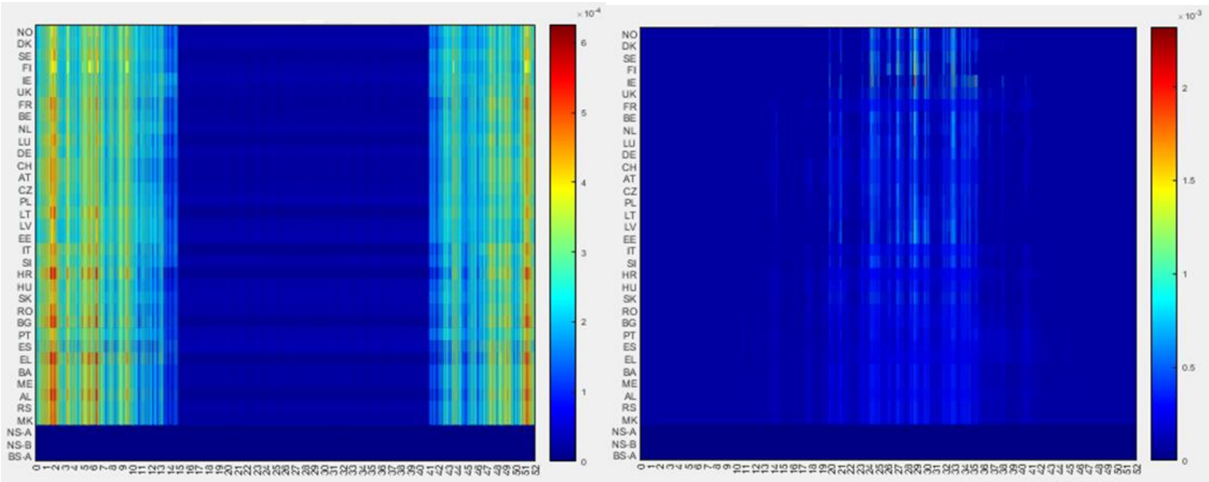


Figure 9 Temporal regional distribution of the hourly energy demand for reference year 2015 by left: space heating demand; right: space cooling demand (y-axis: regions; x-axis: reference year [week])

3.2.4 MIM Regional Distributions of Capacity and Generation/Demand

To improve solving times the MIM approach uses a split description for inputs of zone data, e.g. installed capacities or energy vectors per region resulting in a globally aggregated value and a linked normalised regional distribution (RD).

Thereby, data is distinguished in a 'global' value $k_{cs,y}^{tot}$, which is aggregated over all regions $x \in X$ and a correlated normalized distribution $D_{cs,x}^{distr,value,X}$ representing the proportional contribution of each region x *to* $k_{cs,y}^{tot}$. Equation (3-3) defines the regional distribution $D_{cs,x}^{distr,value,X}$ in the sense of 'given regional distribution', while Equation (3-4) sets the regional availability in the sense of 'max available value per region' per year $y \in \mathrm{Y}$.

$$k_{cs,x,y} = D_{cs,x}^{distr,\mathrm{cap},X} \cdot k_{cs,y}^{\mathrm{tot}} \qquad \forall cs \in \mathrm{CS}, x \in X, y \in \mathrm{Y}, I_{\mathrm{Regdistrgiven}cs} \qquad (3\text{-}4)$$

$$k_{cs,x,y} \leq V_{cs,x}^{distr,X} \cdot k_{cs,y}^{\mathrm{tot}} \qquad \forall cs \in \mathrm{CS}, x \in X, y \in \mathrm{Y}, I_{\mathrm{Regavailgiven}cs} \qquad (3\text{-}5)$$

Furthermore, analogously to TD / TRD considering differences in installed capacity and correlated energy output, two basic types must be distinguished in regional distributions based on installed capacity RD_C and those based on energy output RD_E.

- RD_C (Capacity) → name convention RD_C__TechName
  Regional distribution, normalized by dividing all regionally installed capacity values, e.g. $GW_{el,inst}$, by the sum of all regions. Units are arbitrary. Integration results in 1.

  Multiplication with the corresponding globally aggregated installed capacity value results in the installed capacity per region by this technology.
- RD_E (Energy) → name convention RD_E__TechName A regional distribution normalized by dividing all regional energy output values, e.g. TWh_{el} p.a., by the sum of all regions. Units are arbitrary. Integration of results in 1.

- Input data - Installed base (in 2020)

MIM modelling results in an optimized investment pathway from, e.g. 2020 to 2050. Consequently, and as 'staring point', the historically grown, yet not optimized, installed capacity base per technology must be inserted as 'forced installations' for the start year 2020.

- Electric Generation – Power Plants

A good projection of the installed base of power plants in all 33 modelled countries can be derived from [TYNDP] using the best estimate 2020 scenario (BE2020). The data set comprises projections done in 2017. Thus, this data set has been updated with more recent data from the ENTSO-E's

Factsheet 2018 [ENSTO-E FACTSHEET], wherever the actual installed base in 2018 already exceeds projections of the BE2020.

ENTSO-E Factsheet 2018 is also used as best source for projection of electric generation in terms of annual energy generated per year in 2020.

Electricity Generation RES	Process Heating	Individual Space Heating
RD_C_PV_Plan30 RD_C_PV_BE20 RD_C_WindOn_BE20 RD_C_WindOf_BE20 RD_C_HydroLake_BE2020 RD_C_RoR_BE2020 RD_C_PHS_BE2020 RD_C_BiomassPP_BE2020	RD_C_LignitePP_deco25 RD_C_LignitePP_deco35 RD_C_LignitePP_conti RD_C_CoalPP_deco25 RD_C_CoalPP_deco35 RD_C_CoalPP_conti RD_C_GasP_BE2020 RD_C_OilPP_BE2020	RD_E_SHeat_HRE4 RD_C_SHeat_HRE4 RD_E_SHeat_DHS RD_E_SHeat_COAL RD_E_SHeat_OIL RD_E_SHeat_GAS RD_E_SHeat_BIO RD_E_SHeat_HP RD_E_SHeat_EL
Mobility Demand	**Process Heating**	**Individual Space Heating**
RD_E_RoadTkm_2020 RD_E_RoadPkm_2020 **Biomass/-fuel Availability** RD_E_Wood_2020 RD_E_WasteWood_2020	RD_E_PHeat_BIO_HRE4 RD_E_PHeat_EL_HRE4 RD_E_PHeat_COAL_HRE4 RD_E_PHeat_EL_HRE4 RD_E_PHeat_DHS_HER4 RD_E_PHeat_HP_HRE4 RD_E_PHeat_HRE4 RD_C_SolarThermal_HRE4	RD_E_SHeat_HRE4 RD_C_SHeat_HRE4 RD_E_SHeat_DHS_HRE4 RD_E_SHeat_COAL_HRE4 RD_E_SHeat_OIL_HRE4 RD_E_SHeat_GAS_HER4 RD_E_SHeat_BIO_HRE4 RD_E_SHeat_HP_HRE4 RD_E_SHeat_EL_HRE4

Figure 10 List of currently created regional distribution currently used in MIM modelling

- Thermal Heat and Cooling Demand and Generation Technologies

A good projection of the regional thermal energy demands and installed base of technology for the EU28 countries can be derived from the heat roadmap project [HRE4]. In this project analysis of existing heating and cooling infrastructure was done for the reference year 2015.

This data set has been extended to all 33 modelled countries using curing method "weighted mean from similar countries' using population for all decentral (small, distributed) heating or cooling technologies and GDP for all central (large units) ones.

- Mobility – Transport Demand and Generation

A good projection of the current and future transport demand in terms of person x kilometres resp. tons x kilometres can be derived from the EU Ref Scenario 2016 data set [EUREF16]. This data set provides god transport demand and energy consumption data for the technology clusters public road transport, individual road transport, rail, inland navigation, aviation.

This data set has been extended to all 33 modelled countries using curing method "weighted mean from similar countries' using population for all individual person transport and technologies and GDP for all freight transport modes.

- Format RD
  - Type: type of regional distribution: RD_C (Installed Capacity) or RD_E (Energy)
  - ID: unique identifier of the RD
  - Region_ID_Type indicates to which ZoneHierarchy the value zone is belonging.

    It is optional but recommended to use. Reason: Allocating to a Zone Hierarchy set helps to uniquely identify zone if duplicate zone names, e.g. created by different modellers exits, e.g. cell_1, cell_2 etc., are existing.
  - Zone: identifier for data zone or region where the normalized value is valid
  - Value: normalized value of the given zone belonging to this regional distribution
  - MinValue, MaxValue - not applicable for RD
  - Profil_Timeseries - not applicable for RD
  - Unit: unit of normalized value of the given zone belonging to the regional distribution set. Typical input is au (arbitrary units)
  - Year (optional) indicates corresponding year / interval the RD was originally valid resp. created for.
  - Scenario: Identification for which scenario the RD is valid
  - Regional-Distribution - not applicable for RD

Type	ID	Region	Region_ID_Type	Zone	Value	minValue	maxValue	Profil_Timeserie	Unit	Year	Scenarios	Regional_Distribution
RD_C	RD_C__PV_ex		MIM_EU33	AL	0.0000				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	AT	0.0152				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	BA	0.0000				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	BE	0.0308				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	BG	0.0099				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	CH	0.0198				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	CZ	0.0181				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	DE	0.3731				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	DK	0.0082				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	EE	0.0002				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	EL	0.0206				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	ES	0.0442				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	FI	0.0008				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	FR	0.0883				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	HR	0.0002				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	HU	0.0057				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	IE	0.0005				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	IT	0.1595				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	LT	0.0005				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	LU	0.0011				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	LV	0.0000				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	ME	0.0001				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	MK	0.0002				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	NL	0.0333				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	NO	0.0000				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	PL	0.0027				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	PT	0.0138				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	RO	0.0113				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	RS	0.0001				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	SE	0.0056				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	SI	0.0021				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	SK	0.0042				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	UK	0.1298				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	NSA	0.0000				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	NSB	0.0000				au	2020		
RD_C	RD_C__PV_ex		MIM_EU33	BSA	0.0000				au	2020		

Table 6: Format Example regional distributions RD

3.2.5 MIM ZoneValue Data - installed capacity and annual energy output

The multi-modal investment model (MIM) is used to determine optimal investment decisions along the pathway from today to a chosen horizon of interest. Along the pathway in equal intervals for each interval the annual early retirements, new capacity and infrastructure installations, and the hourly generation/load schedules are simulated for each implemented technology.

The model starts its optimization from a historically grown technology mix currently existing in Europe. Consequently, for modelling the installed base in terms of installed generation capacities resp. current energy output / demand must be provided for each technology.

Table 7 shows exemplary data for the electric technology mix as projected by the [TYNDP] BE2020.

In order to create a consistent data set, data from the same data sources as have been used for creation of the regional distributions (see section 3.2.4) is used. From these data sets also projections of demands for heating, cooling, mobility and the exogenous electricity demand have been derived.

Country		Gas	Hard coal	Hydro-pump	Hydro-run	Hydro-turbine	Lignite	Nuclear	Oil	Other non-RES	Other RES	Solar-thermal	Solar-PV	Wind On	Wind Off
Albania	AL	100	0	0	394	1818	0	0	0	0	0	0	0	0	0
Austria	AT	4820	598	4287	4509	9989	0	0	174	984	620	0	2000	3880	0
Bosnia-Herzegovina	BA	0	0	440	1079	961	2323	0	0	0	0	0	0	100	0
Belgium	BE	4285	0	1150	117	1308	0	5919	0	1157	658	0	4044	2413	2310
Bulgaria	BG	12	168	933	540	2650	3895	1926	0	1314	90	0	1300	900	0
Switzerland	CH	0	0	4105	4139	13580	0	2905	0	520	380	0	2600	120	0
Czech Republic	CZ	1390	987	1000	365	1050	6704	4055	0	1907	917	0	2380	600	0
Germany	DE	23235	22700	6213	4329	6300	16635	8107	1713	7944	7827	0	49000	55500	6800
Denmark	DK	430	1190	0	7	0	0	0	817	126	790	0	1083	4346	2468
Estonia	EE	94	0	0	10	0	0	0	1947	150	127	0	30	500	0
Greece	EL	5214	0	699	252	3331	2240	0	0	0	325	100	2700	2700	0
Spain	ES	24560	3900	5980	3600	16890	0	7117	0	7570	1250	2300	5800	26100	0
Finland	FI	1394	2022	0	0	3200	0	4489	1900	450	2200	0	100	1600	40
France	FR	11035	2930	3500	13600	11500	0	61260	1358	0	2191	0	11600	16300	1400
Croatia	HR	1500	200	300	300	1800	0	0	0	200	250	15	30	750	0
Hungary	HU	2260	165	0	60	0	852	1888	410	585	330	0	750	329	0
Ireland	IE	3634	855	292	238	292	196	0	266	160	114	0	70	4100	0
Italy	IT	36000	7056	5732	5390	16456	0	0	1146	7564	5213	125	20952	11175	197
Lithuania	LT	1509	0	950	138	1125	0	0	0	227	164	0	70	500	0
Luxembourg	LU	0	0	1026	34	1310	0	0	0	90	41	0	140	150	0
Latvia	LV	1031	0	0	0	1619	0	0	0	121	192	0	0	109	24
Montenegro	ME	0	0	0	91	729	200	0	0	0	33	0	10	151	0
FYR of Macedonia	MK	290	0	0	141	579	615	0	198	0	26	0	32	50	0
The Netherlands	NL	9286	4608	0	38	0	0	486	0	4289	507	0	4376	5140	3057
Norway	NO	435	0	1115	0	33777	0	0	0	0	76	0	0	2850	0
Poland	PL	1506	15102	1488	983	1413	7136	0	0	7500	985	0	350	7050	240
Portugal	PT	3829	1756	2685	735	6466	0	0	0	1052	843	0	1816	5456	45
Romania	RO	3428	428	0	3215	3290	3217	1300	0	0	180	0	1480	3200	0
Serbia (ncl. Kosovo)	RS	140	0	560	2025	1063	4864	0	0	0	24	0	10	1068	0
Sweden	SE	448	80	0	0	16184	0	6852	520	390	4167	0	740	6900	190
Slovenia	SI	479	50	185	1197	180	787	696	0	141	61	0	277	42	0
Slovak Republic	SK	867	197	916	848	1708	240	1820	0	864	364	0	555	55	0
Great Britain	UK	28930	4782	0	92	1553	0	8985	1020	9774	6788	0	17050	13350	11790
North Sea	NS-A	0	0	0	0	0	0	0	0	0	0	0	0	0	
North Sea	NS-B	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Baltic Sea	BS-A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**EU33**	**172141**	**69774**	**43555**	**48465**	**162120**	**49903**	**117805**	**11469**	**55078**	**37733**	**2540**	**131345**	**177485**	**28561**

Table 7 Excerpt of installed capacities in 2020 as projected by source TYNDP2018 BE2020 updated (yellow) with data from ENTSO-E Statistical Factsheet 2018

These data is highly scenario dependent and has been defined in a way to meet the requirement of the scenarios planned in case study 1 for plan4res (see [5]). The corresponding datasets will be uploaded to the repository.

Furthermore, by using MinValue, MaxValue in combination with information for which year this restrictions are valid, a 'corridor of freedom' can be defined providing the solver important information, which restrictions for early retirements, planned decommission after end of lifetime, and or restrictions to new additions he has to meet, or simply what min or max energy generation is possible from 'model exogenous restrictions'.

- Format Zone Value Data

Type	ID	Region	Region_ID_Type	Zone	Value	minValue	maxValue	Profil_Timeserie	Unit	Year	Scenarios	Regional_Distribution
CapInst	CapInst__PV_L_ex		MIM_EU33	EU33	154	154	154	EU33c3_PV_2015_ninja_CAP	GW_el	2020	MIM_CS1__base	RD_C__PV_BE2020
CapInst	CapInst__PV_L_ex		MIM_EU33	EU33		0	169	EU33c3_PV_2015_ninja_CAP	GW_el	2030	MIM_CS1__base	RD_C__PV_BE2020
CapInst	CapInst__PV_L_ex		MIM_EU33	EU33		0	169	EU33c3_PV_2015_ninja_CAP	GW_el	2050	MIM_CS1__base	RD_C__PV_BE2020
CapInst	CapInst__PV_L_new		MIM_EU33	EU33	0	0	0	EU33c3_PV_2015_ninja_CAP	GW_el	2020	MIM_CS1__base	
CapInst	CapInst__PV_L_new		MIM_EU33	EU33		0	inf	EU33c3_PV_2015_ninja_CAP	GW_el	2021	MIM_CS1__base	
CapInst	CapInst__PV_L_new		MIM_EU33	EU33		0	inf	EU33c3_PV_2015_ninja_CAP	GW_el	2050	MIM_CS1__base	
CapInst	CapInst__PV_L_pan		MIM_EU33	EU33	0	0	0	EU33c3_PV_2015_ninja_CAP	GW_el	2020	MIM_CS1__base	RD_C__PV_Plan
CapInst	CapInst__PV_L_pan		MIM_EU33	EU33		113	169	EU33c3_PV_2015_ninja_CAP	GW_el	2030	MIM_CS1__base	RD_C__PV_Plan

Table 8: Format Example Zone Value 1 used in combination with RD from Table 6

Type	ID	Region_ID_Type	Zone	value	minValue	maxValue	Profil_Timeserie	Unit	Year	Scenarios	Regional_Distribution
CapInst	CapInst__Biomass_SPP_ex	MIM_EU33	EU33	24100	24100	24100		MW_el	2020	MIM_CS1__base	RD_C__BiomassPP_BE2020
CapInst	CapInst__Biomass_SPP_ex	MIM_EU33	EU33		0	0		MW_el	2050	MIM_CS1__base	RD_C__BiomassPP_BE2020
EnergyOut	EnergyOut__Biomass_SPP_ex	MIM_EU33	EU33	118	118	118		TWh_el	2020	MIM_CS1__base	
EnergyOut	EnergyOut__Biomass_SPP_ex	MIM_EU33	EU33		0	148		TWh_el	2025	MIM_CS1__base	
EnergyOut	EnergyOut__Biomass_SPP_ex	MIM_EU33	EU33		0	148		TWh_el	2050	MIM_CS1__base	
...											
CapInst	CapInst__PV_L_ex	MIM_EU33	EU33	154	154	154	TRD_CAP__PV_2015_NINJA__CAP	MW_el	2020	MIM_CS1__base	RD_C__PV_BE2020
CapInst	CapInst__PV_L_ex	MIM_EU33	EU33		92.4	154	TRD_CAP__PV_2015_NINJA__CAP	MW_el	2030	MIM_CS1__base	RD_C__PV_BE2020
CapInst	CapInst__PV_L_ex	MIM_EU33	EU33		0	0	TRD_CAP__PV_2015_NINJA__CAP	MW_el	2045	MIM_CS1__base	RD_C__PV_BE2020
CapInst	CapInst__PV_L_new	MIM_EU33	EU33	0	0	0	TRD_CAP__PV_2015_NINJA__CAP	MW_el	2020	MIM_CS1__base	
CapInst	CapInst__PV_L_new	MIM_EU33	EU33		0	inf	TRD_CAP__PV_2015_NINJA__CAP	MW_el	2021	MIM_CS1__base	
...											
EnergyDemand	EnergyDemand__ElectricityExo	MIM_EU33	EU33	2300	2300	2300	TRD_OUT__ElectricityExo	TWh_el	2020	MIM_CS1__base	RD_E__ElectricityExo
EnergyDemand	EnergyDemand__HeatInd	MIM_EU33	EU33	2879	2879	2879	TRD_OUT__HeatInd_HRE4	TWh_el	2020	MIM_CS1__base	RD_E__HeatInd
EnergyDemand	EnergyDemand__HeatInd	MIM_EU33	EU33	3167	3167	3167	TRD_OUT__HeatInd_HRE4	TWh_el	2050	MIM_CS1__base	RD_E__HeatInd

Table 9: Format example Zone Value 2

- Type: technical parameter installed capacity or energy out from technology identified in ID (e.g. CapInst, EnergyOut, EnergyDemand)

  NOTE: EnergyOUT and EnergyDemand are equal if EnergyOUT is not applied to a technology or conversion process, but to an energy carrier ('commodity'). Then both describe the given demand or consumption of this energy carrier, which can be linked to a TRD or TD profile to include consideration of temporal generation or demand patterns into modelling!

- ID identifier to the parameters with the technology (name convention: TypeName__TechIdentifier,

  Example_ CapInst__Biomass_SPP_ex indicates the installed capacity of the existing biomass fuelled steam power plants.

  Region_ID_Type indicates to which Zone Hierarchy the zone is belonging.

  It is optional but recommended to use. Reason: Allocating to a Zone Hierarchy set helps to uniquely identify zone if duplicate zone names, e.g. created by different modellers exits, e.g. cell_1, cell_2 etc., are existing.

- Zone: identifier for data zone or region where the value is valid

EU33 indicates that the technical parameter is valid for the sum all regions (see ZoneHierarchy).

Aggregated values, e.g. on EU33 level can be disaggregated by multiplying this value with the regional distribution (see section 3.2.4)

- Value: value of technical parameter
- MinValue, MaxValue: upper and lower limit of installed capacity or energy produced used as input for MIM modelling, describing the degree of freedom can use resp. the constraints the solver must consider while optimisation.

  Note: if this scheme is used for results from MIM modelling, then MinValue, MaxValue are usually not used. Instead discrete values for installed capacity or energy output are listed. Per technology
- Profil_Timeseries - connected TD or TRD profile - if available and applicable.
- Unit: unit of value of technical parameter typical options are:

CapInst	for electricity MW_el or GW_el for heating MW_th or GW_th
EnergyOUT	for electricity MWh_el or GWh_el for heating MWh_th or GWh_th for mobility G pkm or G tkm for physical product flows mio t
EnergyDemand	see EnergyOUT

- Year indicates corresponding year / interval the value is valid.

  Use linear interpolate between two base values stated for two years

  Use constant value if not required year is not between two base values
- Scenario: Identification for which scenario the value is valid
- Regional-Distribution (optional)

  Describes the corresponding RD defined

3.2.6 MIM Electric Cross Border Exchange – Interconnections

National energy systems of Europe are not independent. Instead at least by cross-border electricity exchange a strong coupling of the national energy systems exist, even on sub-hourly resolution.

Since regional resolution for MIM modelling is limited to country level, a grid representation of the interconnections for electric cross-border exchange is implemented.

Cross-border electricity exchange can be simulated by using a simplified approach considering maximum net transfer capacities (NTC) between regions and using link length for calculation of losses as fixed percentage per 1000km of transport.

- Existing grid and projected grid extension for interconnection

As data source projected NTC link data from entso-e’s dataset [TYND] is used. And, since modelling electric grid extension is in principle possible by the MIM but is not in focus for this case study two scenarios have been selected as ‘given starting grid’ and ‘given grid extension’ of the pan-European electric interconnecting grid.

  - CBA2027 represents the ‘existing’ grid, integrating all started or approved investment projects scheduled for commissioning till 2027.
  - ST2040 represents a projected grid extension between 2030 and 2040 optimised to enable a sustainable transition (ST) of the pan-European energy system.

The corresponding link data has been pre-processed to fit to the MIM model requirements:

1) To meet regional resolution all NTC links are reduced to country level by eliminating all intra-country links.
2) Multiple links between two countries, e.g. from different regions within a country, were aggregated to one ‘representing’ NTC value per country pair resp. link
3) Unidirectional links are changed to bi-directional nature, using as a rule the minimum NTC value from both directions.
4) Link length results from distance between centroid centre of the regional cells

Link	CBA2027	ST2040	Link	CBA2027	ST2040	Link	CBA2027	ST2040
AL-EL	250	350	CZ-DE	2000	2000	FR-LU	380	380
AL-ME	400	900	CZ-PL	600	600	UK-IE	780	2000
AL-MK	500	500	CZ-SK	1100	1100	UK-NL	1000	2500
AL-RS	500	830	DE-DK	3985	4000	UK-NO	2800	1400
AT-CH	1700	1700	DE-FR	4500	4800	EL-IT	500	500
AT-CZ	1000	1000	DE-UK	1400	1400	EL-MK	1200	1350
AT-DE	7500	7500	DE-LUG	2300	3300	HR-HU	2000	2000
AT-HU	800	800	DE-NL	5000	5000	HR-RS	600	2100
AT-IT	850	1335	DE-NO	1400	1400	HR-SI	2000	2500

AT-SI	1200	2200	DE-PL	2000	3000	HU-RO	1300	1300
BA-HR	1250	1812	DE-SE	1300	1815	HU-RS	600	1100
BA-ME	750	400	DK-PL	0	500	HU-SI	1200	1200
BA-RS	1100	1100	DK-SE	1980	1980	HU-SK	2000	2000
BE-DE	1000	1000	DK-UK	1400	1400	IT-ME	1200	1200
BE-FR	2800	4300	DK-NL	700	700	IT-SI	1640	1610
BE-UK	1000	2500	DK-NO	1640	2140	LT-LV	1200	1200
BE-LU	180	180	EE-FI	1016	1000	LT-PL	1000	500
BE-NL	3400	4900	EE-LV	1379	1250	LT-SE	700	700
BG-EL	800	1032	ES-FR	5000	9000	ME-RS	700	1000
BG-MK	500	100	ES-PT	3500	4000	MK-RS	750	650
BG-RO	1100	1400	FI-NO	0	0	NL-NO	700	1700
BG-RS	200	1350	FI-SE	3200	4100	NO-SE	3695	3695
CH-DE	3300	4100	FR-UK	6900	6900	PL-SK	990	990
CH-FR	1300	2800	FR-IE	0	700	PL-SE	600	600
CH-IT	3700	3700	FR-IT	2160	2160	RO-RS	1300	1050

Table 10 Bi-directional NTCs from the TYNDP projections for scenario CBA2027 ('existing grid') and ST2040 ('grid extension') after pre-processing to meet requirements of MIM modelling

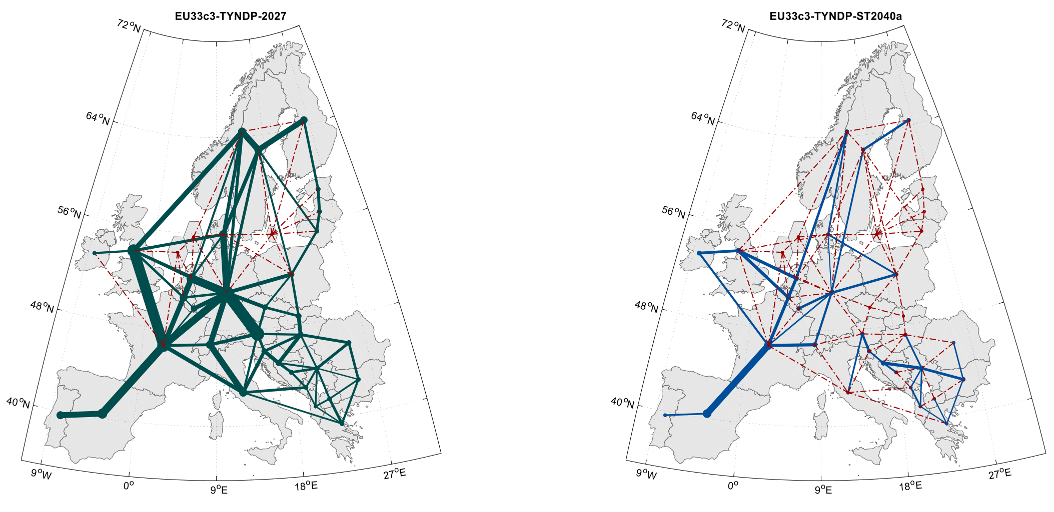


Figure 11 NTC based grid representation of (left) the existing grid according to CBA2027 (right) grid extension according to ST2040 displayed as delta to CBA2027

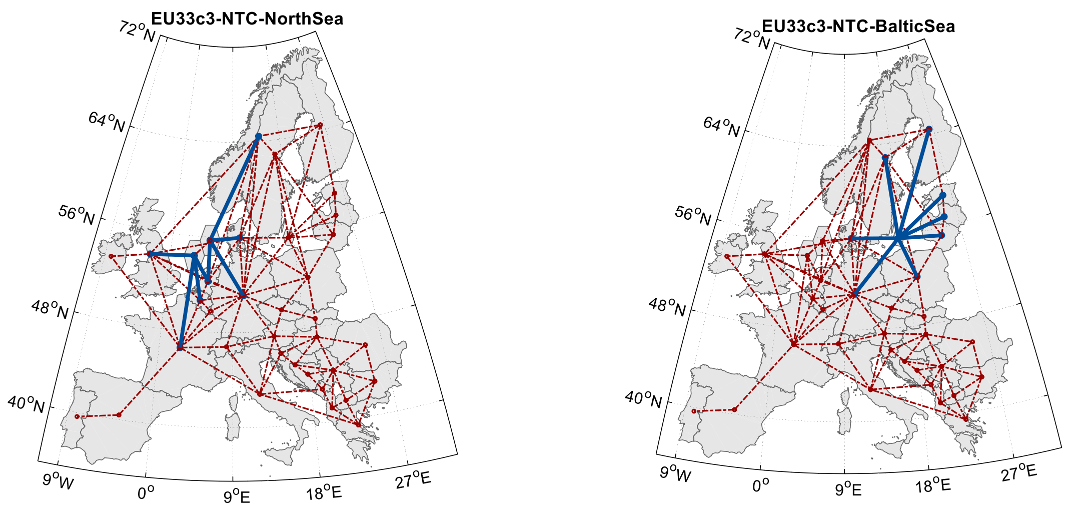


Figure 12 Potential grid extension for integration of wind offshore energy farms in the (left) north sea connecting region NSA and NSB to nearby countries (right) Baltic sea connecting region BSA to nearby countries

- Linking offshore North Sea and Baltic Sea cells

The North Sea and the Baltic Sea provide excellent wind offshore conditions. Nevertheless, a connection of these regions is currently not included in the TYNDP planning.

To enable modelling of wind offshore opportunities the potential new links are included to connect these cells to the adjacent countries. Initially NTC values of these links are set to zero, but, dependent on the detailed scenario constraints, NTC capacities can be set or the MIM optimizer can be enabled to install a limited amount of NTC capacities.

With the public dataset four datasets are provided:

- MIM__Interconnections_BaseNTC__20181231___20200131
- MIM__Interconnections_WindOffshore_NorthSeaNTC__20200131___20200131
- MIM__Interconnections_WindOffshore_BalticSeaNTC__20200131___20200131
- MIM__Interconnections_WindOffshore_NorthBalticSeaNTC__20200131___20200131

- Format Interconnections

Link_Name	Link_Type	Direction	Link_Origin	Link_Destination	MaxFlow	Impedance	Year
AL-EL	LIMIT	Bidirectional	AL	EL	250		2020
AL-ME	LIMIT	Bidirectional	AL	ME	400		2020
AL-MK	LIMIT	Bidirectional	AL	MK	500		2020
AL-RS	LIMIT	Bidirectional	AL	RS	500		2020
AT-CH	LIMIT	Bidirectional	AT	CH	1700		2020
...							
AL-EL	LIMIT	Bidirectional	AL	EL	250		2030
AL-ME	LIMIT	Bidirectional	AL	ME	400		2030
AL-MK	LIMIT	Bidirectional	AL	MK	500		2030
AL-RS	LIMIT	Bidirectional	AL	RS	500		2030
AT-CH	LIMIT	Bidirectional	AT	CH	1700		2030
...							
AL-EL	LIMIT	Bidirectional	AL	EL	350		2040
AL-ME	LIMIT	Bidirectional	AL	ME	900		2040
AL-MK	LIMIT	Bidirectional	AL	MK	500		2040
AL-RS	LIMIT	Bidirectional	AL	RS	830		2040
AT-CH	LIMIT	Bidirectional	AT	CH	1700		2040

Table 11: Format example grid Interconnections

This dataset describes the characteristics of electric interconnection lines that are linking the cells/regions forming a simplified model of the pan-European electric cross-border exchange.

- Link Name (optional): name of the line (used for processing results)
- Type: type of the line: (use only LIMIT for MIM modelling) LIMIT indicates usage of simplified NTC (max power in MW) without considering line impedance but line length for calculation of losses.
- StartLine and EndLine must be regions available in the model
- MaxFlow (MW) are the power constraints on the electrical flow represented as maximum net transfer capacities for this link
- Impedance (not relevant for MIM modelling): nan
- Direction: bi- or unidirectional (unidirectional: from first node to second only)
- Year indicates max power flow in the corresponding year / interval

  Interpolate values between given years.

3.2.7 MIM Technology Parameter - CAPEX, O&M, Efficiency, Lifetime

For evaluating investment decisions, costs are aggregated over several simulated years $y \in Y$ and discounted to a net present value in today's terms. Operational costs comprise all variable costs of all conversion processes $cp \in CS$, years $y \in Y$ and countries $co \in CO$, including fuel, CO_2 emission allowance and O&M costs which are linked to each conversion process. As side constraint the CO_2 emissions are minimized.

Data for all technologies from several technologies has been assembled to a consistent data set. Data sources used for determination of techno-economic cost, lifetime and efficiency, but also for required generation / demand energy output and installed technology base, including constraints for new installations or retirements are:

- [ENTSOFACTSHEET] see section 4.1.5
- [HRE4] see section 4.1.6
- [FhG ISE MODEL DATA] see section 4.1.7
- [HOTMAPS] see section 4.1.8
- [EUREF16] see section 4.1.9
- [JRC HEATING] see section 4.1.10
- [TYNDP] see section 4.1.12

Further references with information 'hidden in text' and only available as pdf or website are:

- IRENA – Electricity Storage and Renewables: Costs and Markets to 2030 [6]
- www.world-nuclear.org - Plans for new reactors worldwide [7]
- Agora Energiewende – RES vs. fossil fuels - costs of electricity systems [8]
- (German) UBA – Endbericht Energieversorgung Verkehr [9]

These data sets describe the characteristics and technical model parameters efficiency, lifetime, CAPEX and O&M costs of the implemented conversion processes CP. Corresponding data sets are created for all used technology (fleets).

An excerpt of the available data is listed in Table 14 to Table 15.

The following data sets have been created:

- Electricity generation by conventional technologies incl. co-generation plants

  MIM_ZoneValue_OPEXCAPEX_PP_CONV__20200131__20200131

- Electricity generation by conventional technologies using renewable energy sources

  MIM_ZoneValue_OPEXCAPEX_PP_RES__20200131__20200131
- Thermal heating energy generation technologies

  MIM_ZoneValue_OPEXCAPEX_Heating __20200131__20200131
- Thermal cooling energy generation technologies

  MIM_ZoneValue_OPEXCAPEX_Cooling__20200131__20200131
- Mobility - Technologies used for transport of persons or kilometers

  MIM_ZoneValue_OPEXCAPEX_Mobility __20200131__20200131

  Note: For the mobility sector CAPEX costs are modelled not with full investment costs, but as additional costs to the currently existing established technology in the particular subclass. These are:

  - Car IC (Diesel / Petrol)
  - BUS Public IC (Diesel)
  - Truck IC light (Diesel)
  - Truck IC heavy (Diesel)

  Due to modelling reasons delta CAPEX of the currently dominant technologies cannot be set to zero but is set to 1 instead.
- PowerToGas - Technologies used for power-to-gas technologies and related to hydrogen, synfuels

  MIM_ZoneValue_OPEXCAPEX_PowerToGas_conv__20200131__20200131
- Other technologies incl. generic industrial processes for methanol or ammonia synthesis

  MIM_ZoneValue_OPEXCAPEX_Industry_conv__20200131__20200131

- Format ZoneValue

Type	ID	Zone	value	minValue	maxValue	Profil_Timeserie	Unit	Year	Scenarios
CAPEX	CAPEX__Gas_CC	EU33	640				€/kW_inst	2020	base
CAPEX	CAPEX__Gas_CC	EU33	608				€/kW_inst	2030	base
CAPEX	CAPEX__Gas_CC	EU33	547				€/kW_inst	2050	base
OPEX	OPEX__GAS_CC	EU33	23				€/kW_inst/a	2020	base
OPEX	OPEX__GAS_CC	EU33	23				€/kW_inst/a	2030	base
OPEX	OPEX__GAS_CC	EU33	23				€/kW_inst/a	2050	base
Lifetime	Lifetime__GAS_CC	EU33	40				yrs	2020	base
Efficiency	Efficiency__GAS_CC	EU33	0.63				au	2020	base

Table 12: Format Example ZoneValue for technical parameters CAPEX, OPEX, technical lifetime, efficiency, here for an exemplary combined cycle gas turbine power plant

This dataset describes the characteristics and technical model parameters efficiency, lifetime, CAPEX and O&M of the implemented conversion processes resp. technologies.

- Type: type of technical model parameters (e.g. CAPEX, OPEX, technical lifetime, efficiency (and optional fuel efficiency for technologies with co-generation)
- ID identifier to connect technical model parameters with the technology (fleet) (name convention: TypeName__TechIdentifier, e.g. CAPEX__GAS_CC for CAPEX of gas-powered combined cycle power plants)
- Zone: identifier for region where the value is valid
  EU33 indicates that technical parameter is valid for all regions
- Value: value of technical parameter
- MinValue, MaxValue, Profil_Timeseries - not used

- Unit: unit of value of technical parameter with options:
  - Technical Lifetime — yrs
  - Net Efficiency — au or %
  - CAPEX — €/kW_inst
    - for storage — €/kWh_stor
    - for mobility — delta_€/vehicle
  - OPEX — €/kW_inst/a
    - for storage — €/kWh_stor/a
    - for mobility — €/1000 km

Note: Given Technical parameters represent the average of an installed technical fleet. This is important when dealing with existing installed base, where technical parameters might be lower than for new installations.

- Year indicates corresponding year / interval the value is valid.

  Use linear interpolate between two base values stated for two years

  Use constant value if not required year is not between two base values

- Scenario: Identification for which scenario the value is valid

	EFF	Lifetime	CAPEX [€/kW]			O&M [€/kW/a]			Source for Base Data in 2020
	[au]	[yrs]	2020	2030	2050	2020	2030	2050	
Gas CC	0.63	40	640	608	547	23	23	23	Agora 2017 (RES vs. fossil power plants - costs)
Gas SC	0.40	30	450	428	385	21	21	21	Agora 2017 (RES vs. fossil power plants - costs)
Gas SPP	0.45	40	990	941	847	41	41	41	Agora 2017 (RES vs. fossil power plants - costs)
Oil SC	0.40	30	495	470	423	23	23	23	Agora 2017 (RES vs. fossil power plants - costs)
Oil SPP	0.43	40	1073	1019	917	41	41	41	Agora 2017 (RES vs. fossil power plants - costs)
Gas CHP large	0.41	25	500	459	428	20	20	20	Agora 2017 (RES vs. fossil power plants - costs)
Gas CHP small	0.39	25	735	677	630	29	29	29	Agora 2017 (RES vs. fossil power plants - costs)
Other PP	0.30	25	1000	967	1000	41	41	41	Agora 2017 (RES vs. fossil power plants - costs)
Nuclear PP (refurbish)	0.33	20	1000	1000	1000	86	86	86	estimated from PPE France - refurbishment 50 b€ for 50GW for 20yrs
Nuclear PP (new)	0.34	40	6453	5163	4302	86	86	86	DIW 2019 Weekly Report 30;opex 1505 of SPP
Coal SPP	0.35	40	1650	1568	1411	41	41	41	Agora 2017 (RES vs. fossil power plants - costs) de
Lignite SPP	0.35	40	1900	1805	1625	41	41	41	Agora 2017 (RES vs. fossil power plants - costs) de
PV large	na	30	700	560	525	14	11	11	EU JRC 2019 kjna29938enn_1 p.56
PV small	na	30	1100	880	825	22	18	17	EU JRC 2019 kjna29938enn_1 p.51
Wind On	na	25	1365	1048	802	27	21	16	IRENA 2019 (Future of Wind) p.33
Wind Off	na	25	3965	2370	2124	79	47	43	IRENA 2019 (Future of Wind) p.47
Hydro River	0.90	45	1155	1155	1155	40	40	40	Agora 2017 (RES vs. fossil power plants - costs) de
Hydro Lake (Turbine)	0.90	45	1050	1050	1050	40	40	40	Agora 2017 (RES vs. fossil power plants - costs) de
Pumped Hydro (Turbine)	0.81	50	1000	1000	1000	40	40	40	Agora 2017 (RES vs. fossil power plants - costs) de
Biomass SPP	0.25	25	800	773	720	40	40	40	FhG ISE 2020 MODEL DATA
Biogas CHP MW	0.35	20	556	528	500	14	13	13	FhG ISE 2020 MODEL DATA
MSW PP	0.19	30	7000	6800	6500	210	210	210	Siemens 2019
Other PP (ind. Waste, ..)	0.15	40	5000	5000	5000	100	100	100	Siemens 2019
Battery Li-Ion - Power Unit (Inverter e.g. for Battery)	0.95	15	50	48	45	0.4	0.4	0.4	Siemens 2019
Battery Carnot - Power Unit	0.45	20	1000	967	900	20	19	18	Siemens 2019
Battery Carnot Brownfield - Power Unit	0.38	20	450	435	405	9	8.7	8.1	Siemens 2019
Chiller Absorption 1Stage	0.66	20	208	208	208	8	8	8	HRE4
Chiller Absorption 2Stage	1.19	20	351	351	351	14	14	14	Siemens 2019
Freezer Compression large	2.89	20	234	234	234	9	9	9	HRE4
Chiller Compression large	2.33	20	234	234	234	9	9	9	HRE4
Chiller Compression small	2.11	12	330	330	330	13	13	13	HRE4
Chiller District Cooling	3.87	20	234	234	234	9	9	9	HRE4
District Cooling	0.86	30	100	100	100	4	4	4	Siemens 2019
Furnace Coal (VHT)	0.85	30	1100	1100	1100	55	55	55	EU JRC 2019 Large Heating
Furnace Gas (HT)	0.80	30	1700	1650	1450	34	33	29	EU JRC 2019 Large Heating
Furnace Oil (VHT)	0.85	30	2000	1900	1800	40	38	36	EU JRC 2019 Large Heating
Furnace Biomass (VHT)	0.85	30	3600	3400	3000	72	68	60	EU JRC 2019 Large Heating
Furnance Electric (VHT)	0.95	30	1200	1200	1200	12	12	12	EU JRC 2019 Large Heating
Boiler Gas L (HT)	0.92	20	92	92	90	2	2	2	EU JRC 2019 Large Heating
Boiler Oil L (HT)	0.88	20	136	134	130	3	3	3	EU JRC 2019 Large Heating
Boiler Biomass L (HT)	0.85	20	251	236	26	5	5	1	EU JRC 2019 Large Heating
Heater Electric L (MT)	0.97	30	136	134	130	3	3	3	EU JRC 2019 Large Heating
Heat Pump L (MT)	4.17	20	692	638	625	14	13	13	EU JRC 2019 Large Heating
Heat Pump L (LT)	4.00	20	400	350	205	8	7	4	EU JRC 2019 Large Heating
Solar Thermal L (MT)	na	30	475	465	435	5	5	4	EU JRC 2019 Large Heating
Storage Heat HT - Power Unit	0.95	30	50	40	40	2.0	1.6	1.6	EU JRC 2019 Large Heating
Storage Heat MT - Power Unit	0.95	30	50	40	40	2.0	1.6	1.6	EU JRC 2019 Large Heating
Storage Heat LT - Power Unit	0.95	40	50	40	40	0.5	0.4	0.4	EU JRC 2019 Large Heating
Distritc Heating	na	35	74	72	70	0.7	0.7	0.7	EU JRC 2019 Large Heating
Boiler Hard Coal S (Heat decentral)	0.80	20	300	285	270	9	9	8	EU JRC 2017 Small Heating
Boiler Oil S (Heat decentral)	0.85	20	202	192	182	6	6	5	EU JRC 2017 Small Heating
Boiler Gas S (Heat decentral)	0.95	20	172	163	155	5	5	5	EU JRC 2017 Small Heating
Boiler Biomass S (Heat decentral)	0.80	20	400	380	360	12	11	11	EU JRC 2017 Small Heating
Solar Thermal S (Heat decentral)	na	30	773	657	580	15	13	12	EU JRC 2017 Small Heating
Heat Pump Air S (Heat decentral)	3.70	20	525	394	368	21	16	15	EU JRC 2017 Small Heating
Heat Pump Ground S (Heat decentral)	4.35	20	815	611	571	33	24	23	EU JRC 2017 Small Heating
Electric Heater S (Heat decentral)	1.00	20	128	115	102	3	2	2	EU JRC 2017 Small Heating
Insulation Old Building (Heat decentral)	1.00	50	300	280	250	0	0	0	Siemens 2019
Insulation New Building (Heat decentral)	1.00	50	150	140	125	0	0	0	Siemens 2019

Table 13 Technical model parameters efficiency, lifetime, CAPEX and O&M costs for generation technologies of sectors heating, cooling and electricity

	EFF_stor	Lifetime	CAPEX [€/kWh_stor]			O&M [€/kWh_stor/a]			Source for Base Data in 2020
	[au]	[yrs]	2020	2030	2050	2020	2030	2050	
Battery Carnot Brownfield	na	20	29	28	26	1	1	1	IRENA 2017 (Electricity Storage Costs)
Battery Carnot	na	20	29	28	26	1	1	1	IRENA 2017 (Electricity Storage Costs)
Battery Li-Ion central	0.90	15	241	179	169	4.8	3.6	3.4	IRENA 2017 (Electricity Storage Costs)
Battery Li-Ion decentral	0.90	15	303	199	182	9.1	6	5.5	IRENA 2017 (Electricity Storage Costs)
Hydro Lake (Dam / Storage)	0.95	100	2.9	3	3	0.4	1.0	0.4	IRENA 2017 (Electricity Storage Costs)
Pumped Hydro (Dam / Storage)	0.95	100	20	20	20	0.4	1.0	0.4	IRENA 2017 (Electricity Storage Costs)
Cold Storage	0.91	20	25	25	25	1	1	1	Siemens 2019
Ice Storage	0.86	20	25	25	25	1	1	1	Siemens 2019
Storage Heat HT		30	4	3	3	0.08	0.06	0.06	EU JRC 2019 Large Heating
Storage Heat MT	0.90	30	10	8	6	0.40	0.32	0.24	EU JRC 2019 Large Heating
Storage Heat LT	0.90	40	4	3	3	0.16	0.12	0.12	EU JRC 2019 Large Heating
Storage Pit Heat LT	0.90		0.4	0.38	0.35	0.01	0.02	0.01	Siemens 2019
Storage Heat decentral	0.95	20	29	29	29	0.9	0.9	0.9	EU JRC 2017 Small Heating

Table 14 Technical model parameters efficiency, lifetime, CAPEX and O&M costs for storage technologies of the energy carriers heating, cooling and electricity

	EFF_drive	Lifetime	Delta CAPEX [Delta €/vehicle]			O&M [€/1000 km]			Source for Base Data in 2020
	[kWh/km]	[yrs]	2020	2030	2050	2020	2030	2050	
Car IC	0.47	15	1	1	1	37	38	47	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
Car IC Gas	0.47	15	1798.5	1748	1658	42	43	51	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
eCar	0.20	15	8428.5	3810	1	58	48	47	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
eCar Fuel-Cell	0.20	15	9823.5	4616	1194	62	50	50	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
Bus Public Diesel	3.50	17	1	1	1	96	99	99	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
Bus Public Gas	3.94	17	26001	25634	20001	110	113	110	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
eBus Public Battery	1.48	17	100001	68001	27001	149	135	114	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
eBus Public FCEV	2.67	17	177315	49834	26882	191	126	114	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
Truck Diesel light	1.21	11	1	1	1	51	51	51	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
Truck Gas light	1.21	11	4501	4501	1	57	57	51	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
eTruck light	0.86	11	8428.5	3810	1	61	56	51	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
Truck Diesel heavy	2.25	11	1	1	1	49	59	55	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
Truck Gas heavy	2.52	11	26406	23095	20841	67	74	69	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
eTruck eHighway Hybrid heavy	2.35	11	37083	19603	19011	34	33	31	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)
eTruck eHighway Battery heavy	1.36	11	48202.5	30370.7	29206.5	38	36	35	UBA 2016 (Endbericht Energieversorgung Verkehrs 2050)

Table 15 Technical model parameters efficiency, lifetime, CAPEX and O&M costs for technologies of the sector mobility - note here CAPEX is stated as delta costs to existing technologies

3.2.8 MIM Fuel and CO2 emission costs

Cost for CO_2 emissions allowance and fuel costs are highly scenario dependent. A set of fuel costs parameters has been already defined in the plan4res deliverable D2.1 [5] which is used for the base the public dataset. This includes the energy carriers’ natural gas, crude oil, liquid fuel, hard coal and lignite. Additionally, the model needs inputs for various types of biomass, e.g. wood and waste wood, energy crops, sewage sludge, straw.

The MIM_ZoneValue_FuelCosts__20200131__20200131 dataset includes fuel cost information for all primary energy carries, (potentially) ‘imported’ to Europe.

- Format

Type	ID	Zone	value	minValue	maxValue	Profil_Timeserie	Unit	Year	Scenarios
FuelCosts	FuelCosts__Natural_Ga	EU33	16.6				€/MWh	2020	base
FuelCosts	FuelCosts__Natural_Ga	EU33	30.7				€/MWh	2030	base
FuelCosts	FuelCosts__Natural_Ga	EU33	32.7				€/MWh	2050	base
FuelCosts	FuelCosts__Crude_Oil	EU33	35.2				€/MWh	2020	base
FuelCosts	FuelCosts__Crude_Oil	EU33	39.4				€/MWh	2030	base
FuelCosts	FuelCosts__Crude_Oil	EU33	37.2				€/MWh	2050	base
CO2Costs	CO2Costs	EU33	25				€/t_CO2	2020	base
CO2Costs	CO2Costs	EU33	33				€/t_CO2	2030	base
CO2Costs	CO2Costs	EU33	90				€/t_CO2	2050	base

Table 16: Format Example ZoneValue for fuel costs, here for the exemplary primal energy carriers natural gas and crude oil, and for CO_2 emissions allowance costs

- Type: type of fuel cost parameters (e.g. FuelCost or CO2Costs)
- ID identifier to connect cost parameters with the energy carrier (name convention: TypeName__CarrierIdentifier, e.g. FuelCosts__Natural_Gas for fuel costs of natural gas imports).
- Zone: identifier for region where the value is valid
  EU33 indicates that technical parameter is valid for all regions
- Value: value of fuel cost parameter
- MinValue, MaxValue, Profil_Timeseries - not used
- Unit: unit of value of technical parameter with options:
  - fuel costs €/MWh
  - CO_2 costs €/t_CO_2

  Note: Given fuel cost parameters represent the average of an installed technical fleet. This is important when dealing with existing installed base, where technical parameters might be lower than for new installations.
- Year indicates corresponding year / interval the value is valid.

  Use linear interpolate between two base values stated for two years

  Use constant value if not required year is not between two base values
- Scenario: Identification for which scenario the value is valid

3.3 European Market Simulation Files

This section describes the public available data used for the European market simulation. Further input data are based on commercial data or processed using background knowledge and preexisting tools of the respective partner and thus not further described here.

The public data include the electricity demand timeseries in Megawatt (MW) for the historical year 2012 which are a main input to the model since it determines the temporal structure of the demand that has to be met:

- An excel file entsoe__electric_demand_2012__20200414T115001Z__20200414T113100Z.xlsx that contains
    - A column stating the timestamp in UTC timeformat
    - One column each for the electricity demand per country for one specific year (8760 hours)

3.4 Transmission expansion

This section provides an insight into the data that are used in case study 2.

- In the deterministic model, there are 4 nodes in total, each for every epoch. That is, node 1 belongs to epoch1, node 2 to epoch 2 etc.
- The deterministic planning includes 1 scenario (perfect information).
- The topology comprises countries, that act as 'buses' in a grid, as per the figure below. Specifically, circular nodes represent the countries considered in the study, while the black lines represent interconnector power transmission lines. There are 69 interconnectors in total assumed in the study and 33 busbars(countries).
- For each interconnector some technical details are assumed such as the reactance of the cable (in per unit) , as well as the corresponding rating (MW)– which are all internal data of Imperial College.
- Note that the interconnectors used represent aggregate interconnectors' capacities i.e. between any two countries there is only one such interconnector representing the total capacity of interconnectors between the two countries in reality.

- A total of 69 interconnectors are assumed in the model. These link two different countries, and have some initial capacity. They can all be upgraded by the planner, optimally, based on the model solution process.
- A total of 69 interconnectors are assumed in the model. These link two different countries, and have some initial capacity. They can all be upgraded by the planner, optimally, based on the model solution process.
- Each interconnector is characterized by a variable cost for investment i.e. capacity upgrade.
- Each interconnector is characterized by a fixed cost for investment i.e. capacity upgrade. T

3.5 CEM – SSV – EUC Input Files

This section describes the format of data used to feed the models used in Capacity Expansion Model, Seasonal Storage Valuation Model and European Unit Commitment model.

The dataset is organized as follows:

- An excel file InputDataXXX.xlsx (which is based on the common format described in 3.1. It is composed of the following sheets :
    - Parameter: contains all parameters for the tool and a description of coupling constraints
    - ZP_ZonePartition: contains the description of the different geographical partitions (follows common format for patitions)
    - ZV_ZoneValues : contains data linked to zones (follows common format for data depending on zones)
    - IN_Interconnections: contains the description of the network (follows common format on interconnections)
    - TU_ThermalUnits: contains the description of the thermal power plants (follows common format for data depending on zones)
    - SS_SeasonalStorage: contains the description of the hydrovalleys and other long term storages (follows common format for data depending on zones)
    - STS_ShortTermStorage: contains the description of other storages: batteries but also demand-response. (follows common format for data depending on zones)
    - RES_RenewableUnits: contains the description of PV, WindPower and RunofRiver (follows common format for data depending on zones)
    - SYN_SynchCond: contains the description of synchronous compensers (follows common format for data depending on zones)

- TS_xxx: sheets containing timeseries profiles. There may be different sheets with different time granularity (follows common format on time series)

- A set of CSV files containing scenarised time series: those files follow the common format on time series, ie 2 lines of heading; The first column contains the UCT timestamp (yyyy/mm/dd hh:mm) and the following columns are different scenarios of the current timeserie=> one CSV file contains one scenarized timeserie. Scenarios are stamped by the value in the line2 (usually past years, eg 1970, 1971, 1972…);

In the following section we describe the different components.

3.5.1 Excel sheet Parameter

CouplingConstraints								
Name	Unit	Partition	Is a sum of					
ActivePowerDemand	MWh	Level2	ElecHeating	AirCondition	nonthermo	ElecVehicle	fatal	import
InertiaDemand	MWs/MWA	Level4						
SecondaryDemand	MWh	Level3Part1						
PrimaryDemand	MWh	Level3Part1						
PollutantBudget	tons	Level3Part2						
Calendar								
	Unit							
UCBegin	UTC	02/01/2050 00:00						
UCEnd	UTC	04/01/2050 23:00						
UCTimeStep	hours	1						
UCScenarios		1982	1983	1984				
SSVTimeStep	hours	24						
DataScenarios		ActivePowerDemand	Thermal:MaxP	Hydro:Inflows	Renewable:MaxPowerProfile			
Mode	SSV	-500						

Figure 13: Sheet 'Parameter'

This sheet is composed of 2 sets of data:

- Coupling Constraints: this lists the different coupling constraints that may be used. If a coupling constraint is not used, the line is deleted. For each constraint, the Unit is given as well as the Partition, which describes the zones attached to each coupling constraint. The following constraints may be included :
  - ActivePowerDemand: this is related to the equilibrium constraint Active power = Active Power demand at each node of the network. The Active Power Demand is computed as the sum of different time-series that are listed in the corresponding line (this means that the power demand is computed as the sum of the electric heating demand, the electric cooling demands….)

  - PrimaryDemand: this is related to the primary reserve, in each “zone” (can be a country….)
  - SecondaryDemand: this is related to the secondary reserve.
  - InertiaDemand: this is related to the inertia requirement.
  - PollutantBudget: this constraint is not used in the current version of the tool. It is related to the maximum amount of polluting emissions, for a specific pollutant.
- Model Parameters :
  - Time horizon parameters
  - Scenario parameters
  - Mode can be:
    - UC: this means that only a Unit Commitment problem will be solved for the first timeset (ie the first SSV timestep), on the first scenario of the list
    - SSV: this means that the seasonal storage problem will be solved. SSV needs a parameter (an estimation of the lower bound of the polyhedral function), which is given here.
    - SIM: this means that Unit Commitment problems will be solved on all time steps of the SSV, one after the other, for a given scenario (or list of scenarios)
    - There may be a parameter in the column after ‘mode’, which is a solver parameter (for SSV, it is an approximation of the lower bound)

`Time`

The parameter sheets contains parameters that describe the coupling constraints, parameter that describe the time horizon and model parameters.

Time is discretized in:

- Time Sets (usually 1 week)
- Time Steps (usually 1 hour)

The granularity of the data in the different groups of TimeSeries may be different. In practice, there may exist hourly, daily or weekly time series. If the time step of the given data is different than the time step of the variable to be filled, it means that:

- If the unit is % or MW/GW, the value of the variable at lower timesteps will be the one that is in the dataset.

- If the unit is MWh/GWh, the value of the variable at lower timesteps has to be adapted (eg 24GWh on a daily timestep means 1GWh on an hourly timestep)

The time horizon is described in by the following variables in the 'calendar' block of the Sheet Parameter.

- UCBegin: is the first timestep of the study. It has to be provided as a UTC timestamp.
- UCEnd is the last timestep of the study
- UCTimestep is the timestep duration. If 'hours' is specified in the unit column, it means that it is a number of hours. This means that the total number of time steps of the whole Time Horizon is (UCEnd-UCBegin)/UCTimeStep (in the example below, we have 3 days and a timestep of 1 hour then 72 timesteps. Each time a profile is used, only the data comprised between UCBegin and UCEnd are used
- SSVTimeStep gives the duration of the Time Sets (which is the seasonal storage timestep). In the current example, it is 24 hours (1 days) which means that there are 3 Time Sets of 1 day each. SSVTimeStep has to be at least bigger than UCTimeStep.

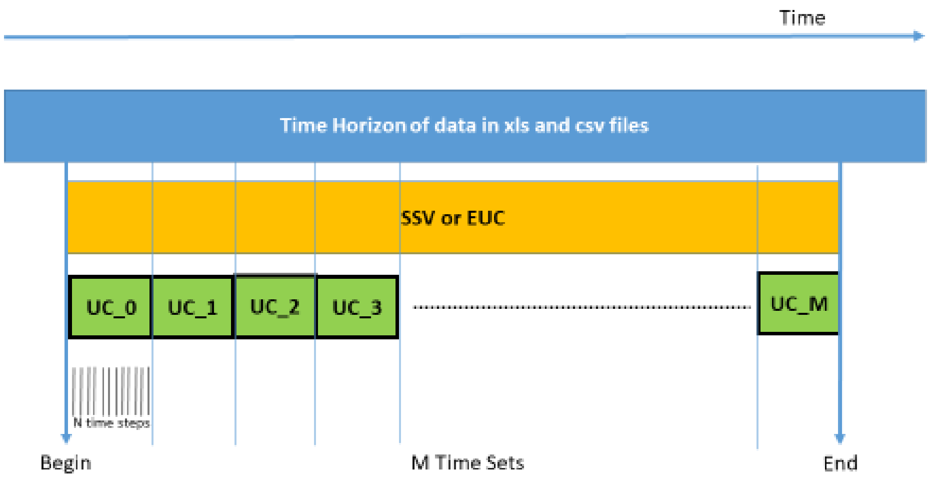


Figure 14: Time Management

Scenarios

The UC solver (and the UC simulator) are deterministic, which means it runs on 1 scenario only. The line UCScenario contains the list of scenarios identifiers that will be used for generating the scenario data (not yet included). Here in the example we have 3 identified scenarios: 1982, 1983, 1984. In the data we may have some scenarized timeseries (in our example only the timeseries from the csv file), and some non scenarized timeseries. Scenarized timeseries are identified by a scenario tag (here it is the historic year that was used for computing the data).

When using a deterministic mode, only the first scenario will be used.

The parameters related to scenarios in Parameter sheet are the following:

- UCScenarios is the list of scenarios identifiers. Those identifiers have to be at the top of the column related to this scenario, for all variables of the current scenario.
- DataScenario is the list of variables that are scenarised in the current run. This list can comprise:
    - ActivePowerDemand
    - Thermal:MaxPower (the maximum power for thermal plants, accounting for unavailabilities schedules)
    - Hydro:Inflows (the hydraulic inflows at seasonal reservoirs)
    - Renewable:PmaxProfile (the maximum capacity of renewables)

3.5.2 Excel sheet ZP_ZonePartition

Level1	Level2	Level3Part1	Level3Part2	Level4
FR1cluster1	FR1	FR	North	EU
FR1cluster2	FR1	FR	North	EU
FR1cluster3	FR1	FR	North	EU
FR2	FR2	FR	South	EU
EScluster1	ES	ES	South	EU
EScluster2	ES	ES	South	EU
BE	BE	BE	North	EU

Figure 15: Sheet 'ZP_ZonePartition'

The sheet ZP_ZonePartition describes the different partitions that are used for dealing with different coupling constraints.

The mapping between the coupling constraints and the partitions is defined in the first block of the sheet parameter:

- Here ActivePowerDemand is using level2. This means that level2 is the level to be used to generate the nodes of the model. In the example we have 4 nodes: FR1, FR2, ES and BE. (which is consistent with the description of the network in the sheet IN_Interconnections).
    - In practice the model will receive the constraint at each node FR1, FR2, ES, BE ActivePower in the current node=ActivePowerDemand of the current node
- InertiaDemand uses level4 (which in the example is EU). This means that there is only one InertiaDemand constraint
    - In practice the model will receive the constraint Total inertia (ie sum of the inertia in the 4 nodes)=inertiademand
- PrimaryDemand and SecondaryDemand use level3partition1 (which in the example is FR-=FR1+FR2, ES, BE). This means that there is are 3 PrimaryDemand constraints and 3 SecondaryDemand constraints
    - In practice the model will receive the constraints
        - PrimaryPower in FR1+PrimaryPower in FR2=PrimaryDemand in FR
        - PrimaryPower in ES =PrimaryDemand in ES
        - …

3.5.3 Excel sheet ZV_ZoneValues

Type	Zone	value	minValue	maxValue	Profile_Timeserie	Unit	2050
ElecHeating	FR1	1500	0	15000	EDF__HourlyCoef-Heating-PresentClim	MW	2050
aircondition	FR1	400	0	15000	EDF__HourlyCoef-AirCondition-Present	MW	2050
nonthermo	FR1	3400	0	15000	nate-FR__20062019__28062019__v1.csv	MW	2050
ElecVehicle	FR1	200	0	15000	EDF__HourlyCoef-ElecVehicle__200620	MW	2050
nonthermo	FR2	1			ActiveDemand_FR2	MW	2050
nonthermo	ES	1			ActiveDemand_ES	MW	2050
nonthermo	BE	1			ActiveDemand_BE	MW	2050
InertiaDemand	EU	15				MWs/MWA	2050
SecondaryDemand	BE	5000			AncillaryProfile	MWh	2050
SecondaryDemand	ES	2000			AncillaryProfile	MWh	2050
SecondaryDemand	FR	3000			AncillaryProfile	MWh	2050
PrimaryDemand	BE	1000			AncillaryProfile	MWh	2050
PrimaryDemand	ES	300			AncillaryProfile	MWh	2050
PrimaryDemand	FR	2000			AncillaryProfile	MWh	2050
CostActivePowerDeman	FR	3200				€/MWh	2050
CostActivePowerDeman	EU	3000				€/MWh	2050
CostInertia	EU	1000				€/MWh	2050
CostSecondaryDemand	FR	500				€/MWh	2050
CostSecondaryDemand	ES	600				€/MWh	2050
CostSecondaryDemand	BE	400				€/MWh	2050
CostPrimaryDemand	EU	800				€/MWh	2050
fatal	FR1	-1			runofriverFR1	MW	
MaxInertiaDemand	EU	6000				MWs/MWA	2050
MaxSecondaryDemand	BE	5000			0,05	MWh	2050
MaxPrimaryDemand	ES	8000			0,05	MWh	2050
PrimaryDemand	ES	300			0,05	MWh	2050
MaxActivePowerDeman	FR	12000			0,05	MWh	2050

Figure 16: ZV_ZoneValue sheet

This sheet contains the values of all coupling constraints, as well as the costs associated (imbalance costs).

3.5.4 Excel sheet IN_Interconnections

Unit Name	Type	Direction	StartLine	EndLine	MWh MaxPowerFl	S Impedance	Year	MWh MinPowerFl
1	AC	Bidirectional	FR1	FR2	100	6,5	2050	0
2	AC	Bidirectional	FR1	BE	200	6,5	2050	0
3	DC	Bidirectional	BE	ES	50		2050	0
4	LIMIT	Bidirectional	FR2	ES	50		2050	0
6	AC	Bidirectional	FR2	BE	300	60	2050	0

Figure 17: IN_Interconnections sheet

This sheet describes the characteristics of the lines that are linking the nodes of the network, where the nodes are those described in the partition linked to the ActivePowerDemand variable:

- Name (optional): name of the line (used for processing results)
- Type: type of the line
- StartLine and EndLine must be nodes defined in the partition linked to the ActivePowerDemand
- MaxPowerFlow and MinPowerFlow are the bounds on the flows for this line
- Impedance
- All lines are bidirectionnal.
- Year is optionnal

3.5.5 Excel Sheet TU_ThermalUnits

Units		integer	MW	MW	MW	€	€	€/MWh	€/Mw^2.h	hours	hours	MWs/MWA			MW/h	MW/h	%	days	%
Name	Zone	NumberUnits	MaxPower	MinPower	Pauxiliary	Fixed Cost	StartUp Cost	Variable Cost	QuadTerm	MinUp Time	MinDownTime	Inertia	Primary Rho	Secondary Rho	Delta Ramp Down	Delta Ramp Up	UnavailabilityRate	MeanUnavailabilityDuratio	MaintenanceRate
Type3	FR1	1	MaxPower_FR1	300	-25	4	0	5	0	24	24	50	0,1	0,2	100	100	0,1	1	0,2
Type4	FR1	2	300	0	0		0	90	0	12	12	10	0	0,5	300	300	0,01	4	0,15
Type1	FR2	1	200	100	0		25000	30	1	1	1	20	1	1	100	100	0,02	3	0,1
Type2	FR2	1	266	80	-20		0	90	0	2	2	10	0,1	0,2			0,02	2	0,25
Type4	ES	1	300	0	0		0	90	0	12	12	10	1	1,2	150	100	0,02	1	0,1
Type1	BE	1	200	100	0		25000	30	0	1	1	20	0,1	2	ramp1	ramp2	0,02	1	0,05
Type2	BE	1	266	80	0		0	90	0	2	2	10	0,1	0	50	100	0,02	1	0,01

Figure 18: TU_ThermalUnits sheet

This sheets gives the characteristics of all thermal power plants.

It contains the following data:

- Name
- Zone
- NumberUnits : number of units of the same type at the same location
- MaxPower
- MinPower (optional, 0 by default)
- Pauxiliary: Power taken from the system when off. Optional (0 by default)
- FixedCost: Optional (0 by default) ;

- VariableCost: proportional cost; Optional (0 by default).
- Quadterm: quadratic cost; Optional (0 by default)
- StartUpCost: Optional (0 by default)
- MinUpTime: minimum duration when the plant is on; Optional (0 by default)
- MinDownTime: minimum duration when the plant is off; Optional (0 by default)
- Inertia: max inertia that can be provided by a unit; Optional (0 by default)
- PrimaryRho: this parameter, multiplied by Maxpower, gives the maximum primary reserve that can be provided by a unit; Optional (0 by default)
- SecondaryRho: this parameter, multiplied by Maxpower, gives the maximum secondary reserve that can be provided by a unit; Optional (0 by default)
- DeltaRampDown: maximum gradient when the power is decreased from one time step to the other. Optional (MaxPower by default)
- DeltaRampUp: maximum gradient when the power is increased from one time step to the other. Optional (MaxPower by default)
- UnavailabilityRate: rate of unavailability for failure. Optional (0 by default)
- MeanUnavailabilityDuration: mean duration of unavailability. Optional (0 by default)
- MaintenanceRate: rate of unavailability for maintenance. Optional (0 by default)

3.5.6 Excel sheet SS_SeasonalStorage

Unit			€/MWh	MW	MW	MW/h	MW/h	MWh	MWh				MWh	MWh			MWs/MWA	€/MWh
Name	Zone	Number Units	Variable Cost	MaxPower	MinPower	Delta Ramp Up	Delta Ramp Down	MaxVolume	MinVolume	TurbineEfficiency	PumpingEfficiency	Inflows	InitialVolume	VolumeLevelTarget	Primary Rho	Secondary Rho	Inertia	WaterValues
SSFR	FR1	1		150	0	100	100	1000	0	1	0	InflowFR	0		0,2	0,2	20	east-A_LAC_AGREGE
SSSP	ES	1		330	-100	100	100	2000	0	1	0,7	InflowES	0		0	0	10	west-A_LAC_AGREGE
SSDR	FR2	1		PmaxDR	0	100	100	300	0	1	0	InflowsDR	0		0	0	0	

Figure 19: SS_SeasonalStorage sheet

This sheets gives the characteristics of all seasonal storages.

It contains the following:

- Name
- Zone
- NumberUnits : number of units of the same type at the same location

- MaxPower
- MinPower (optional, 0 by default)
- VariableCost: proportional cost. (optional, 0 by default)
- DeltaRampDown: maximum gradient when the power is decreased from one time step to the other. Optional (MaxPower by default)
- DeltaRampUp: maximum gradient when the power is increased from one time step to the other. Optional (MaxPower by default)
- MaxVolume
- MinVolume (optional, 0 by default)
- TurbineEfficiency: (optional, 1 by default). This value, multiplied by the flow, gives the generated power.
- PumpingEfficiency: (optional, 1 by default). This value, multiplied by the flow, gives the generated power.
- Inflows: (optional, 0 by default). Inflows to the upstream reservoir (energy per year).
- Inflows profile: (optional): time serie profile for Inflows. Multiplied by the Inflows in energy, gives the inflows time serie.
- InitialVolume: (optional, 0 by default). Initial Volume of the upstream reservoir
- Inertia: max inertia that can be provided by a unit; Optional (0 by default)
- PrimaryRho: this parameter, multiplied by Maxpower, gives the maximum primary reserve that can be provided by a unit; Optional (0 by default)
- SecondaryRho: this parameter, multiplied by Maxpower, gives the maximum secondary reserve that can be provided by a unit; Optional (0 by default)
- WaterValues: Optional; Used if external water values are used in the current run. Contains the name of the file/sheet where the water values are stored.

3.5.7 Excel sheet STS_ShortTermStorage

			€/MWh	hours	MW	MW	MWh	MWh	TurbineEfficiency		MWh	MW	MW	MWh
Nam e	Zone	Numbe rUnits	Cost	Window Size	MaxPower	MinPower	MaxVolume	MinVolume	TurbineE fficiency	PumpingEf ficiency	Volum eLevel Target	MaxPrim aryPowe r	MaxSecon daryPowe r	Inflows
Bat1	FR1	2	30	24	4	-5	30	0	1,1	0,85		4	2	10
BatLS	ES	1	5	24	20	-10	100	0	1,2	0,65		0	0	InflowsLS

Figure 20: STS_ShortTermStorage sheet

This sheets gives the characteristics of all short term storages.

It contains the following data (:

- Name
- Zone
- NumberUnits : number of units of the same type at the same location
- WindowsSize (optional): size of the windows where load shifting is allowed
- MaxPower
- MinPower (optional, 0 by default)
- Cost: proportional cost. (optional, 0 by default)
- MaxVolume
- MinVolume (optional, 0 by default)
- TurbineEfficiency: (optional, 1 by default). This value, multiplied by the flow, gives the generated power.
- PumpingEfficiency: (optional, 1 by default). This value, multiplied by the flow, gives the generated power.
- Inflows: (optional, 0 by default). Inflows to the upstream reservoir.
- InitialVolume: (optional, 0 by default)
- VolumeLevelTarget: used to force the optimisation to reach this volume at the end of each time set. If there is a VolumeLevelTarget filled, then the minimum volume constraint is replaced by this value at first and last timesteps of each time set.
- MaxPrimaryPower: maximum primary reserve that can be provided by a unit; Optional (0 by default)

- MaxSecondaryPower: maximum secondary reserve that can be provided by a unit; Optional (0 by default)

3.5.8 Excel Sheet RES_RenewableUnits

Unit			MW	MW	Link to profile of fixed %	MWs/MWA	percentage
Name	Zone	NumberUnits	MaxPower	MinPower	MaxPowerProfile	Inertia	Gamma
WindPlantType1	FR2	2	10	0	WindOnshore	0	0,5
WindPantType2	BE	1	10	0	WindOnshore	0	0,5
WindOffshore	BE	1	50	0	WindOffShore	0	0,5
PVType1	FR2	3	30	0	PVFR	0	0,8
PVType2	ES	1	10	0	PVES	0	0,5
RunofRiver	FR1	1	2000	0	runofriverFR1	1	1

Figure 21: RES_renewableUnits sheet

This sheets gives the characteristics of all renewable units: windpower, PV power and run-of-river.

It contains the following data:

- Name
- Zone
- NumberUnits: number of units of the same type at the same location
- MaxPower
- MinPower (optional, 0 by default)
- Inertia: max inertia that can be provided by a unit; Optional (0 by default)
- Gamma (optional, 1 by default): this parameter is used by the model to determine the maximum available primary and secondary reserve. It is used to take into account the fact that some renewable units, due to the uncertainty in their maximum capacity, may not be able to provide reserve at full capacity.

3.5.9 Excel Sheet SYN_SynchCond

Unit	Text			MW	€	€	MWs/MWA
Name	Techno	Zone	NumberUnits	RotatingConsumption	ConstTerm	StartUpCost	Inertia
SynchCondTypeC1	SynchConde	FR1	1	-20	2	300	20
SynchCondTypeC3	SynchConde	FR2	2	-30	3	500	10

Figure 22: SYN_SynchCond sheet

This sheets gives the characteristics of all synchronous condensers. Synchronous condensers are units that consume energy from the grid and provide inertia.

It contains the following data:

- Name
- Zone
- NumberUnits: number of units of the same type at the same location
- MaxRotatingConsumption: this is the maximum power of the unit, that being consumed by the unit, will allow it to provide inertia.
- ConstTerm: Optional (0 by default) ;fixed cost
- Inertia: max inertia that can be provided by a unit; Optional (0 by default)

3.5.10 Excel Sheets TS_xxx (time series)

TS sheets contain time series with different time granularity. 3 different sheets can be used:

- TS_HourlyTimeSeries, for hourly data:

Unit	%	MW	MW	MW	MW
	AncillaryProfile	ActiveDemand_FR2	ActiveDemand_ES	ActiveDemand_BE	MaxPower_FR1
nestamp [UTC] / scenario					
02/01/2050 00:00:00	0,1	554,6	301,3	148,8	400
02/01/2050 01:00:00	0,1	554,6	301,8	158,8	400
02/01/2050 02:00:00	0,05	504,6	151,8	158,8	450
02/01/2050 03:00:00	0,05	561	155	276	450
02/01/2050 04:00:00	0,05	561	34,5	266	400
02/01/2050 05:00:00	0,1	554,6	301,3	148,8	400
02/01/2050 06:00:00	0,1	554,6	301,8	158,8	400
02/01/2050 07:00:00	0,05	504,6	151,8	158,8	450
02/01/2050 08:00:00	0,05	561	155	276	450
02/01/2050 09:00:00	0,05	561	34,5	266	400
02/01/2050 10:00:00	0,1	554,6	301,3	148,8	400

Figure 23: TS_HourlyTimeSeries sheet

- TS_DailyTimeSeries, for daily data. In that case the convention in the model is that in case of data in MW (or GW…), the data will be duplicated at each timestep of the day (if timesteps are lower than 1 day); In case of MWh (or GWh…), the data has to be either associated to the first time step of the day (and 0 at the others), or it has to be converted to the duration of the timestep and then duplicated.

Unit	MW	MW	MW	MWh
Timestamp [UTC]	InflowFR	InflowES	InflowsDR	InflowsLS
01/01/2050	70	200	0	5
02/01/2050	80	200	0	5
03/01/2050	80	200	0	5
04/01/2050	80	200	0	5
05/01/2050	80	200	0	2
06/01/2050	80	200	0	2
07/01/2050	80	200	75	0
08/01/2050	80	200	75	0
08/01/2050	80	200	75	0

Figure 24: TS_DailyTimeSeries sheet

- TS_WeeklyTimeSeries: for weekly data. The same rules apply for MW/MWh data than for daily data.

Unit	MW	MW
Timestamp [UTC]	InflowFR	InflowES
01/01/2050	70	200
02/01/2050	80	200
03/01/2050	80	200
04/01/2050	80	200
05/01/2050	80	200
06/01/2050	80	200
07/01/2050	80	200
08/01/2050	80	200
08/01/2050	80	200

Figure 25: TS_WeeklyTimeSeries sheet

3.5.11 Time Series for electricity demand

Electricity demand time series given in the following files:

- EDF__HourlyCoef-ElecVehicle__ddmmyyyy__ddmmyyyy__vi.csv (where the first date is the creation date and the second date is the upload date, I being the version number) which is the hourly profile time series of the electric demand for electric vehicles
- EDF__HourlyCoef-AirCondition-ScenarioName-CT__ddmmyyyy__ddmmyyyy__vi.csv (where CT is the country code, the first date is the creation date and the second date is the upload date, I being the version number), which is the hourly profile time series of the electric demand for cooling
- EDF__HourlyCoef-Heating-ScenarioName-CT__ddmmyyyy__ddmmyyyy__vi.csv (where CT is the country code, the first date is the creation date and the second date is the upload date, I being the version number), which is the hourly profile time series of the electric demand for heating
- EDF__HourlyCoef-non-thermo-ScenarioName-CT__ddmmyyyy__ddmmyyyy__vi.csv (where CT is the country code, the first date is the creation date and the second date is the upload date, I being the version number), which is the hourly profile time series of the electric demand for 'others uses'

Demand hourly time series in MW are computed as the weighted sum of those time series, using as weights the yearly energy demands per uses provided in ZV_ZoneValue.

3.5.12 Time Series for WindPower and PVPower profiles

Max power profiles for renewable generation (ie. Hourly profile time series for the maximum generation of Windpower and PV, at 'plan4res' clusters geographic granularity) are given in the following files:

- EDF__PV-loadFactor-ScenarioName-CT_ZoneCode__ddmmyyyy__ddmmyyyy__vi.csv (where CT is the country code, the first date is the creation date and the second date is the upload date, I being the version number) is the profile time serie of the photovoltaic power generation
- EDF__WindOnshore-loadFactor-ScenarioName-CT_ZoneCode__ddmmyyyy__ddmmyyyy__vi.csv (where CT is the country code, the first date is the creation date and the second date is the upload date, I being the version number) is the profile time serie of the onshore Windpower generation
- EDF__WindOffshore-loadFactor-ScenarioName-CT_ZoneCode__ddmmyyyy__ddmmyyyy__vi.csv (where CT is the country code, the first

date is the creation date and the second date is the upload date, I being the version number) is the profile time serie of the offshore Windpower generation

Max Power hourly time series in MW are computed by multipliying those time series by the installed capacity in mW of each unit provided in RES_RenewableUnits.

3.5.13 Time Series for run-of-river

Max power profiles for run-of-river power generation (hourly profile time series at counrtry geographic granularity) are given in the following files:

- EDF__RunOfRiver-HourlyCoefficient-ScenarioName-CT_ZoneCode__ddmmyyyy__ddmmyyyy__vi.csv is the profile time serie of the inflows to seasonal storages (in %)

Unlike all above CSV files, RunOfRiver coefficients are given only daily.

Max Power hourly time series in MW are computed by duplicating the value of each day on the 24 hours of the day, and multipliying the resultant time serie by the installed capacity in mW of each unit provided in RES_RenewableUnits.

3.5.14 Time Series for Inflows

Inflows at seasonal reservoirs (weekly profile time series at country geographic granularity) are given in the following files:

- EDF__Inflow-HourlyProfile-ScenarioName-CT_ZoneCode__ddmmyyyy__ddmmyyyy__vi.csv is the profile time serie of the inflows to seasonal storages (in MW)

Inflows time series in MW are provided with a weekly timestep. The value has to be duplicated on each hour of the week.

3.5.15 Time Series for Water Values

This optional time series contains water values that will be used in the simulation when computed outside plan4res.

It has to be provided via one csv file per seasonal storage.

Figure 26: example of Bellman values with 4 volume steps and daily SSV steps

Each CSV file is following the common data format, with a first column containing time stamps, a second column containing the volumes (in MWh) and the third column containing the Bellman values. For a given unit, the number of volume steps must be the same at each time step of the sheet. The function Value(Volume) must be convex. The sheet must contain 1 line per volume 'step' per SSVTimeStep.

3.6 Gas Network Model Input Files

west-A_LAC_	BellmanValues	
Timestamp [	Volume	Value
01/01/2050	0	0
01/01/2050	750000	-34328493,1
01/01/2050	1500000	-68399327,6
01/01/2050	2250000	-102316457
02/01/2050	0	0
02/01/2050	750000	-34333758
02/01/2050	1500000	-68407735,6
02/01/2050	2250000	-102326623
03/01/2050	0	0
03/01/2050	750000	-34339066,2
03/01/2050	1500000	-68416215,2
03/01/2050	2250000	-102336879

Data required by the gas network optimization model are roughly grouped into two types, as network topology data and gas supply/demand data. Network topology data defines the high-pressure gas network used to transport gas. Hence, it includes technical properties of gas network components such as pipes and compressor stations and gas properties as gross calorific value and gas density. Gas supply and demand data, which constitutes the nomination in NOVA, specifies the amount of data inflow and outflow via gas network entry and exit nodes, respectively.

In the context of plan4res, we use the data format and data attributes as defined by network description, compressor station description, and nomination data types provided by GasLib. GasLib uses a well-defined XML format for input and output files. This format, which we call GasLib data format throughout this document, is presented in detail on [10] and in Schmidt et al.'s paper [11]. In this document, we provide a brief summary about the data format.

In GasLib format, network topology data is defined by the following:

- The network description data comprises the topology of the network and the technical data of all network elements. It includes data for connections of network such as pipes, short pipes, compressor stations, control valves, vales and resistors, and nodes of the network as source nodes, sink nodes and inner nodes. We format the network description data as a .net file (See Figure 27 for the general structure).

- The compressor station description data includes the complete and detailed description of all compressor stations that have been listed in the corresponding network description data. The compressor station data defines each compressor data with the compressors and drives of the compressor station, and the possible configurations of those. We format the compressor station data as a .cs file (see Figure 28 for the general structure).

The nomination data defines stationary nominations, i.e., inflow and outflow scenarios for the entry and exit nodes are balanced such that the amount of gas entering the network is equal to the amount of gas leaving. We format the nominations data as a.scn file.

The data attributes to define each component in .net and .cs files, and nominations in .scn file are provided in GasLib XSD schema documentation [12]. Besides, Schmidt et al. provides examples for each component using the XML format in connection with the nomination validation model [11].

Information Framework		< define each compressor station with its components and id>
Nodes Framework		< define each node according to its type>
	Innodes	< define each innode: >
		innode1
		innode2
		…
	Source nodes	< define each source node: >
		source1
		source2
		…
	Sink nodes	< define each sink node: >
		sink1
		sink2
		…
Connections Framework		< define each connection according to its type>
	Pipes	< define each pipe >
		pipe1
		pipe2
		…
	Shortpipes	< define each short pipe: >
		shortPipe1
		shortPipe2
		…
	Resistors	< define each resistor with the structure determined by its type: >
		resistor1
		resistor2
		…
	Valves	< define each valve: >
		valve1
		valve2
		…
	ControlValves	< define each control valve with the structure determined by its type: >
		controlValve1
		controlValve2
		…
	Compressor Stations	< define each compressor station with the structure determined by its type: >
		compressorStation1
		compressorStation2
		…

Figure 27. General Structure of .net file in GasLib

Compressor Station File	< define each compressor station with its components and id>

compressorStation1:

Compressors	< define each compressor of the compressor station with the structure determined by the compressor type, i.e., turbo compressor or piston compressor: >
	compressor1 compressor2 …
Drives	< define each drive of the compressor station with the structure determined by the drive type, i.e., gas turbine drive or gas driven motor drive: >
	drive1 drive2 …
Configurations	< define each possible configuration of compressors and drives of the compressor station: >
	configuration1 configuration2 …

compressorStation2:

Compressors	< define each compressor of the compressor station with the structure determined by the compressor type, i.e., turbo compressor or piston compressor: >
	compressor1 compressor2 …
Drives	< define each drive of the compressor station with the structure determined by the drive type, i.e., gas turbine drive or gas driven motor drive: >
	drive1 drive2 …
Configurations	< define each possible configuration of compressors and drives of the compressor station: >
	configuration1 configuration2 …

compressorStation3:
….

Figure 28. General Structure of .cs file in GasLib

Gas network model input files make use of network topology data and results of the upper level models. These are still under construction. However, we make use of ENTSO-G forecast and historical data to prepare nominations data. In the public data set, we provide these data with the format that is usable with the gas time series transformation tool. Gas supply and demand data in the public data set mainly uses the common plan4res data format:

-The geographical partitioning provided in ENTSO-G is balancing zones and countries. The data is provided in ZoneHierarchy format as defined in Section 3.1.3, where Level_1 is the balancing zones and Level_2 is the countries. If the data for a single country is defined as a single balancing zone, then the data entry for Level_1 is also the country code. Level_3 indicates whether the country is in EU or not. This file is given as BalancingZones.csv in the public data set.

-The historical data are provided time series format as defined in Section 3.1.5. The data is given in the GasTimeSeries.csv file in the public data set.

-The time series belong to gas supply or gas demand of particular balancing zones. The time series profiles are defined with the labels listed in Section 3.1.4. The data is provided in the GasTimeSeriesProfiles.csv file in the public data set.

In addition to those, gas supply and demand forecasts are provided in GasForecasts.csv file using the following labels:

-Profile_TimeSerie_Names: The name defines the time series profile to be transformed. Time series profile is given as “Type_<for demand: Zone; for supply: ZoneSource>”

where Source is either “Prod” for indigenous production, “Bio” for Biomethane, “LNG” for LNG or “” for import, and Type is either “Gas_Demand” or “Gas_Supply”, Zone is the Level_1 provided in ZoneHierarchy for type Gas_Demand and for type Gas_Supply depends on the source, i.e., Level 1 for production and biomethane, Level2 for imports, and Level3 for LNG.

-Total_Forecast_Value: Defines the forecast amount.

-Total_Forecast_Unit: Defines the unit of the forecast.

-Total_Forecast_Year: Defines the year that the forecast belongs to. The profiled time series of historical data consist of several years of data. But, in gas network optimization, we have yearly forecasts and we have to use a single yearly-distribution for that forecast to temporally disaggregate. Year defines the particular year of the profile timeseries that is going to serve as data distribution for our transformation.

-Forecast_Source: Defines source and the scenario of the forecast value.

Note that, the GasForecasts.csv file includes all supply and demand forecasts available in ENTSOG Ten-Year Network Development Plan 2018 given in source ENTSO-G Web Page. A relevant subset of these forecasts are used in the analysis.

4 Building the public datasets

This chapter describes the public dataset, how they are used and their acquisition. More specifically, plan4res will use the dataset from the H2020 project Ehighway2050, from the Copernicus Climate Change Service, ENTSO-e anf ENTSO-g for electricity and gas data, Heat Roadmap Europe 4, FHG ISE Study – Techno-economic Model Data, HOTMAPS, U Reference Scenario 2016 for the transport activities, Renewables.NINJA for PV and WIND Generation.

Finally the chapter describes the transformation tool for geographical and time data aggregation and disaggregation.

4.1 Identification of source data and acquisition

This chapter describes the data sources used and their acquisition.

4.1.1 Ehighway2050

Ehighway2050[1], which is an H2020 project answering to the call ENERGY.2012.7.2.1, whose objective was is to develop a top-down planning methodology to provide a first version of a modular and robust expansion plan for the Pan-European Transmission Network from 2020 to 2050, in line with the pillars of European energy policy. The project aimed at planning the Pan-European Transmission Network, including possible highways, capable of meeting European needs between 2020 and 2050. The project has published 4 different scenarios among those plan4res chose to work with the 'large scale RES', which seems the most appropriate. Among the results of ehighway2050, plan4res will use:

- D2.1: Data sets of scenarios for 2050
- D2.2: European cluster model of the pan-european transmission grid
- The ehighway database per country (e_Highway_database_per_country-08022016.xlsx)
- The ehighway country and cluster installed capacities database (e_Highway2050_2050_Country_and_cluster_installed_capacities_31-03-2015.xlsx)

The main ehighway data that will be used are:

1 https://docs.entsoe.eu/baltic-conf/bites/www.e-highway2050.eu/e-highway2050/

- Definition of countries and clusters
- Target for annual demand
- Target for RES installed capacities (hydro, PV, wind, biomass)
- Target for thermal generation installed capacities if plan4res is used in simulation mode otherwise thermal capacities can be an output of the model if it used in optimisation mode
- Interconnection characteristics if model used in simulation mode or output of the model if used in optimisation mode

4.1.2 Copernicus Climate Change Service

Copernicus Climate Change Service (C3S)[2]: The mission of C3S is to provide authoritative, quality-assured information to support adaptation and mitigation policies in a changing climate. At the heart of the C3S infrastructure is the Climate Data Store (CDS), which provides information about the past, present and future climate in terms of Essential Climate Variables (ECVs) and derived climate indicators. C3S was used to create scenarised time series of energy variables that are deeply linked to climate (electricity demand, hydro, PV, Windpower). From the C3S data, plan4res will use:

- Temperature time series that will be used to derive Hourly demand time series using a statistical model, implemented by EDF, encounting for the correlation between demand and temperature.
- Load factors times series for renewable energy sources

4.1.3 ENTSO-e Transparency platform

https://transparency.entsoe.eu/dashboard/show

The main ENTSO-e data used are:

- Filling Rates of Reservoirs
- FCR and aFRR data

4.1.4 ENTSO-e Power Statistics

https://www.entsoe.eu/data/data-portal/

  - Monthly Hourly load values 2006 – 2015

2 https://climate.copernicus.eu/energy

4.1.5 ENTSO-E Statistical Factsheets

Referenced in the document by [ENTSO-E Factsheet]

Data repository: see [13] (updated annually – last: Statistical Factsheet 2018 in June 2019)

Or https://www.entsoe.eu/publications/statistics-and-data/#statistical-factsheet

Statistical factsheets (pdf) with annual figures of the pan-European electricity system, i.e.

- installed capacity of generation units clustered by technologies & country
- installed capacity of hydro reservoir and pump storage clustered by technologies & country
- annual energy generated clustered by technologies & country
- annual energy consumed clustered by country
- annual cross-border imports and exports clustered by country
- days and time of max peak power in the pan-European electricity system in each country and globally

4.1.6 Heat Roadmap Europe 4

Referenced in the document by [HRE4]

Documentation: see [14]

or https://heatroadmap.eu/heating-and-cooling-energy-demand-profiles/

Published in June 2017, this dataset presents an overview of the profiles and gives a current state of the energy demand for heating and cooling demand, generation and infrastructure in the EU28 countries.

The developed profiles and baselines provide a detailed picture of today’s hourly heating and cooling energy use in the industrial, residential and service sectors. Furthermore, the profiles for 2015 also show which types of energy http://heatroadmap.eu/resources/3.1 Profile of the heating and cooling demand in the base year in the 14 MSs in the EU28.pdf inputs (e.g. electricity, natural gas, biomass, etc.) and technologies are used to supply the identified heating and cooling demands for each (sub-)sector. Published in June 2017, this dataset presents an overview of the profiles and gives a current state of the energy demand for heating and cooling in EU28 countries in 2015.

Data repository: https://www.energyplan.eu/hre4/

- Used version of sub-dataset for demand / generation figures:

HRE4 Exchange Template WP3_v22b_website.xlsx (Final Data Set of March 2017)

- Used version of sub-dataset temporal profiles:

  EnergyPLAN HRE4 Baseline scenarios (Data Set of Oct 2017)

4.1.7 FHG ISE Study – Techno-economic Model Data

Referenced in the document by [FhG ISE MODEL DATA]

Data repository: (see appendix to study [15] pdf document)

https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Anhang-Studie-Wege-zu-einem-klimaneutralen-Energiesystem.pdf

In the study 'Wege zu einem klimaneutralen Energiesystem (German)' the researchers examine the course, technical feasibility and the costs of the energy system transformation in the context of various developments in societal behavior and attitudes. To this end they calculated four main scenarios. The appendix provides key parameters needed for technical and economic assessments of the technologies and for systemic modelling activities, e.g. lifetime, efficiency, financial data (CAPEX, OPEX etc.) with focus on Germany.

Examples of covered technologies are:

- various types of small and large-scale electricity generation units incl. electricity storages,
- various types of small and large-scale power-to-gas, power-to-chem units
- various types of small and large-scale heating and cooling technologies, as boilers, heat pumps, CHP, solar heating, electric heating and heat storage incl. building insulation and district heating.
- various types of technologies used in the sector mobility for person and freight transport

4.1.8 HOTMAPS

Referenced in the document by [HOTMAPS]

This dataset provides, besides others the hourly heat demand in the industry clusters for typical days. Profiles are not measured but modelled taking into consideration factors amongst others shift work patterns, historical output per month/weekday. The profiles can be used to assemble a yearlong demand profile for a NUTS2 region, if the structure of the days in a year (i.e. sequence of weekdays, Saturdays and Sundays/Holidays) for the specific region and year is available.

Yearlong profiles can be generated from the generic profiles provided and following the steps:

- determining the structure year for which the profiles are generated
- ordering the typedays for each month according to the selected year
- allocating the respective load value for the typeday/month tuple to each hour
- scaling the total sum of the annual yearlong profile (i.e. the integral of the profile) according to the annual total demand

Data set repositories:

https://gitlab.com/hotmaps/load_profile

https://gitlab.com/hotmaps/industrial_sites

- Technological Parameters CAPEX OPEX for large scale industrial heat generation.
- (Generic) Load Profiles for large scale industrial heat generation.

4.1.9 EU Reference Scenario 2016

Referenced in the document by [EUREF16]

The EU Reference Scenario 2016 implements a more sophisticated approach for deriving the transport activity projections by Member State until 2050 compared to the EU Reference Scenario 2013. It employs a combined econometric and engineering approach for deriving transport activity by transport mode.

Detailed documentation of the project see [16]

Data set repository: https://data.europa.eu/euodp/de/data/dataset/energy-modelling

- Transport activity projections from 2020 - 2050

4.1.10 EU JRC - Technical Data on large and small heating systems

Referenced in the document by [JRC HEATING]

These studies [17] [18] provide data and projections for smaller and large heating and cooling technologies for the industrial residential and tertiary sectors including an outlook until 2050.

Data set repositories:

https://data.jrc.ec.europa.eu/dataset/jrc-etri-techno-economics-smaller-heating-cooling-technologies-2017

https://data.europa.eu/euodp/de/data/dataset/jrc-etri-techno-economics-larger-heating-cooling-technologies-2017

They cover key parameters needed for technical and economic assessments of the energy technologies and for systemic modelling activities, e.g. conversion efficiency, capital and operating costs; also touching upon the needs for environmental assessments (e.g. emissions of pollutants). The technologies covered are various types of boilers, heat pumps, CHP, solar heating, electric heating and heat storage.

4.1.11 Renewables.NINJA – PV and WIND Generation

Referenced in the document by [NINJA]

- PV v1.1, Europe, 1985-2016

  Hourly PV capacity factors for the EU-28 plus Norway and Switzerland, simulated with MERRA-2 and CM-SAF SARAH, as described in [19]

- Wind v1.1, Europe, 1980-2016

  Hourly wind capacity factors for the EU-28 plus Norway and Switzerland, based on MERRA-2, simulating the present-day fleet of wind farms, the near-term future and long-term future fleets, as described in [20]

Data set repository (zip only): https://www.renewables.ninja/downloads

4.1.12 ENTSO-E TYNDP

Referenced in the document by [TYNDP] [21]

Data set repository (zip only): https://tyndp.entsoe.eu/maps-data/

- ENTSO Scenario 2018 Generation Capacities

4.1.13 ENTSO-G Transparency Platform

https://transparency.entsog.eu/

Historical gas flow data of ENTSO-G interconnection points are obtained from ENTSO-G Transparency Platform.

4.1.14 ENTSO-G Web Page

https://www.entsog.eu/

Main ENTSO-G data obtained from web page are:

- Gas supply forecasts published within the Ten Year Network Development Plans
- Gas demand forecasts published within the Ten Year Network Development Plans
- Existing and planned ENTSO-G interconnection point capacities from Transmission Capacity Map data

4.1.15 GIE Transparency Platform, GIE Storage Investment Database

Transparency Platform:

Investment Database:

The storage data obtained from GIE sources are:

- Working volume of the storage
- Withdrawal rate of the storage
- Injection rate of the storage

4.2 The transformation tools

Once raw data has been either collected or generated we need to produce the datasets in the required data-formats for the models described in section 2. The first step in the definition ofr the input data requires aggregation or disaggregation operations at geographical and time level. To manage the high quantity of data used by plan4res, we have designed and implemented a software tool the automatically perform the required modifications (see also plan4res deliverable D4.1). The tool was written in C++14 and compiled in an executable file called "Transformation.exe" (https://gitlab.com/cerl/plan4res/transformation-tools). In this section we present the software tool and how to use it

4.2.1 The plan4res data transformation tool for aggregation/disaggregation

The tool provides aggregation for the Zones, for the Timeseries and for the Interconnections, depending on the set of input files given in the command line. In the same command line a set of *parameters* allow to specify the required operations to be executed on the input data. The syntax is as follow:

Transformate.exe ZONEHIERARCHY=<file> ZONEVALUESAGGR=<file> [TIMESERIES=<file>] [INTERCONNECTIONS=<file>] [ZONEVALUESDISAGGR=<file>] [GASFORECAST=<file>] [NETINFOFILE=<file>] [NETFILE=<file>] [CSFILE=<file>] [SCFILE=<file>] [PARAMETER1=<value>, PARAMETER2=<value>,…]

Program inputs are: csv files and parameters

a) CSV files:

- the ZoneHierarchy is mandatory unless NetInfoFile is provided,
- the ZoneValuesAggr is mandatory unless NetInfoFile is provided
- the others are optional parameters with the following rules:
    1. Only ZoneHierarchy and ZoneValuesAggr are provided: the aggregator produces the ZoneValueAggr_OUT file but the Profile_TimeSerie values do not correspond to real timeseries.
    2. ZoneHierarchy, ZoneValuesAggr and TimeSeries are provided: the aggregator produces the ZoneValueAggr_OUT and the TimeSeries_OUT files.
    3. ZoneHierarchy and Interconnections files are provided: the aggregator produces the Interconnections_OUT files.
    4. ZoneHierarchy, ZoneValuesAggr and Interconnections files are provided: the aggregator produces the ZoneValuesAggr_OUT and Interconnections_OUT files, but

the Profile_TimeSerie names generated do not necessarily correspond to an existing timeseries.

5. ZoneHierarchy, ZoneValuesAggr, TimeSeries and Interconnections files are provided: the aggregator produces the ZoneValuesAggr_OUT, TimeSeries_OUT and Interconnections_OUT files.
6. ZoneHierarchy, ZoneValuesAggr, ZoneValuesDisAggr files are provided: the aggregator produces the ZoneValuesAggr_OUT, ZoneValuesDisAggr_OUT files.
7. TimeSeries and GasForecast are provided: timeseries special transformation for gas flows will be applied and two files ZoneValues_OUT and TimeSeries_OUT will be produced.
8. No file or none of the above combination is provided: a warning message is issued a no activity is performed
   ▪

b) Configuration parameters: used to define the specific aggregation to be done. If the parameter is not provided the default is used. The syntax is PARAMETER=<value>

- OPERATION (string): accepted values "SUM", "MAX", "AVG" (possibly others in the future) Default = SUM. According to this parameter the computations of Value, minValue and maxValue are made using this operator on the original data.
- TIMEOPERATION (string): accepted values "SUM", "AVG". Default=SUM. This is the operator that is used during the timeseries generation.
- PRENORMALIZE (bool): accepted values "true" or "false". Default=false. If true then each timeseries is normalized so that the sum of all values of the series is **one, for the given year**
- POSTNORMALIZE (bool): accepted values "true" or "false". Default=false. If true then each timeseries in the output file is normalized so that the sum of all values of the series is **one, for the given year**
- YEAR (integer): accepted value: a number representing a valid year (between 2000 and 2100). If provided the aggregator filters the data according to the year and applies the aggregation only to this year.
- TIMEAGGREGATION (bool): accepted values "true" or "false". Default="false". If "true" then timestamp generation will be applied.
- PRETIMEAGGREGATION (bool): accepted values "true" or "false". Default="false". If "true" then timestamp generation will be applied without aggregation.

- LEVEL (integer): accepted values 1, 2, … up to the number of levels in the hierarchy. Default = 1. Aggregate/ Disaggregate the zones one or more levels up/down

The program output

The output files depend on the input one. The name of the files is the same as in input with the postfix "_OUT".

AGGREGATION

a. **ZoneValuesAggr_OU**T has the same structure as ZoneValuesAggr, but the Zone column contains the zones of an upper level, with respect to the input level.
    - **Type:** report the original name: we will aggregate values of the same type (i.e., more than one row can be written for the same upper level zone, corresponding to different types)
    - Fields **Value/minValue, maxValue** are computed using OPERATOR according to the parameter
    - **Datazone_ID =** (Siemens) concatenation of Datazone_ID from the previous level plus the identifier of the operation performed to aggregate the data
    - Field **Profil_TimeSerie** refer to the new timeserie generated by the transformation (see below)**.** The name of the newly generated timeserie is given by the **type** concatenated (underscore) with the name of the **upper level zone** (es. If 49_AT, 50_AT and 51_AT are aggregated to *AT*, for type *Elec_Heating*, the timeserie name will be "Elec_Heating_AT").
        -

b. TimeSeries_OUT contains as first column the single timestamps column of the ReferenceTimeStamps file plus a number of columns with timeseries. If the original input file has timeserie labels with the number of the **scenario**, the output timeseries are aggregated scenario per scenario and the label contain the number of the scenario (preceded by two underline) as last element.

- We give here an example of aggregation from Level_1 to Level_2. The same kind of operations are executed for an aggregation from Level_2 to Level_3. If parameter AGGR_LEVEL, ask for two levels of aggregation the aggregator executes the aggregation Level_1 to Level_2 followed by the aggregation Level_2 to Level_3.

- **Aggregation Level_1 to Level2**: If the input file ZoneHierarchy has zones of Level_1, the transformation considers, in turn, each zone L2 of Level_2 identified by ZoneHierarchy
- For each zone L2 the transformation determines the set *L* of all Level_1 zones of L2, as defined by ZoneHierarchy, and the set *ST* of all *Types* of timeseries (heating, cooling, etc) of the zones in *L*, as defined by ZoneValues.
- For each type *T* in *ST* consider each timestamp *t* in the ReferenceTimeStamps and sums the values of all the timeseries of type *T* from the zones in *L,* for timestamp *t,* multiplied by Value, i.e., [Timeseries of type T] (t) = Sum_{j in *L*: type_j = T} Profil_Timeserie_j (t) x Value_j

c. **Interconnections_OUT** has the same structure as Interconnections. The aggregator shrinks the zones one or two levels up, as described above in the **TimeSeries_OUT** section. Between a pair of shrinked zones, say Z1 and Z2, it is included in this file a single interconnection summing up the values of all interconnections going from a zone of lower level inside Z1 to a zone of lower level inside Z2.

N.B. We sum the values of all arcs between two zones **disregarding the directions.** *If there are different directions, we leave* ***blank*** *the "Direction" field in the output (see below).*

- **Link_type:** if all the links of the lower level zones going from upper zone Z1 to upper zone Z2 have the same type, this type is reported in output. Otherwise (different link types), the value in output is **blank**
- **Direction:** (same as link_type): if all the links of the lower level zones going from upper zone Z1 to upper zone Z2 have the same direction, this direction is reported in output. Otherwise (different directions), the value in output is **blank**
- **MaxFlow** = is computed as SUM of all MaxFlow values of all links to be aggregated
- **Impedance** = impedance of the link is computed as the *inverse of the SUM of all inverse*

DISAGGREGATION

- **ZoneValuesDisAggr_OU**T has the same structure as ZoneValuesDisAggr, but the Zone column contains the zones of a lower level, with respect to the input level.
  - **Type:** report the original name: we will disaggregate values of the same type
  - Fields **Value/minValue, maxValue** are computed using a proportional operator given by the values in the corresponding (input) ZoneValuesAggr.

- **Datazone_ID =** (Siemens) from the previous level
- Field **Profil_TimeSerie** from the previous level

Example

ZoneValuesAggr:

Zone	Value
49_AT	20
50_AT	30
51_AT	50

49_AT, 50_AT and 51_AT are aggregated to upper level **AT** with value 100 (operator SUM)

ZoneValuesDisAggr:

Zone	Value
AT	500
FR	600
DE	850

Disaggregate AT to the lower level_1 according to the distribution in ZoneValuesAggr. The result is:

Zone	Value
49_AT	500 x 20 / 100
50_AT	500 x 30 / 100

51_AT	500 x 50 / 100

TIME AGGREGATION

This transformation performs a "normalization" of the timesteps in the timeseries to a step of 1 hour according to the rules below.

The transformation occurs as a postprocessing on the aggregated timeseries, if a zone aggregation is performed, but also on the original timeseries when no aggregation is required (set PRETIMEAGGREGATION="true" to achieve this).

To activate this function parameter TIMEAGGREGATION must be set to "true".

In both cases the resulting timeseries have time steps of 1 hour according to the following two rules:

1) Original timestep > 1 hour

- Each timestamp *t* in the output correspond to one hour (e.g., 8:00, 9:00, …) and the corresponding new is equal to the interpolated value.
    a. If the timeseries has timestamps smaller and greater than *t* let t*1* < *t2* be the two timestamps of the timeseries that are closer to *t,* with *t1* < *t* < *t2*;
    b. if *t* is smaller than all the timestamps of the series let *t1* < *t2* be the two smallest timestamps of the timeseries;
    c. if instead, *t* is larger than all the timestamps of the series let *t1* < *t2 be* the two greatest timestamps of the timeseries.

  The interpolated value is computed as

$$f(t) = f(t1) + \big(f(t2) - f(t1)\big)\,(t - t1)/(t2 - t1)$$

  Where *f(x)* denotes the value of the timeseries for timestamp *x.*

  Example:

▪ Input	▪	▪ Output

■ Timestamp	■ Value		■ Timestamp	■ Value
■ 8:00	■ 100		■ 8:00	■ 100
■ 10:00	■ 200		■ 9:00	■ 150
■ 12:00	■ 300		■ 10:00	■ 200
■ 14:00	■ 400		■ 11:00	■ 250
■	■	■	■ 12:00	■ 300
■	■	■	■ 13:00	■ 350
■	■	■	■ 14:00	■ 400

2) Original timestamp < 1 hour

- Each timestamp *t* in the output correspond to one hour (e.g., 8:00, 9:00, …) and the corresponding new is calculated as the average/sum of the two timestamps value *t1* and *t2*, where *t1* is maximum value <= *t*, and *t2* is the minimum value >= *t.*
- The choice of the AVG or SUM operator is made using parameter TIMEOPERATOR

Example (average)

■ **Input**		■	■ **Output**		■
■ Timesta	■ Valu		■ Timesta	■ Valu	■
■ 8:00	■ 100		■ 8:00	■ 100	■
■ 8:30	■ 200		■ 9:00	■ 250	■ Avg(8:30

▪ 9:00	▪ 300	▪ 10:00	▪ 450	▪ Avg(9:30
▪ 9:30	▪ 400	▪ 11:00	▪ 650	▪ Avg(10:3
▪ 10:00	▪ 500	▪ ▪	▪	▪
▪ 10:30	▪ 600	▪ ▪	▪	▪
▪ 11:00	▪ 700	▪ ▪	▪	▪

4.2.2 The gaslib transformation tool

Gas network optimization model uses GasLib format, which is presented in Section 3.5, for the input files. GasLib data format is a well-defined XML format and GasLib transformation tool converts .csv files including data for network topology, compressor stations and nominations to .net, .cs and .scn files, respectively.

For the transformation, the data for network topology, compressor stations and nominations are provided to the gaslib transformation tool as the .csv format provided in the "ExampleInput" sheets of the following files:

- netFile.xlsx - Example csv file for .net file.
- csFile.xlsx Example csv file for .cs file.
- scnFile.xlsx Example csv file for .scen file.

The following commands are used in data transformation tool for performing the transformation:

Transformation.exe NetInfoFile=<Path to NetInfoFile csv file> NetFile=<path to netFile csv>

Transformation.exe CSFile=<Path to compressor stations csv file>

Transformation.exe ScFile=<Path to scenario csv file>

4.2.3 Gas time series transformation tool

The purpose of this functionality is to construct a time series for an entity by using its distribution information from historical time series data and a forecast value, which is the sum of the entity in an a priori known future time duration. The syntax is as follows

Transformate.exe ZoneHierarchy=<file> ZonesValuesAggr=<file> TimeSeries=<file> GasForecast=<file> YEAR=<year>

Program inputs are the .csv files describing geographical description, i.e., ZoneHierarchy, describing data linked to geographical partitions, i.e., ZoneValuesAggr, time series, i.e., TimeSeries, and parameters describing the gas forecasts, i.e., GasForecast. The parameter YEAR depicts the year of the input time series to be used in the transformation.

The function is used to transform the time series by updating their values in such a way that their sum is equal to the value forecasted value defined by the input:

For each input timeseries value *x*, the new value *x’ = (x * FC) / S*, where *FC* is the Total_Forecast_Value for the timeseries (from GasForecast), and *S* is the sum of the input timeseries values.

Example:

Input GasForecast.csv

Profile_TimeSerie_Names	Total_Forecast_Value	Total_Forecast_Unit	Total_Forecast_Year	Forecast_Source
Gas_Supply_DE275_1	15000	kWh/h	2025	ENTSOGScen1

Input TimeSeries.csv		**Operation**	**Output**	
Gas_Supply_DE275_1			**Gas_Supply_DE275_1_2015_ENTSOGScen1**	
Timestamp	Value		Timestamp	Value
1/1/2015 8:00	6000	(6000 * 15000) / 10000	1/1/2025 8:00	9000

1/1/2015 9:00	3000	(3000 * 15000) / 10000	1/1/2025 9:00	4500
1/1/2015 10:00	1000	(1000 * 15000) / 10000	1/1/2025 10:00	1500
Sum	**10000**		**Sum**	**15000**

4.3 Dataset Building

This chapter describes, for each model, the process used to obtain the data stored in the public repository, starting from the source data.

4.3.1 Multimodal Investment Data Building

Since the multimodal investment model is based on modeling one historic year, here 2015, per interval along the pathway, country-specific and regionally resolved timeseries are needed. Regionally resolved data for energy demand or 'forced' generation, and installed technology mix in the starting year and if applicable constraints for new additions and retirement along the pathway are required, too. Additionally, projections of operational KPIs, e.g. CAPEX, O&M costs, technical lifetime, and efficiency for all technologies implemented as well as cost for all primary energy sources, must be provided.

This compendium of data was not available from one external data source only. Data from different sources have been assembled and checked for compliance. Furthermore, curing of regional gaps has been done upfront by using either curing rule 'mean from neighbours' or 'weighted mean from socio-economic analogous' countries.

This way data from various sources and data sets covering all energy-relevant carriers and technologies for sectors electricity, heating & cooling, mobility, gas/fuel, and industrial, CTS and residential prosumers have been pre-processed and finally combined to consistent data sets, which fit in formats and quality meet the requirements of MIM modelling.

Data type, origin and data preprocessing, as well as formats are described in section 3.2. All created data set for input to MIM modelling, and which are listed in this chapter will be made available for download from the data repository.

Data set comprising outputs and results of the MIM modelling, and which will be used by other models in the project for further analysis, will be added in a future. The corresponding data scenarios will be made public as soon as they are available.

4.3.2 European Market simulation Data Building

Data for historical electricity demand timeseries have to be transformed to fit the desired data format for the tool. The raw data use the structure with a row for each day per country, year, month and day. Each Hour or the day is presented by a column. Since the modeling is based on one historic year and country-specific timeseries is needed, the data is transformed to the desired format described in section 3.3. Transformation from local time to UTC time is performed by shifting the timeseries by the country-specific offset regarding UTC time.

4.3.3 SSV – EUC data building

2 different instances of this dataset will be built:

- Reference dataset: this dataset is built out of public data and does not include any input from other plan4res models.
- Plan4res Demonstration Workflow dataset: this dataset is a variant of the reference dataset, which has as objective to demonstrate the plan4res workflow as illustrated in Figure 2: plan4res Models Workflow. As this dataset requires outputs from case studies that will be completed only at the end of the project, it will be available only et this time.

We describe below, data per data, the process that was used to build them, either from public sources or from scratch.

4.3.3.1 Transmission network

Reference dataset

Source: e-Highway 2050 D2.2

This deliverable introduces a European grid model, based on the pan-european transmission system which is split into 106 geographical clusters (see Figure 29), leading to a simplified interconnected system. These clusters are considered free of grid constraints and the equivalent connections between them have been derived from the real transmission network.

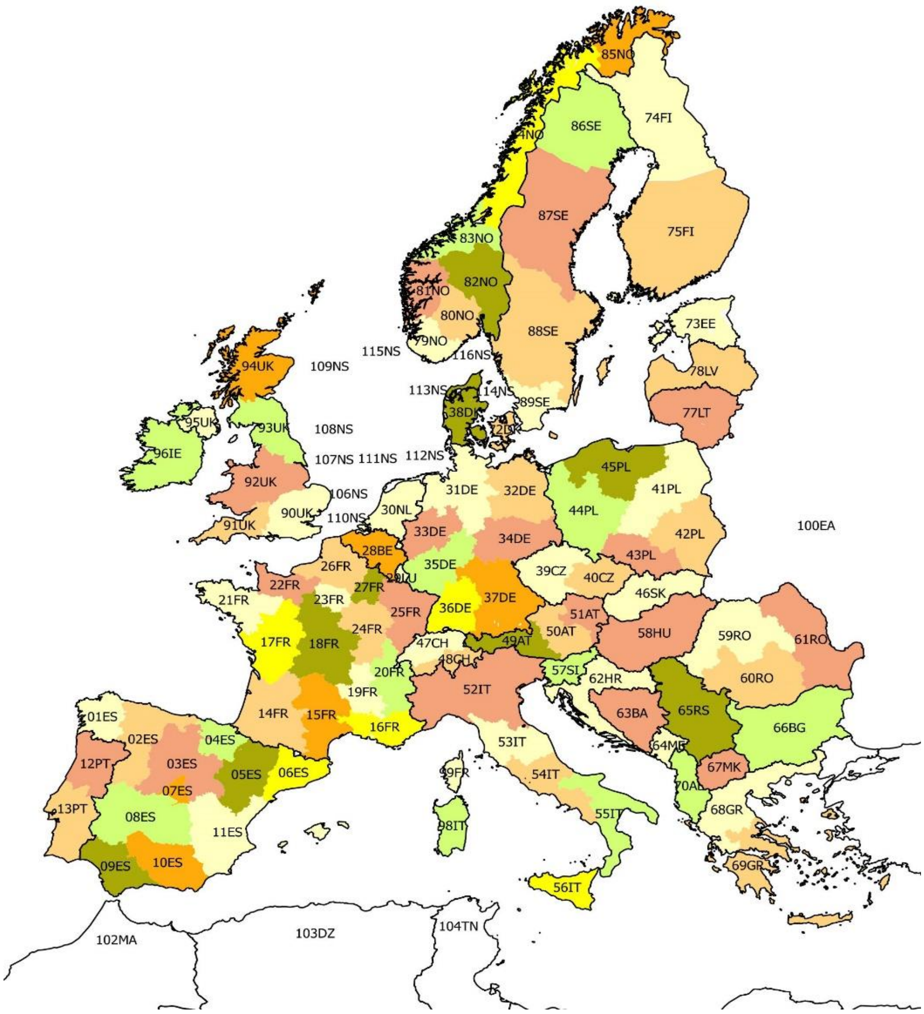


Figure 29: eHighway 2050 geographical clusters

In the context of CS3, the plan4res transformation tool has been used to aggregate some countries and clusters. The plan4res resulting modelling in this dataset is carried out at the country level for all countries except for France and Germany that are modelled at the cluster level as in ehighway, Italy that is separated in 2 clusters only, and some countries that are aggregated in the 3 regional clusters: Balkans, Scandinavia and Baltics.

The resulting cluster is illustrated in Figure 30

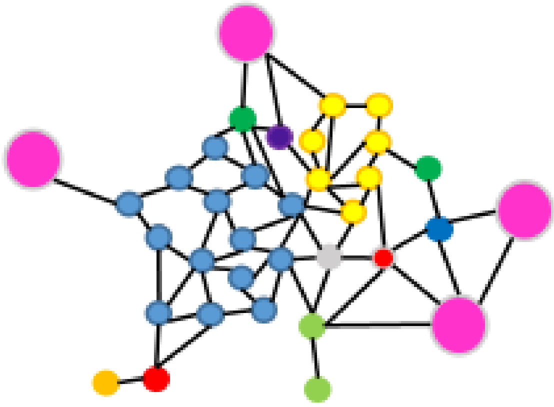


Figure 30: plan4res cluster

eHighway also includes the description of interconnections between clusters. They are defined by their capacities and impedances. In the case where we do not use the capacity expansion model to re-optimize the interconnection capacities, we use the 2050 scenario. In the other case we use the 2030 scenario.

To adapt the description to the plan4res aggregated clusters (see above), the plan4res transformation tool computes the new interconnection capacities (MW) and Impedances.

Figure 31 Illustrates the impedances as computed in ehighway 2050.

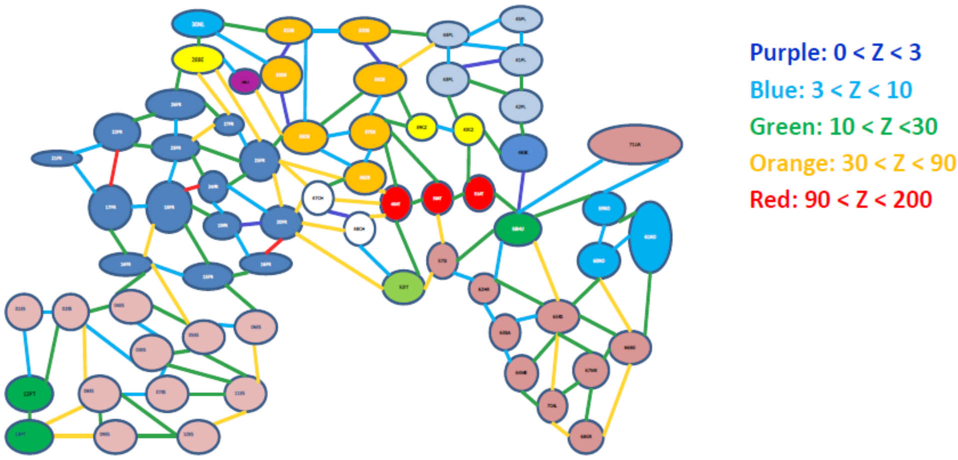


Figure 31: ehighway2050 Impedances (from ehighway D2.1)

<u>Plan4res demonstration workflow dataset:</u>

The values of Min/Max Flows and impedances between countries, will be a result of the Transmission expansion model (see 2.3). They will be converted to the geographic granularity of the current dataset by using the transformation tool (see 4.2.1)

4.3.3.2 Exchanges at Boundaries

Reference dataset

Source eHighway2050: e_Highway_database_per_country-08022016.xlsx, sheet T53 and map from D2.2

The eHighway 2050 scenario defines exchanges with the countries at the border of the area modelled: eg. exchanges with North Africa due to RES installed capacities in these countries (see Figure 32).

Countries at the boarder are defined within clusters (below DZ, LY, MA, MEA, TN). Assumptions regarding the PV installed capacity are available (in MW) from the ehighway database per country. Those figures are associated with a PV time serie profile in order to obtain imports as time series.

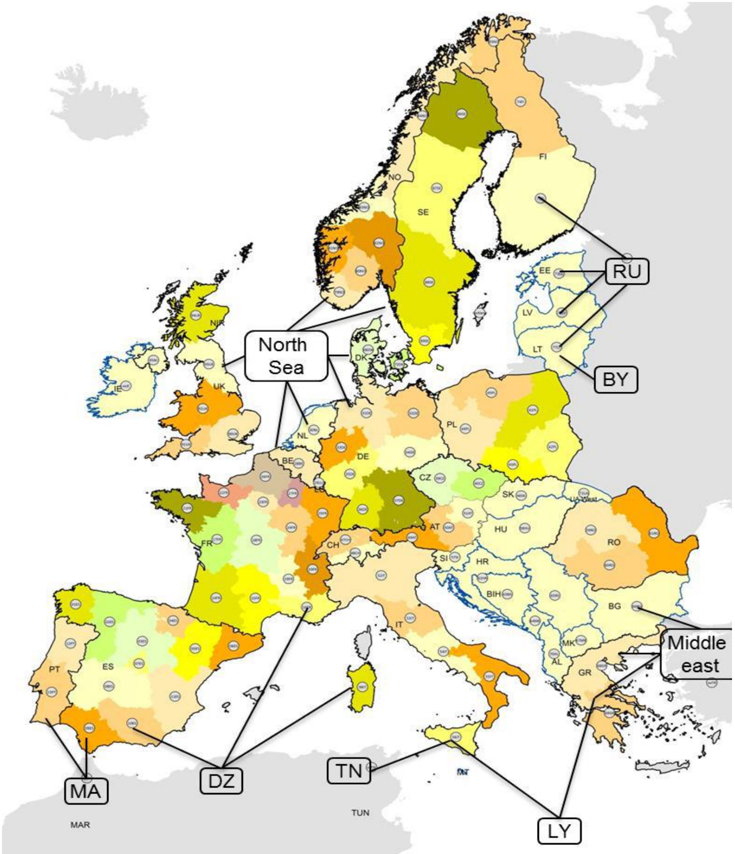


Figure 32: exchanges with North Africa (eHighway D2.1)

Plan4res demonstration workflow dataset:

The values of exchanges at boundaries, will be those used as inputs to the MIM (see 2.1) result of the Transmission expansion model (see 2.3). They will be converted to the geographic granularity of the current dataset by using the transformation tool (see 4.2.1)

4.3.3.3 Electricity demand

Reference Dataset

Plan4res uses the same methodology as eHighway 2050 :

- The national electricity demand of each country is broken down in 4 kinds of uses:
  - Electric vehicles
  - Electric Heating

  - Electric Cooling
  - Other uses of electricity
- Annual energy targets per country are taken from e-Highway2050 "2050 country and cluster installed capacity" database (e_Highway_database_per_country-08022016.xlsx table 40, Large Scale RES column)
- Those targets are broken into uses using weight information from eHighway D2.1 (appendix C page 76))
- Finally they are broken per clusters using weight information from eHighway e_Highway2050_2050_Country_and_cluster_installed_capacities_31-03-2015.xlsx, sheet Cluster X5.
- Electric vehicles hourly profiles are computed out of information taken from eHighway2050 D2.1 (annual weekly profile, week-day profiles, load type for non-responsive or responsive to price vehicles, daily profiles for those 2 catagories).
- Hourly profiles (coefficients between 0 and 1 which, multiplied by an energy in MWh/yr give an hourly demand in MWh) for heating, cooling, and other uses. The method used to compute them is based on a climatic correction modelling :
  - Which takes as inputs historic data for hourly demand and temperatures by country
  - A statistical model defines the relation between the hourly demand and the temperature, per uses (heating, cooling, other)
  - Then the statistical load model is applied to temperature time series for present climate conditions or future climate conditions (temperature time series from Copernicus C3S). It includes accounting for the impact of temperature on demand (see Figure 33), as well as yearly, weekly, daily profiles (see Figure 34)

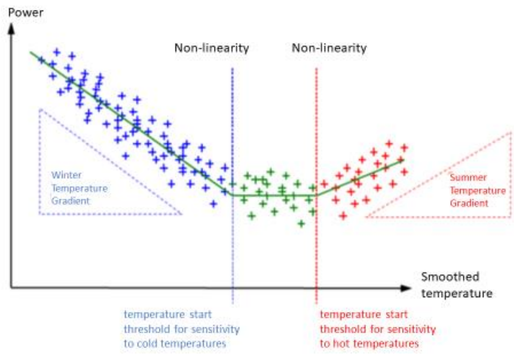


Figure 33: Statistical Demand/Temperature model

Figure 34: cycles

Plan4res demonstration workflow dataset (to be updated S2 2020)

The same procedure will be applied but the Annual electricity demand targets per country per use will be replaced by results of the MIM model (see 2.1)

4.3.3.4 Generation Mix

`Installed capacities`

Reference dataset

We will use the ehighway2050 installed capacities for all units.

Source: **e-Highway2050_2050_Country_and_cluster_installed capacities_31-03-2015.xlsx**

This source gives the installed capacity per cluster in MW, for the following technologies:

- WindPower
- PVPower
- CSP (Concentration Solar Power)
- Biomass (divided into Biomass1 and Biomass2)
- Nuclear
- OCGT (Open Cycle Gas Turbine)
- Gas with and without CCS (Carbon Capture Storage)
- Coal with and without CCS
- Lignite with and without CCS

- Hydro with reservoir
- PSP (Pumped Storage Plant)
- PSP with reservoir
- RoR (Run-of-River)

Plan4res demonstration workflow dataset (to be updated S2 2020)

Installed capacities per technologies will be replaced by results of the MIM model (see 2.1)

Fuel Prices

Reference Dataset

Ehighway defines variable costs that take into account fuel and CO2 prices.
Prices from **D2_1_Data_sets_of_scenarios_for_2050_20072015.pdf** are used.

Plan4res demonstration workflow dataset (to be updated S2 2020)

Costs of technologies will be replaced by results of the MIM model (see 2.1)

Thermal units

Technical parameters for units are available in **D2_1_Data_sets_of_scenarios_for_2050_20072015.pdf (see** Figure 35**)**

	Rated power (MW)	Minimum stable power (MW)	Min up/down time (hours)	Forced outage rate (%)	Planned outage rate (%)	Outage duration (days)	CO_2 emis-sions (t/MWh)
Nuclear	1600	800	168	5	15	7	0
Hard coal with-out CCS	800	320	6	5	15	7	0,644
Hard coal with CCS	800	320	24	5	15	7	0,084
Lignite without CCS	800	320	24	5	15	7	0,767
Lignite with CCS	800	320	24	5	15	7	0,045
CCGT without CCS	500	150	3	5	15	7	0,327
CCGT with CCS	500	150	24	5	15	7	0,017
OCGT	250	150	3	5	15	7	0,488
Biomass 1	250	150	3	5	15	7	0
Biomass 2	250	150	3	5	15	7	0

Figure 35: technical parameters of thermal units

Fuel and CO2 prices for thermal units can be found in D2_1_Data_sets_of_scenarios_for_2050_20072015.pdf (see Figure 36). They are converted in variable costs as in the table below.

OCGT	189
CCGT without CCS	131
CCGT with CCS	not considered
Coal without CCS	180
Coal with CCS	not considered
Lignite without CCS	180
Lignite with CCS	not considered
Nuclear	14
Biomass1	20
Biomass2	135

Figure 36: thermal unit variable costs

Hydro units

The modelling of hydro is based on the following 3 different kinds of assets:

- A 'national' storage capacity per country defined with its volume (in MWh), Maximum/minimum power (MW) and Inflows scenarised time series. Those were created for all countries where Inflows were available.
    - Inflows are provided by C3S as time series of coefficients which, multiplied by a yearly energy (MWh) give an hourly energy (MWh). .
    - The installed capacity is available in ehighway.
    - As ehighway does not publish the reservoir volume, we computed it by using historic filling rates time series from ENTSO-e transparency platform. The maximum value over the whole historic (from 2015) is taken and increased of 20%. The maximum capacity is the one from ehighway.
- Short-Term storages, defined by a capacity and a volume.
    - The installed capacity for Pumped Storage Plants from ehighway (e_Highway2050_2050_Country_and_cluster_installed_capacities_31-03-2015.xlsx sheet Cluster X5, category PSP) was used. 1 short term storage unit was created for each line of the sheet, using the column PSP (MW) for the capacity and the column

PSP reservoir (GWh) for the volume. As no information are available regarding the pumping efficiency, we chose to use 0,75, which is a typical mean value.

- For some countries (Greece, Hungary, Albany, Bosnia, Czech republic, Macedonia and UK), there exist 'Hydro with reservoir' capacities in ehighway (e_Highway2050_2050_Country_and_cluster_installed_capacities_31-03-2015.xlsx sheet Cluster X5), but we do not have Inflows time series (as no data are available in ENTSO-e Transparency platform). Those capacities are then seen as Short Term Storages in our dataset. Volumes needed then to be calculated with the same metholodlogy than above, but given lack of data in ENTSO-e, it was possible onmy for Greece and Hungary. For the other countries, the volume was computed by multipliying the maximum capacity by a coefficient400, which was derived from statistics over the other countries.
-

- National Run-of-river per country, defined as a scenarised maximum capacity time serie. Run-of-River time series are provided as time series of coefficients which, multiplied by the annual energy in MWh (as given in eHighway) gives an hourly energy. Those time series are not available for all countries in C3S. For countries without a run-of-river time serie, the annual energy from eHighway is divided by 8760, which gives a maximum capacity for this unit.

Each kind of hydro is then distributed at cluster level using the shares per clusters defined in **e-Highway2050_2050_Country_and_cluster_installed capacities_31-03-2015.xlsx**
When pumping is possible, the pumping efficiency used is (arbitrary) classical 0,75.

PV and WindPower

The generation hourly loadfactor profiles for for PV and WindPower have been computed within the Copernicus Climate Change Service (C3S)[3]. The following variables (named according to C3S Energy's data management plan) have been downloaded:

- WON: Wind ONshore
- WOF : Wind OFFshore
- SPV : Solar PV

3 https://climate.copernicus.eu/energy

- HRE : Hydropower Generation from REservoirs
- HRO : Hydropower Generation from Run-Of-river
- INF : INFlows to reservoirs

These variables are available at the following different levels:

- WON, SPV, HRE, HRO and INF : NUTS0 ~ countries
- WON and SPV : e-HighWay 2050 clusters
- WOF : MAR0 and MAR1. These are NUTS equivalent areas that were designed in C3S Energy for offshore wind, because NUTS regions are defined only on land. MAR0 corresponds to country level (1 area per country), and MAR 1 corresponds to sub-regions.

Those data have been aggregated in order to map with our dataset geographic granularity. Formatting was also necessary to respect the plan4res format.

Hydro Inflows

Hydro Inflows were computed using a 3 steps process.

Step1: preprocessing of ENTSO-e data

Inflows (expressed as an energy) have been defined based on available ENTSOE data as:

$$Inf(w) = \left(FR(w) - FR(w-1)\right) + HRE(w)$$

where:

- Inf(w) = inflow to reservoirs for week w
- FR(w) = filling rate of reservoirs for week w (data from ENTSOE, dataset = AggregatedFillingRateReservoirs)
- HRE(w) = Hydropower production from reservoirs for week w (data from ENTSOE, dataset = AggregatedGenerationPerType)

Step2 – build a statistical model using WEMC[4] and C3S data and methodology to reconstruct inflows

Step3 – run randomForest models to simulate inflows to reservoirs and runofriver

4 World Energy & Meteorology Council

Biomass

Biomass: is modelled as a thermal unit in plan4res, using data from eHighway (see `Thermal units`)

4.3.3.5 Demand Response

Demand Response in plan4res accounts for 2 different modelling, that are complementary:

- Demand curtailment, which is modelled as a storage whose Maximal Generation capacity is a % of the demand peak (7 to 10%), and Volume is equivalent to 20 days at full capacity.
- Load-shifting, which is modelled as short term storages, that could account for 5% of the electricity heating demand

Demand response Curtailment potentials in Europe can be found in a study by Sia Partners[5]. The following graphics (see Figure 37 and Figure 38) have been taken from this study.

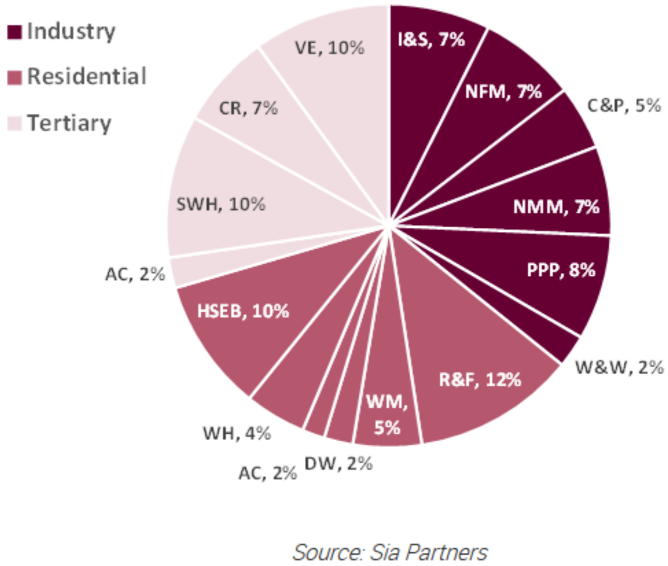


Figure 37: Load curtailement potentials per uses

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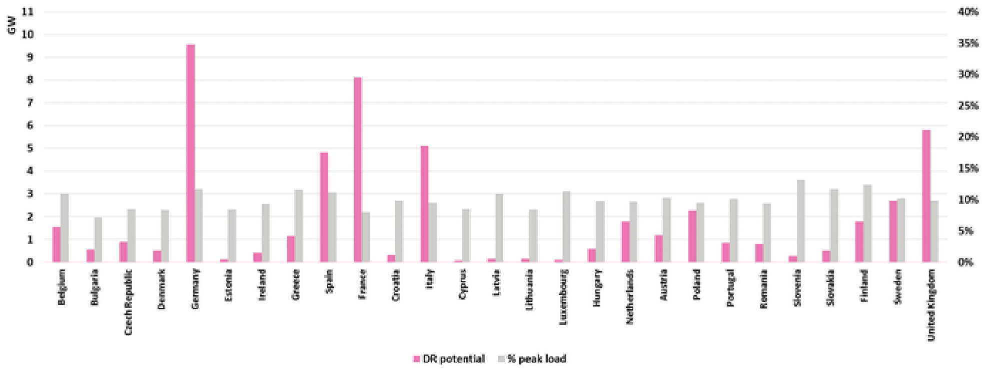
5 http://energy.sia-partners.com/demand-response-study-its-potential-europe



Source: Sia Partners

Figure 38: load curtailment potentials per country

Demand response Load-Shifting potentials in Europe can be found in [22][6]. The corresponding tables and in appendix have been taken from this study.

4.3.3.6 Ancillary services and inertia

We could not find any public data regarding the provision capacity for system services (primary, secondary reserves, or inertia).

Reserves: Data detailing the maximum potential capacity of units in primary (FCR) or secondary (aFRR) reserve are not publicly available.

- The modelled plan4res constraints are that the optimised primary (resp. secondary) reserve is lower than a coefficient primaryRho (resp. SecondaryRho) multiplied by the maximum capacity of the unit. We then use PrimaryRho=SecondaryRho=10% as a default value.
- For RES units (PV and WindPower) we also use a coefficient Gamma coefficient that accounts for this unit in the reserve is uncertain. We use 0,5 as a default value.

Inertia: Regarding inertia, we used an average value of 5s (from [23]), and increased it of 10% for some units (nuclear, coal), or decreased it of 10% for others (hydrau, biomasse), in order to

6 Hans-Christian Gils, « Assessment of the theoretical demand response potential in Europe", Institute of Technical Thermodynamics, German Aerospace Center (DLR), Wankelstraße 5, 70563 Stuttgart, Germany

represent variability depending on the technology. The inertia capacity for PV and WindPower units is 0, as well as for batteries.

Regarding the **'Demands' in Primary/Secondary reserve**, only historic data are available (on ENTSO-e transparency Platform).

Regarding **primary reserve** we used the following rule: the requirement for the European region is equal to the capacity of the biggest group of assets (~3000MW), which is then decomposed per country using a ratio between the generation of each country and the European generation during year n-2. Those values were computed using ENTSO-e data from 2019.

Regarding **secondary reserve**, we used ENTSO-e historic data from 2019.

Of course the rules and values may evolve in the future, which will require to update those data.

Regarding the '**Inertia demand'**, we used the following rule, based on [24]:

InertieDemand = f0 x DeltaP/(2*RocoFMax)

with

- DeltaP the capacity of the biggest unit in the inertia region (in our dataset we chose Europe)
- f0 =50Hz ('normal' frequency)

RocoFMax= maximum 'ramping' of event (we chose 1Hz)

4.3.4 Gas Network Optimization

The nomination data used in plan4res analysis is generated from data provided by ENTSO-G and the results of European market and electricity grid simulation. Gas supply and demand forecasts as used in nomination generation process is provided in the public data set. Section 4.3.4.1 presents how we build this dataset from raw data provided by ENTOS-G.

In addition, the gas storage data that is used as a part of network topology dataset, is presented in Section 4.3.4.2.

4.3.4.1 Daily Gas Supply and Demand Forecasts

Source: ENSTO-G Web Site, ENTSO-G Transparency Platform

The European level supply and demand forecast data are provided in ENTSO-G at country or balancing zone level on a yearly basis. However, our analysis in plan4res on gas network integration to electricity grid have a daily temporal resolution. Consequently, we have to employ a set of data transformation to make use of ENTSO-G supply and demand forecasts in our analysis as nominations data.

Input data:

EU level supply and demand data is in scenario reports of Ten Year Network Development Plans published by ENTSO-G.

- Data Set 1: EU level demand forecasts for years 2018-2040 are obtained from ENTSOs TYNDP 2018 Final Scenario Report, ENTSOG TYNDP 2018 Final Scenario Report Supply: https://www.entsog.eu/sites/default/files/entsog-migration/publications/TYNDP/2018/entsog_tyndp_2018_Final_Scenario_Report_Supply.xlsx
- Data Set 2: EU level supply forecasts for years 2018-2040 are obtained from ENTSOs TYNDP 2018 Final Scenario Report, ENTSOG TYNDP 2018 Final Scenario Report Demand: https://www.entsog.eu/sites/default/files/entsog-migration/publications/TYNDP/2018/ENTSOG_TYNDP_2018_Scenario_Report_Demand.xlsx

Existing capacities and planned capacities up to (and including) 2040 for interconnection points are published by ENTSO-G transmission capacity map data.

- Data Set 3: Existing capacities and planned capacities up to (and including) 2040 for interconnection points are obtained from ENTSOG Capacity map dataset in Excel Format – 2019:

  https://www.entsog.eu/sites/default/files/2019-10/Capacities%20for%20Transmission%20Capacity%20Map%20RTS008_NS%20-%20DWH_final.xlsx

Historical daily gas flow data for balancing zones between 2015-2019 are downloadable from ENTSO-G Transparency Platform. The data can be downloaded using the API of provided by ENTSO-G by pasting the following address to the web browser:

Address 1:
https://transparency.entsog.eu/api/v1/aggregateddata.<FORMAT>?forceDownload=true&directionKey=<DIRECTION>&from=<STARTING_DATE>&to=<ENDING_DATE>&indicator=Physical%20Flow&periodType=day&timezone=CET&limit=-1

where

- FORMAT is the downloaded file format. It can be either "csv" or "xlsx".
- STARTING_DATE and ENDING_DATE specify the time duration for the data. The date should be formatted as "YYYY-MM-DD".

- DIRECTION is the flow direction of gas. It should be either "entry" or "exit"

- Data Set 4: Daily distribution time series for demand of each balancing zone is obtained from the data downloaded by using Address 1 provided above with the DIRECTION option is set to "exit" and relevant start and end dates. Data is processed by summing up the daily flows of relevant interconnection points, i.e., the adjacent gas system is either final consumer, distribution or transmission to a non-EU country. The resulting data is a daily time series of gas demand for each balancing zone for each year.

Historical daily gas flow data for interconnection points between 2015-2019 are also downloadable from ENTSO-G Transparency Platform. The data can be downloaded using the API of provided by ENTSO-G by pasting the following address to the web browser:

Address 2:

https://transparency.entsog.eu/api/v1/operationalData.<FORMAT>?forceDownload=true&pointDirection=<POINT_ID_LIST><DIRECTION>&from==<STARTING_DATE>&to=<ENDING_DATE>&&indicator=Physical%20Flow&periodType=day&timezone=CET&limit=-1&dataset=1

where

- FORMAT is the downloaded file format. It can be either "csv" or "xlsx".
- STARTING_DATE and ENDING_DATE specify the time duration for the data. The date should be formatted as "YYYY-MM-DD".
- DIRECTION is the flow direction of gas. It should be "entry" or "exit"
- POINT_ID_LIST is the list of relevant ENTSOG point ids

- Data Set 5: Daily distribution time series for supply from Russia, Norway, Algeria, Libya and LNG facilities are obtained by processing the data downloaded by using Address 2 with DIRECTION "entry" and, POINT_ID_LIST including the ENTSO-G point id's having either the "from zone" is one of RU, NO, DZ, LY, or "from infrastructure" is LNG or "Production". The downloaded data is processed by summing up daily flows for all points belonging to each supply source, i.e., Russia, Norway or LNG. The resulting data is a daily time series of gas supply for each supply source for each year.

Temporal disaggregation of yearly supply and demand forecasts:

Yearly supply and demand data given by balancing zone or country are temporally disaggregated to daily supply and demand data by using the "Gas Time Series Transformation" in plan4res Data Transformation tool. The supply and demand forecasts in Data Set 1 and Data Set 2 data serve as the input GasForecast.csv:

Profile_TimeSerie_Names	Total_Forecast_Value	Total_Forecast_Unit	Total_Forecast_Year	Forecast_Source
Gas_Supply_DE275_1	15000	kWh/h	2025	ENTSOGScen1

The historical data for demand and supply in Data Set 3 and Data Set 4 are the time series in input TimeSeries.csv.

After applying the "Gas Time Series Transformation" to these input data, we obtain the daily time series for gas supply and demand.

4.3.4.2 Gas Storage Data

Source: GIE Transparency Platform, GIE Storage Investment Database

We include the storages in our model to have more precise supply and cross-border demand data. Storage facilities serve as exit and entry points to the gas network. The maximum amount of gas in a single storage is given as its total working volume. In our analysis, we assume that the storages are not completely full initially, i.e., a percentage of the total working volume is available as supply to the network initially. The amount of gas withdrawn from (injected to) a particular storage is dependent on its withdrawal (injection) rate, respectively. Those rates are not constant, and they depend on the amount of gas in a particular storage. Since our model is stationary, we compute the rates corresponding to the available amount of gas in the storages in the beginning.

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6 Appendix

Correspondance between ehighway and plan4res dataset clusters

Country	Cluster eHighway	ClusterPlan4res
ES	01_ES	ES
ES	02_ES	ES
ES	03_ES	ES
ES	04_ES	ES
ES	05_ES	ES
ES	06_ES	ES
ES	07_ES	ES
ES	08_ES	ES
ES	09_ES	ES
ES	10_ES	ES
ES	11_ES	ES
PT	12_PT	PT
PT	13_PT	PT
FR	14_FR	14_FR
FR	15_FR	15_FR
FR	16_FR	16_FR
FR	17_FR	17_FR
FR	18_FR	18_FR
FR	19_FR	19_FR
FR	20_FR	20_FR
FR	21_FR	21_FR
FR	22_FR	22_FR
FR	23_FR	23_FR
FR	24_FR	24_FR
FR	25_FR	25_FR
FR	26_FR	26_FR
FR	27_FR	27_FR
BE	28_BE	BE
LU	29_LU	27_FR
NL	30_NL	NL
DE	31_DE	31_DE
DE	32_DE	32_DE
DE	33_DE	33_DE
DE	34_DE	34_DE
DE	35_DE	35_DE
DE	36_DE	36_DE
DE	37_DE	37_DE
DK	38_DK	SCAND
CZ	39_CZ	CZ
CZ	40_CZ	CZ
PL	41_PL	PL
PL	42_PL	PL
PL	43_PL	PL
PL	44_PL	PL
PL	45_PL	PL
SK	46_SK	SK
CH	47_CH	CH
CH	48_CH	CH
AT	49_AT	AT
AT	50_AT	AT
AT	51_AT	AT
IT	52_IT	ITN
IT	53_IT	ITN
IT	54_IT	ITS
IT	55_IT	ITS
IT	56_IT	ITS
SI	57_SI	BALKAN
HU	58_HU	HU
RO	59_RO	BALKAN
RO	60_RO	BALKAN
RO	61_RO	BALKAN
HR	62_HR	BALKAN
BA	63_BA	BALKAN
ME	64_ME	BALKAN
RS	65_RS	BALKAN
BG	66_BG	BALKAN
MK	67_MK	BALKAN
GR	68_GR	BALKAN
GR	69_GR	BALKAN
AL	70_AL	BALKAN
DK	72_DK	SCAND
EE	73_EE	BALTIC
FI	74_FI	SCAND
FI	75_FI	SCAND
LT	77_LT	BALTIC
LV	78_LV	BALTIC
NO	79_NO	SCAND
NO	80_NO	SCAND
NO	81_NO	SCAND
NO	82_NO	SCAND
NO	83_NO	SCAND
NO	84_NO	SCAND
NO	85_NO	SCAND
SE	86_SE	SCAND
SE	87_SE	SCAND
SE	88_SE	SCAND
SE	89_SE	SCAND
UK	90_UK	UK
UK	91_UK	UK
UK	92_UK	UK
UK	93_UK	UK
UK	94_UK	UK
UK	95_UK	UK
IE	96_IE	IE
IT	98_IT	ITS
FR	99_FR	16_FR
EA	100_EA	Fatal_PL
MEA	101_MEA	Fatal_BALKAN
MA	102_MA	Fatal_ES
DZ	103_DZ	Fatal_ES
TN	104_TN	Fatal_IT
LY	105_LY	Fatal_IT
NS	106_NS	106_NS
NS	107_NS	107_NS
NS	108_NS	108_NS
NS	109_NS	109_NS
NS	111_NS	111_NS
NS	112_NS	112_NS
NS	113_NS	113_NS
NS	114_NS	114_NS
NS	110_NS	110_NS
NS	115_NS	115_NS
NS	116_NS	116_NS

Table 17: clusters plan4res vs eHighway2050

Interconnections derived from eHighway

Link	Impedance (ohm)	MaxFlow 2030 (MW)	MaxFlow 2050 (MW)
01_es - 02_es	6,5	7200	7 200

01_es - 12_pt	6,5	1200	2 200
02_es - 03_es	6,5	19100	19 100
02_es - 04_es	6,5	2400	2 400
02_es - 08_es	60	2400	3 400
02_es - 12_pt	20	950	1 950
03_es - 04_es	6,5	7100	9 100
03_es - 05_es	20	3900	3 900
03_es - 07_es	6,5	10200	12 200
03_es - 11_es	20	2700	2 700
04_es - 05_es	20	900	900
04_es - 14_fr	20	2000	7 000
05_es - 06_es	20	7000	7 000
05_es - 11_es	20	5700	5 700
05_es - 14_fr	60	100	100
06_es - 11_es	60	1100	5 100
06_es - 15_fr	20	1800	11 800
07_es - 08_es	6,5	8700	10 700
07_es - 11_es	20	2100	4 100
08_es - 09_es	20	6100	6 100
08_es - 10_es	20	4000	4 000
08_es - 13_pt	60	900	2 900
09_es - 10_es	20	8100	8 100
09_es - 102_ma	fatal	12000	12 000
09_es - 13_pt	60	500	2 500
10_es - 11_es	60	3200	4 200
106_ns - 90_uk	dc	8000	18 000
107_ns - 92_uk	dc	6023,20545	9 023
108_ns - 93_uk	dc	1003,86757	2 004
109_ns - 94_uk	dc	1003,86757	2 004
110_ns - 28_be	dc	1000	3 000
111_ns - 30_nl	dc	4461,63366	6 462
112_ns - 31_de	dc	8000	18 000
113_ns - 38_dk	dc	8000	17 000

114_ns - 72_dk	dc	3903,92946	5 904
115_ns - 79_no	dc	334,622525	335
116_ns - 88_se	dc	334,622525	1 335
12_pt - 13_pt	6,5	4000	5 000
14_fr - 15_fr	6,5	2000	2 000
14_fr - 17_fr	20	3000	7 000
14_fr - 18_fr	60	1100	2 100
15_fr - 16_fr	20	3500	11 500
15_fr - 18_fr	20	4500	4 500
16_fr - 19_fr	20	5200	7 200
16_fr - 20_fr	145	450	1 450
17_fr - 18_fr	6,5	4200	4 200
17_fr - 21_fr	6,5	5400	6 400
17_fr - 22_fr	145	250	3 250
18_fr - 19_fr	20	2200	4 200
18_fr - 23_fr	6,5	10000	10 000
18_fr - 24_fr	145	125	2 125
19_fr - 20_fr	1,5	6000	7 000
19_fr - 24_fr	6,5	2500	2 500
19_fr - 52_it	60	1000	2 000
20_fr - 24_fr	6,5	3000	3 000
20_fr - 25_fr	60	1150	1 150
20_fr - 47_ch	60	4300	4 300
20_fr - 48_ch	60	1300	1 300
20_fr - 52_it	60	4800	5 800
21_fr - 22_fr	6,5	7000	7 000
21_fr - 96_ie	dc	700	6 700
22_fr - 23_fr	20	2400	3 400
22_fr - 26_fr	20	3200	4 200
22_fr - 90_uk	dc	1000	5 000
23_fr - 24_fr	20	3500	3 500
23_fr - 25_fr	20	4000	4 000
23_fr - 26_fr	6,5	17900	17 900
23_fr - 27_fr	60	1100	1 100

24_fr - 25_fr	20	4200	4 200
25_fr - 27_fr	6,5	3500	3 500
25_fr - 28_be	60	400	400
25_fr - 35_de	20	2100	2 100
25_fr - 36_de	60	1800	2 800
25_fr - 47_ch	60	3900	3 900
26_fr - 27_fr	20	4900	4 900
26_fr - 28_be	20	2900	2 900
26_fr - 90_uk	dc	2000	11 000
27_fr - 28_be	60	1300	1 300
28_be - 29_lu	6,5	700	700
28_be - 30_nl	6,5	3500	3 500
28_be - 33_de	6,5	1000	1 000
28_be - 90_uk	dc	1000	5 000
29_lu - 35_de	6,5	2900	2 900
30_nl - 31_de	20	1400	2 400
30_nl - 33_de	6,5	7100	7 100
30_nl - 38_dk	6,5	700	3 700
30_nl - 79_no	dc	700	7 700
30_nl - 90_uk	dc	1000	5 000
31_de - 32_de	6,5	5400	5 400
31_de - 33_de	1,5	17330	29 330
31_de - 35_de	6,5	6300	6 300
31_de - 36_de	6,5	2000	2 000
31_de - 37_de	6,5	4000	8 000
31_de - 38_dk	6,5	3000	14 000
31_de - 79_no	dc	1400	18 400
31_de - 89_se	dc	1200	1 200
32_de - 34_de	dc	9300	9 300
32_de - 44_pl	20	3400	3 400
32_de - 72_dk	dc	600	2 600
33_de - 35_de	1,5	19050	19 050
33_de - 36_de	6,5	2000	2 000
34_de - 35_de	20	2600	2 600

34_de - 37_de	6,5	14840	14 840
34_de - 39_cz	20	1700	1 700
34_de - 44_pl	60	1700	4 700
35_de - 36_de	6,5	7700	7 700
35_de - 37_de	6,5	6130	6 130
36_de - 37_de	6,5	7500	7 500
36_de - 47_ch	20	6000	6 000
36_de - 49_at	20	2800	2 800
37_de - 39_cz	20	2000	3 000
37_de - 49_at	60	2500	3 500
37_de - 50_at	20	5500	5 500
38_dk - 72_dk	dc	600	1 600
38_dk - 79_no	dc	1700	3 700
38_dk - 88_se	dc	740	740
39_cz - 40_cz	6,5	7600	8 600
40_cz - 43_pl	20	2100	7 100
40_cz - 46_sk	20	2700	3 700
40_cz - 51_at	20	2100	7 100
41_pl - 42_pl	20	4700	4 700
41_pl - 43_pl	1,5	4900	8 900
41_pl - 44_pl	6,5	3400	3 400
41_pl - 45_pl	6,5	4400	4 400
41_pl - 77_lt	dc	1000	9 000
42_pl - 43_pl	20	4300	4 300
42_pl - 46_sk	20	600	3 600
43_pl - 44_pl	6,5	4000	6 000
44_pl - 45_pl	6,5	8900	10 900
45_pl - 89_se	dc	600	600
46_sk - 58_hu	1,5	5400	7 400
47_ch - 48_ch	1,5	19800	19 800
47_ch - 49_at	60	900	900
48_ch - 49_at	60	1500	1 500
48_ch - 52_it	6,5	8500	8 500
49_at - 50_at	20	6300	10 300

49_at - 52_it	20	2300	6 300
50_at - 51_at	20	6100	10 100
50_at - 57_si	60	1600	1 600
51_at - 58_hu	20	1600	2 600
52_it - 53_it	20	2200	13 200
52_it - 57_si	60	3600	3 600
53_it - 54_it	20	2000	13 000
53_it - 62_hr	dc	1000	1 000
53_it - 99_fr	dc	300	300
54_it - 55_it	20	10000	21 000
54_it - 64_me	fatal	1000	2 000
54_it - 98_it	dc	700	8 700
55_it - 56_it	20	1100	10 100
55_it - 68_gr	dc	1000	7 000
55_it - 70_al	dc	1000	1 000
57_si - 58_hu	20	900	1 900
57_si - 62_hr	6,5	3400	3 400
58_hu - 59_ro	20	1400	2 400
58_hu - 62_hr	6,5	2300	2 300
58_hu - 65_rs	60	700	1 700
59_ro - 60_ro	6,5	3500	3 500
59_ro - 61_ro	20	900	900
60_ro - 61_ro	6,5	4700	4 700
60_ro - 65_rs	20	2500	2 500
60_ro - 66_bg	60	800	800
61_ro - 66_bg	20	900	900
62_hr - 63_ba	6,5	4000	4 000
62_hr - 65_rs	6,5	700	700
63_ba - 64_me	6,5	1400	1 400
63_ba - 65_rs	20	3100	3 100
64_me - 65_rs	20	2900	2 900
64_me - 70_al	20	900	900
65_rs - 66_bg	20	900	900
65_rs - 67_mk	20	1900	2 900

65_rs - 70_al	60	900	900
66_bg - 67_mk	20	700	700
66_bg - 68_gr	60	500	500
67_mk - 68_gr	60	600	2 600
67_mk - 70_al	20	700	700
68_gr - 69_gr	20	11600	11 600
68_gr - 70_al	20	800	800
72_dk - 89_se	dc	1700	5 700
73_ee - 75_fi	dc	1000	6 000
73_ee - 78_lv	20	950	5 950
74_fi - 75_fi	20	3500	3 500
74_fi - 85_no	dc	50	1 050
74_fi - 86_se	dc	1800	1 800
75_fi - 88_se	dc	1350	4 350
77_lt - 78_lv	20	1500	6 500
77_lt - 88_se	dc	700	2 700
79_no - 80_no	20	1500	4 500
79_no - 81_no	20	1700	18 700
79_no - 93_uk	dc	1400	1 400
80_no - 81_no	20	1500	1 500
80_no - 82_no	20	5300	5 300
81_no - 83_no	20	800	7 800
82_no - 83_no	20	400	400
82_no - 88_se	dc	2148	4 148
83_no - 84_no	20	200	5 200
83_no - 87_se	dc	1000	1 000
84_no - 85_no	20	700	700
84_no - 86_se	dc	700	700
84_no - 87_se	dc	250	250
86_se - 87_se	20	4200	9 200
87_se - 88_se	20	7300	15 300
88_se - 89_se	20	6500	15 500
90_uk - 91_uk	20	7600	7 600
90_uk - 92_uk	20	8000	21 000

91_uk - 92_uk	20	5000	5 000
92_uk - 93_uk	20	7900	20 900
92_uk - 96_ie	dc	500	1 500
93_uk - 94_uk	20	4500	13 500
93_uk - 95_uk	20	500	1 500
95_uk - 96_ie	dc	1100	2 100
98_it - 99_fr	dc	400	1 200
106_ns - 110_ns	dc	0	2 000
112_ns - 113_ns	dc	0	9 000
114_ns - 116_ns	dc	0	1 000
31_de - 72_dk	dc	0	4 000
32_de - 89_se	dc	0	8 000

Table 18: plan4res interconnections

Exchanges at Boundaries from eHighway

Source: e-Highway_database_per_country-08022016.xlsx

Type Gen.	*Solar*	*Σ Total*
Country	*GWh*	*GWh*
DZ	165 114	165 114
LY	79 322	79 322
MA	85 357	85 357
MEA	8 775	8 775
TN	28 222	28 222
North Africa	**366 788**	**366 788**

Table 19: PV generation in north africa

COUNTRY-TOTAL	Wind (MW)	PV (MW)	CSP (MW)	*TOTAL SOLAR (MW)*
DZ		15700	36600	52300
LY		7500	17600	25100
MA		8300	19300	27600
MEA		800	1900	2700
TN		2600	6100	8700
North Africa	0	34900	81500	116400

Table 20: Solar installed capacity in North Africa

`Electricity demand (GWh) by uses, computed from ehighway`

Recomputed by aggregating figures from e-Highway2050_2050_Country_and_cluster_installed capacities_31-03-2015.xlsx

"country"	Total EV	Total heating	Total air cond	Total Others	Total
BALKAN	2,6	3,1	0,2	9,2	15,0
AT	11,0	26,7	0,1	55,7	93,5
BALKAN	2,7	3,2	0,2	9,5	15,5
BE	15,0	41,0	0,2	92,3	148,5
BALKAN	5,0	6,7	0,5	26,9	39,0
CH	9,0	26,2	0,1	46,4	81,7
CZ	9,0	27,5	0,1	51,3	87,9
DE	101,0	186,0	1,6	526,6	815,2
SCAND	7,0	17,6	0,1	27,5	52,2
BALTIC	1,0	5,0	0,0	9,3	15,3
ES	70,0	69,3	14,6	455,9	609,8
SCAND	7,0	21,3	0,3	72,5	101,1
FR	90,0	205,4	1,1	498,7	795,2
BALKAN	10,0	14,6	1,0	57,5	83,1
BALKAN	5,0	6,1	0,3	17,9	29,3
HU	5,0	18,9	0,5	48,1	72,5
IE	9,0	17,0	0,0	26,7	52,8
IT	76,0	115,0	10,1	327,1	528,2
BALTIC	4,0	9,4	0,0	20,9	34,3
FR	1,0	2,8	0,0	5,2	9,0
BALTIC	2,0	8,3	0,0	15,4	25,7
BALKAN	1,0	0,2	0,0	2,7	3,9
BALKAN	1,8	2,2	0,1	6,3	10,3
NL	17,0	48,1	0,5	131,2	196,8
SCAND	8,0	13,2	0,4	103,4	124,9
PL	30,0	67,0	0,4	113,5	210,9
ES	9,0	10,9	2,1	64,9	86,9
BALKAN	15,0	26,6	0,7	41,3	83,6
BALKAN	6,0	6,6	0,4	25,4	38,4
SCAND	14,0	30,1	0,4	102,0	146,4
BALKAN	3,1	3,8	0,2	11,2	18,3
SK	3,0	10,0	0,0	19,5	32,5
UK	98,0	164,2	0,3	275,1	537,6

Table 21: electricity demand by Uses (GWh)

Demand response potentials

Average potentials for load reduction by shedding or shifting to a later point in time, subdivided by country and consumer in MW.

Country/process[a]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	21	22	23	24	25	26	27	30
Albania	0	0	0	0	0	0	0	15	21	0	0	0	0	4	1	1	7	4	2	0	52	16	2	2	4	19
Algeria	0	0	2	0	0	0	1	12	189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Austria	0	1	0	7	67	46	44	46	57	2	4	27	14	91	12	18	178	14	42	8	268	86	44	79	1	124
Belarus	0	0	0	0	0	3	0	156	35	0	0	0	0	29	4	6	57	2	14	3	184	48	3	6	0	86
Belgium	0	3	22	131	28	17	65	153	103	0	8	68	16	164	22	33	320	25	76	15	333	105	100	80	4	160
Bosnia-Herzegov.	44	0	0	0	0	1	0	32	12	0	0	0	0	11	1	2	21	3	5	1	63	20	2	2	3	24
Bulgaria	0	1	5	13	0	4	2	84	64	0	0	20	5	60	8	12	117	37	27	5	176	58	0	3	27	64
Croatia	0	0	0	0	8	5	0	35	49	0	0	10	3	39	5	8	76	24	18	4	106	37	3	10	37	28
Cyprus	0	0	0	0	0	0	1	0	18	0	0	3	0	17	2	3	33	31	8	2	16	7	1	3	32	4
Czech Republic	0	0	0	30	15	9	13	64	66	0	1	25	24	104	14	21	202	16	48	10	228	88	31	27	3	139
Denmark	0	0	0	0	0	4	34	0	27	0	3	35	8	79	11	16	154	6	37	7	239	60	58	57	0	85
Egypt	108	0	0	0	0	4	11	360	511	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Estonia	0	0	0	0	21	1	2	0	10	0	0	5	2	19	3	4	37	1	9	2	34	14	4	2	0	18
Finland	0	1	21	14	797	126	21	168	12	0	2	30	11	132	18	26	257	10	61	12	160	61	18	51	0	78
France	135	0	18	198	1000	87	170	409	272	0	24	302	91	1078	144	216	2095	332	498	100	2032	644	293	418	87	922
Germany	211	5	12	575	249	204	449	931	422	12	51	275	147	779	104	156	1962	249	466	93	2885	854	543	791	32	1330
Greece	56	0	0	9	0	4	5	432	200	0	2	34	9	133	18	27	259	205	62	12	213	98	9	52	346	69
Hungary	0	0	0	37	0	5	12	30	46	0	1	19	6	84	11	17	164	26	39	8	269	108	2	12	10	129
Ireland	0	0	0	1	0	0	13	0	20	0	15	25	6	68	9	14	132	5	32	6	86	38	35	25	0	64
Italy	65	1	18	41	57	89	159	1181	540	0	17	198	94	635	85	127	1233	684	293	59	1461	667	96	378	756	514
Latvia	0	0	0	0	0	1	2	0	4	0	0	5	1	18	2	4	35	1	8	2	37	19	0	1	0	27
Libya	0	0	0	0	0	0	0	75	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liechtenstein	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1
Lithuania	0	0	0	0	0	1	3	0	14	0	0	0	0	21	3	4	41	2	9	2	61	27	9	8	1	37
Luxembourg	0	0	0	0	0	0	2	171	15	0	0	2	4	15	2	3	28	1	7	1	14	5	3	3	0	7
Macedonia	0	0	0	0	0	0	0	22	10	0	0	0	0	11	1	2	22	7	5	1	34	11	1	1	2	13
Malta	0	0	0	0	0	0	0	0	0	0	0	1	1	5	1	1	9	9	2	0	11	4	3	2	17	2
Moldova	0	0	0	0	0	0	0	66	11	0	0	0	0	6	1	1	12	3	3	1	64	17	1	2	0	28
Montenegro	40	0	0	0	0	0	0	12	0	0	0	0	0	3	0	1	6	1	1	0	10	3	0	0	0	4
Morocco	0	0	0	0	0	1	1	31	132	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	34	0	21	84	19	28	66	10	62	0	12	105	19	254	34	51	494	20	118	24	462	186	180	128	14	256
Norway	396	0	12	32	252	18	13	36	22	0	1	44	9	213	28	43	414	16	98	20	166	50	35	50	0	81
Poland	17	3	6	48	11	26	44	270	198	0	3	78	24	321	43	64	623	49	148	30	737	284	99	88	12	412
Portugal	0	0	0	10	0	14	21	108	121	0	1	27	12	122	16	24	236	56	56	11	272	98	35	50	10	72
Romania	91	0	0	50	5	5	8	255	223	0	0	26	14	56	7	11	109	17	26	5	397	159	6	12	6	175
Serbia and Kosovo	0	1	5	0	0	2	0	0	48	0	0	0	0	46	6	9	89	14	22	4	156	49	6	5	10	57
Slovakia	56	0	0	12	0	8	7	36	47	7	0	8	9	59	8	12	115	9	27	5	152	47	19	17	1	86
Slovenia	29	0	0	2	9	7	4	42	17	0	1	4	4	23	3	5	44	4	10	2	54	19	12	12	7	24
Spain	135	3	32	111	16	59	162	875	529	2	11	188	60	653	87	131	1268	854	301	60	989	422	30	237	888	304
Sweden	37	2	0	19	629	105	46	108	34	3	8	39	19	243	32	49	472	19	112	22	373	90	82	99	0	157
Switzerland	0	0	0	4	23	14	38	79	50	0	0	0	0	131	18	26	255	20	61	12	231	86	50	56	3	139
Tunisia	0	0	0	0	0	1	0	12	77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turkey	22	0	2	0	2	14	29	1375	860	2	0	0	0	334	45	67	650	360	154	31	420	162	11	10	251	84
UK	14	0	0	84	45	46	246	159	150	0	24	180	77	721	96	144	1400	55	333	67	1645	649	549	326	2	1016
Ukraine	0	0	1	0	0	8	10	98	149	0	0	0	0	182	24	36	354	56	84	17	802	209	12	26	4	361

[a] Legend: 1-Aluminium; 2-Copper; 3-Zinc; 4-Chlorine; 5-Pulp; 6-Paper; 7-Recycling paper; 8-Steel; 9-Cement; 10-Calcium carbide; 11-Air separation; 12-Industrial cooling; 13-Industrial ventilation; 14-Cooling retailing; 15-Cold storages; 16-Cooling hotels/restaurants; 17-Commercial ventilation; 18-Commercial AC; 19-Commercial storage water; 20-Commercial storage heating; 21-Water supply; 22-Water treatment; 23-Freezers/refrigerators; 24-Washing machines; 25-Tumble dryers; 26-Dish washers; 27-Residential AC; 28 Residential storage water; 29-Residential storage heater; 30-Heat circulation pump.

Table 22: load shifting reduction potentials per country/uses

Average potentials for load increase by shifting to an earlier point in time, subdivided by country and consumer in MW.

Country/Process[2]	5	6	7	8	9	10	11	12	15	16	19	20	21	22	24	25	26	28	29
Albania	0	0	0	0	5	0	0	0	0	1	10	0	2	1	98	11	10	119	181
Algeria	0	0	0	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Austria	17	28	11	0	14	3	5	25.3	9	14	253	0	34	11	517	263	473	877	1416
Belarus	0	2	0	0	9	0	0	0.0	3	4	82	0	11	4	289	16	36	580	1432
Belgium	7	10	16	0	26	0	10	63.5	16	25	456	0	62	21	631	598	479	759	1556
Bosnia-Herzegov.	0	1	0	0	3	0	0	0.0	1	2	30	0	4	1	118	14	12	162	263
Bulgaria	0	2	1	0	16	0	0	18.3	6	9	166	0	22	7	348	1	20	357	922
Croatia	2	3	0	0	12	0	0	9.3	4	6	108	0	15	5	223	20	60	199	294
Cyprus	0	0	0	0	5	0	0	2.8	2	3	46	0	6	2	41	6	16	34	49
Czech Republic	4	6	3	0	17	0	2	23.4	10	16	287	0	39	13	526	184	162	675	1554
Denmark	0	2	9	0	7	0	4	32	8	12	220	0	30	10	361	348	342	380	967
Egypt	0	2	3	0	128	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Estonia	5	0	0	0	3	0	0	4	2	3	52	0	7	2	81	26	11	115	236
Finland	199	77	5	0	3	0	2	27	13	20	366	0	49	16	364	107	307	885	4121
France	250	53	42	0	68	0	28	280	108	162	2988	6711	402	134	3869	1757	2500	7424	8842
Germany	62	125	112	0	105	14	61	255	78	117	1354	2122	376	125	5127	3261	4734	2999	11292
Greece	0	2	1	0	50	0	2	32	13	20	370	0	50	17	585	52	312	1721	1079
Hungary	0	3	3	0	12	0	1	18	8	13	233	0	31	10	646	9	72	938	1273
Ireland	0	0	3	0	5	0	18	23	7	10	189	0	26	9	229	207	148	89	986
Italy	14	55	40	0	135	0	20	183	63	95	1759	0	237	79	4006	578	2260	5677	8761
Latvia	0	0	1	0	1	0	0	5	2	3	50	0	6	2	112	3	7	270	345
Libya	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liechtenstein	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	1	1	1	6
Lithuania	0	1	1	0	3	0	0	0	2	3	58	0	7	2	161	53	47	305	468
Luxembourg	0	0	0	0	4	0	0	2	1	2	40	0	6	2	30	18	20	22	78
Macedonia	0	0	0	0	3	0	0	0	1	2	31	0	4	1	63	7	6	86	140
Malta	0	0	0	0	0	0	0	1	0	1	13	0	2	1	23	15	13	19	23
Moldova	0	0	0	0	3	0	0	0	1	1	18	0	3	1	100	6	12	182	426
Montenegro	0	0	0	0	0	0	0	0	0	0	8	0	1	0	19	2	2	27	45
Morocco	0	1	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	5	17	16	0	16	0	14	98	25	38	704	0	95	32	1116	1079	767	419	2474
Norway	63	11	3	0	5	0	1	41	21	32	591	0	79	26	300	210	301	294	5937
Poland	3	16	11	0	50	0	4	72	32	48	889	0	120	40	1704	596	525	2771	4878
Portugal	0	9	5	0	30	0	1	25	12	18	337	0	45	15	589	210	300	392	1043
Romania	1	3	2	0	56	0	1	24	6	8	156	0	21	7	953	33	73	1088	2749
Serbia and Kosovo	0	1	0	0	12	0	0	0	5	7	127	0	18	6	292	34	30	400	618
Slovakia	0	5	2	0	12	8	0	8	6	9	164	0	22	7	282	115	101	430	958
Slovenia	2	4	1	0	4	0	1	4	2	3	63	0	8	3	111	72	71	260	275
Spain	4	36	41	0	132	3	13	174	65	98	1809	0	243	81	2535	179	1419	3366	4449
Sweden	157	64	11	0	9	4	9	36	24	36	673	0	90	30	537	495	592	497	7516
Switzerland	6	8	9	0	13	0	0	0	13	20	364	0	49	16	514	303	333	124	1480
Tunisia	0	1	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turkey	1	9	7	0	215	2	0	0	33	50	927	0	124	41	972	68	60	499	0
UK	11	28	61	0	37	0	29	167	72	108	1997	0	269	90	3898	3297	1950	4003	15463
Ukraine	0	5	2	0	37	0	0	0	18	27	505	0	68	23	1256	70	155	2293	5634

Table 23: Load shifting increase potential per country and uses

France distribution clusters

Clusters	High voltage demand (%)	MV rural demand (%)	MV urban demand (%)	MV semiurban demand (%)	High voltage wind (%)	MV rural wind (%)	MV urban wind (%)	MV semiurban wind (%)	High voltage PV (%)	MV rural PV (%)	MV urban PV (%)	MV semiurban PV (%)
14_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
15_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
16_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
17_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
18_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
19_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
20_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
21_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
22_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
23_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
24_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
25_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
26_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%
27_FR	17%	28%	28%	28%	10%	85%	0%	5%	15%	28%	28%	28%

Table 24: example of distribution network mapping