# METIS Technical Note T6

## METIS Power System Module

*METIS Technical Notes*
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# 1. INTRODUCTION

METIS is an on-going project[1] initiated by DG ENER for the development of an energy modelling software, with the aim to further support DG ENER's evidence-based policy making, especially in the areas of electricity and gas. The software is developed by Artelys with the support of IAEW (RWTH Aachen University), ConGas and Frontier Economics as part of Horizons 2020 and is closely followed by DG ENER. METIS first version was delivered at the DG ENER premises in February 2016.

The intention is to provide DG ENER with an in-house tool that can quickly provide insights and robust answers to complex economic and energy related questions, focusing on the short-term operation of the energy system and markets. METIS was used, along with PRIMES, in the impact assessment of the Market Design Initiative.

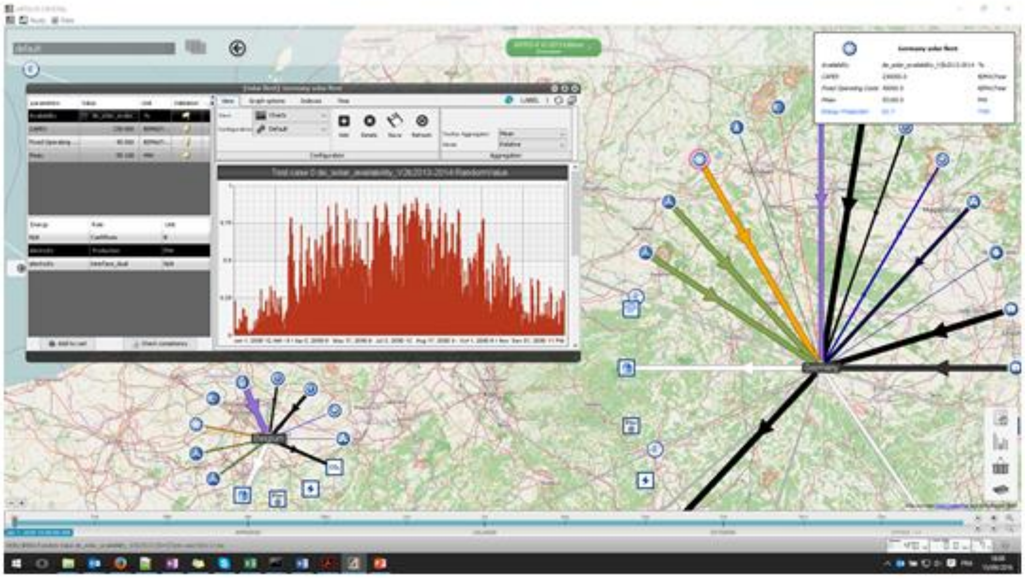

*Figure 1: METIS models displayed in the Crystal Super Grid user interface*

The **Power System Module** of METIS has been designed to address multiple power systems problematics, following a welfare-maximization principle. It can be used to analyse the European power systems' dynamics, by providing production plans, electricity flows, production costs, systemic marginal costs, scarcity periods and loss of load, or other standard indicators detailed further in the document.

Such a modelling tool can be used to conduct different types of studies or quantitative analysis on power systems, among which:

- Generation adequacy analysis,
- Impacts of Renewable Energy Sources integration on the energy system and market functioning,
- Cost-benefit analysis of infrastructure projects, as well as impacts on security of supply,
- Electricity flows between zones
- Impact of new energy usages (e.g. electrical vehicles, demand response) on the network reinforcement and generation costs,

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[1] http://ec.europa.eu/dgs/energy/tenders/doc/2014/2014s_152_272370_specifications.pdf

- Impact of day-ahead market measures such as rules for reserve sizing or participants in reserve procurement.

The present document is organised as follows:

- **Section 2** is dedicated to the description of the general structure of the model, the optimisation problem it implements, and the way it is solved,
- **Section 3** focuses on the specification of the asset models, going in depth into cluster and reserve models,
- **Section 4** describes briefly the main visualization features to display results of the METIS Power System Module,
- **Section 5** recalls the scenarios that are implemented and summarizes the main assumptions for the models that have been delivered to the European Commission.
- **Three appendixes** are also available, detailing technical parameters of assets, demand and RES data generation, and the reserve sizing methodology.

Note that METIS also embeds a Gas System Module (allowing to model the European gas system) and a Power Market Module (containing models for European intra-day and balancing markets) which have their own specific documentation. A demand and a gas market module are also currently in development (as of May 15, 2017).

# 2. MODEL STRUCTURE AND OPTIMISATION PROCESS

## 2.1. MODEL STRUCTURE

In METIS, the power system is represented by a network in which each node stands for a geographical zone[2] that can be linked to other zones with power transmissions. At each node are attached assets that represent all consumption and production of energy at this node. The model aims at minimizing the overall cost of the system to maintain a supply/demand equilibrium at each node, at an hourly time step.

While the typical METIS models are at country-granularity, zones can also be configured to stand for either NUTS2 zones or for aggregations of country, depending on the needs of the study.

The following sections describe the list of assets included in the model, and specify the main characteristics of the optimisation problem built from the model and of its solving method.

## 2.2. ASSET LIBRARY

METIS Power System Module contains a library of assets for production, consumption and transmissions that can be attached to each node of the network. The following assets are included:

- Thermal non-RES assets
    - Nuclear: power generation using nuclear technology,
    - Lignite: power generation using lignite as primary fuel,
    - Coal: power generation using coal as primary fuel,
    - CCGT (gas): power generation, with combined cycles, using gas as primary fuel,
    - Oil: power generation using diesel as primary fuel,
    - OCGT (gas): power generation using gas as primary fuel,
    - Derived gas: power generation using derived gas a fuel,
- Hydro assets
    - Hydro-reservoir: hydro power generation associated with a storage capacity, water inflows and an optional pumping capacity (for mixed PHS),
    - Hydro run-of-the-river: intermittent power generation using run of river turbines,
    - Pure pumped hydro storage: pumped hydro storage without natural hydro inflows.
- Other RES assets
    - Onshore and offshore wind power: intermittent power generation, based on wind scenarios,
    - Solar fleet: intermittent power generation, based on solar irradiation scenarios
    - Geothermal power: intermittent power generation
    - Biomass/Waste fleet: power generation, using biomass/waste as fuel
    - Other RES: intermittent power generation, corresponding to all other RES (includes Tidal power)
- Other storage assets

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[2] Depending on the spatial granularity, a zone may be a subnational region, a country, a set of countries aggregated into one, etc.

    - Batteries
    - Compressed air energy storage
- Power Consumption: represent the aggregated consumption of electricity at this node.
- Power transmission: represent the power exchange capacity between two nodes. If zones correspond to European countries, the power transmission between two nodes represents the NTC capacity,
- Fuel contracts: represent the fuel purchase contracts (taking into account the fuel price) for thermal power assets,
- Water inflow: represent the water inflows for hydro-reservoirs,
- Total $CO_2$ emissions: represent the total $CO_2$ emissions of thermal assets, associated with a $CO_2$ price,
- Reserve requirements: represent the needs for reserve at each node. Used only for models with reserve.
- Loss of load: represents the load curtailment that is done at a node as a last recourse if demand is higher than production, at a very high price (VoLL).
- Well: represents the surplus of energy at a node that happens when production is higher than consumption.

## 2.3. GRANULARITY, HORIZONS, AND OBJECTIVE FUNCTION

### 2.3.1. *GENERAL STRUCTURE OF THE OPTIMIZATION PROBLEM*

Simulations of the power system in METIS are performed with Artelys Crystal Optimisation Engine and aim at determining a cost-minimizing production plan that ensures a supply /demand equilibrium at each node over the study period, at an hourly time step. This is done by solving an optimisation problem whose characteristics are described below.

The **electricity[3] supply-demand equilibrium constraint** at each node $\boldsymbol{n}$ and each time step $\boldsymbol{t}$ is the following:

$$Supply_{n,t} = Demand_{n,t}$$

with

$$Supply_{n,t} = \sum_{\substack{producers\ p \\ at\ node\ n}} Production_{p,t} + \sum_{neighbours\ n'\ of\ n} Flow_{n' \rightarrow n,t} + LossOfLoad_t$$

$$Demand_{n,t} = \sum_{\substack{consumers\ c \\ at\ node\ n}} Consumption_{c,t} + \sum_{neighbours\ n'\ of\ n} Flow_{n \rightarrow n',t} + Surplus_t$$

In country-granularity models, consumers at node n are limited to a national consumption plus the consumption of pumped hydro storages.

The objective function of the system is the total cost of the system:

$$TotalCost = \sum_{producers\ p} ProductionCosts_p + LossOfLoadCosts + SurplusCosts$$

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[3] If the model takes into account reserves, supply/demand equilibrium constraints are set for each reserve type. The objective function remain the same but additional constraints are set on producers, which usually increases the overall costs of the system. More details on reserve constraints are given in section 0.

Where:

- $ProductionCosts_p$ represent the production costs of the producer p, including fuel costs, CO2 costs, Variable OPEX[4]. Fixed annual CAPEX and OPEX can also be considered if relevant.
- $LossOfLoadCosts$ represent the costs associated to loss of load, computed as the product between the total loss of load (across all zones and all time steps) and the value of lost load (VoLL), usually 15 k€/MWh.
- $SurplusCosts$ represent the costs associated to the fact of having surplus energy in some zones, which can be penalised proportionally to the total volume of surplus.

### 2.3.2. *HORIZONS AND OPTIMISATION PROCESS*

METIS models are simulated by performing an optimisation of the production plan over a year, at an hourly time step. This can reveal to be quite complicated as the typical European model has around 30 assets by country and 34 countries, and can be even more complicated with models at NUTS2 geographical granularity.

For that purpose, the optimisation problem is solved using a rolling horizon approach. The solution of for the whole period is obtained by solving iteratively smaller problems as depicted in Figure 2.

Three horizons are defined:

- The **strategic horizon** corresponds to the full duration of the entire problem,
- The **tactical horizon** corresponds to the length of the smaller optimisation problems horizon,
- The **operation horizon** corresponds to the length of the interval for which the solutions of the small optimisation problem are kept in the full solution.

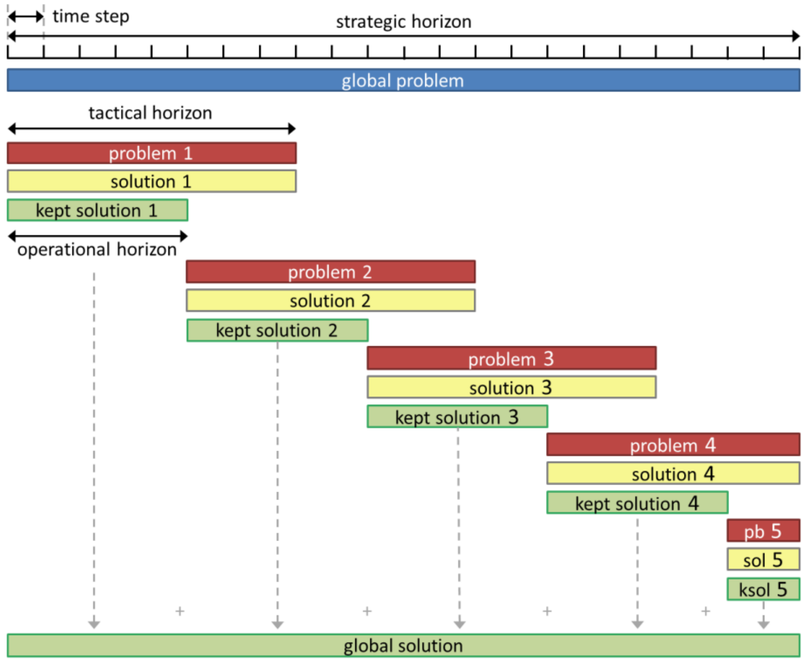

*Figure 2: Optimisation process used to simulate METIS models*

The resolution consists in solving successive simulation problems over a tactical horizon. The solution kept over each iteration is defined by the operational horizon. At each iteration, the initial states of the assets are set using results obtained from the previous

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[4] See section 0 for more details.

iteration (states of the assets at the end of previous operational horizon). Figure 2 and Figure 3 describe the simulation procedure and how results are generated.

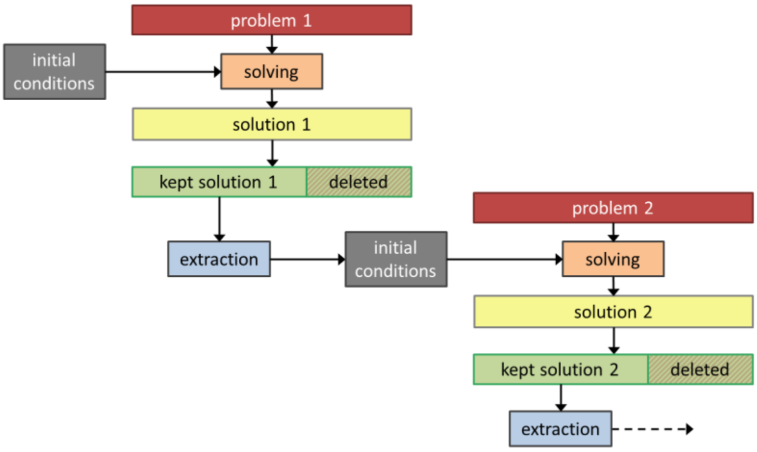

*Figure 3: Extraction of final results using the intermediate problems solutions*

For the standard METIS European power system model, the strategic horizon corresponds to one year. The tactical horizon is usually set to 15 days and the operational horizon to 7 days. The durations of tactical and operational horizon can also be modified if needed, depending on the user needs. However, since these values have been chosen to balance computational accuracy and computation time, it is advised to keep them unchanged. For instance, increasing the tactical horizon can make the overall solution very anticipative.

# 3. ASSET MODELS

This section describes the main assumptions used to model power generation technical constraints. Each asset of the library given in section 2.2 has a specific asset model:

- **Demand assets** (power and reserve) are modelled with demand time series, which have to be satisfied at each time,
- **Intermittent power generation** are modelled with a time series curve corresponding to its maximum possible generation, a variable production cost (usually very cheap) and a possible penalty for curtailment (proportional to the energy curtailed),
- **Thermal power generation (renewable and non-renewable)** are usually modelled with cluster and reserve models described in section 3.1,
- **Hydro assets and storages** are also modelled with cluster models and other specific assets, as described in section 3.2,
- **Loss of load assets** are modelled as an electricity producer with an unlimited capacity and a variable cost of VoLL.

These models are described in more details in the following sections.

## 3.1. FLEXIBLE ASSETS: CLUSTER MODELS

### 3.1.1. *CLUSTER MODEL DESCRIPTION*

In METIS, units of the same technology or using the same fuel in each zone are bundled together into the same asset. Thermal technologies such as Coal, CCGT, Lignite, OCGT are also divided in three assets corresponding to units built before 1999, between 2000 and 2015, and after 2015.

Thermal production and storage units are subject to dynamic constraints such as ramping gradients, minimal generation load, starting costs or minimal durations after turning them off during which they have to be kept off before turning them on again.

These constraints are often taken into account with a unit-by-unit modelling, which is computationally incompatible with a European optimal dispatch of the system. For that purpose, METIS uses so-called **cluster models** which allow to take into account dynamic constraints and starting costs in a relaxed (LP) unit commitment, without having to include any binary variables, hence avoiding excessively increasing the problem complexity.

In addition to the variables for generation at each time step, the cluster model introduces new variables representing the capacity of running units of each cluster at each time step. The generation variable of an asset is then bounded by its running capacity. The constraints are described in details below.

### 3.1.2. *NOTATIONS*

#### Parameters

For each cluster $i$, at each time step $t$:

- $\boldsymbol{C_i}$: Generation cost (€/MWh), Cost to generate 1 MWh of electricity.
  *This cost includes variable OPEX, fuel and CO2 costs.*

- $\boldsymbol{\overline{C}_i}$: Running cost (€/MW/h), Cost to have 1 MW of running capacity (independent from their load level).
  *Generation and running costs are computed using efficiency data at Pmin and Pmax by type of unit (see section 3.1.5), to represent the lower efficiency of partially loaded units*

- $\boldsymbol{\gamma_i}$: Start-up cost (€/MW),
- $\boldsymbol{Pmax_i}$: Installed capacity of the asset (MW)
- $\boldsymbol{minLoad_i}$: Minimum stable generation (%), as a proportion of the running capacity
- $\boldsymbol{Avail_{i,t}}$: Availability (%), as a proportion of the installed capacity of the asset
- $\boldsymbol{T_{off_i}}$: Minimum off-state duration (number of time steps $\geq 1$)

### Variables

For each asset $i$, at each time step $t$:

- $\boldsymbol{P_{i,t}}$ [MW]: Generation variable ($\geq 0$)
- $\boldsymbol{\overline{P}_{i,t}}$ [MW]: Running capacity variable ($\geq 0$)
- Difference variables:
    - $\boldsymbol{\bar{\delta}^{+}_{i,t}}$ [MW]
      Positive part of difference in running capacity between t-1 and t ($\geq 0$).
      Constraints linking $\boldsymbol{\bar{\delta}^{+}_{i,t}}$ to $\boldsymbol{\overline{P}_{i,t}}$ are detailed below.

    - $\boldsymbol{\bar{\delta}^{-}_{i,t}}$ [MW]
      Positive part of the shutdown power between t-1 and t ($\geq 0$)
- $\boldsymbol{\tilde{P}_{i,t}}$ [MW]: Capacity of off-state units which could be started-up ($\geq 0$)

The difference variable $\bar{\delta}^{+}_{i,t}$ represents the capacity that has been started at time step t. Start-up costs are associated with this variable.

As for $\bar{\delta}^{-}_{i,t}$, it represents the capacity that has been shut down at time step t. It will be used to determine power which could be started-up $\tilde{P}_{i,t}$. Indeed, $\tilde{P}_{i,t}$ is the capacity which is turned off at time step t and which was shut down more than $T_{off_i}$ time steps before time step t.

## 3.1.3. *MATHEMATICAL MODELLING*

### Costs

With these notations the following costs can be defined:

- Generation costs: $C_i \cdot P_{i,t}$
- Running costs: $\bar{C}_i \cdot \overline{P}_{i,t}$
- Start-up costs: $\gamma_i \cdot \bar{\delta}^{+}_{i,t}$

The overall cost associated with a cluster $i$ for a given solution of this cluster's decision variables at time step $t$ $(P_{i,t}\,;\,\overline{P}_{i,t}\,;\,\bar{\delta}^{+}_{i,t})$ is the sum those costs:

$$\boldsymbol{clusterCost_{i,t} = C_i \cdot P_{i,t} + \bar{C}_i \cdot \overline{P}_{i,t} + \gamma_i \cdot \bar{\delta}^{+}_{i,t}}$$

Note that variables $\bar{\delta}^{-}_{i,t}$ and $\tilde{P}_{i,t}$ does not have associated costs, however they are linked to costly decision variables $P_{i,t}$, $\overline{P}_{i,t}$ and $\bar{\delta}^{+}_{i,t}$ through constraints (see next paragraph) impacting all variables' dynamics and therefore the overall cluster cost.

### Constraints

A thermal cluster is subjected to the following constraints:

- Generation bounded by running capacity:

$$\boldsymbol{P_{i,t} \leq \overline{P}_{i,t}}$$

- Running capacity bounded by available installed capacity:

$$\boldsymbol{\overline{P}_{i,t} \leq Pmax_i \cdot Avail_{i,t}}$$

- Minimum stable generation constraint:

$$\boldsymbol{minLoad_i \cdot \overline{P}_{i,t} \leq P_{i,t}}$$

- Difference variables:

$$\boldsymbol{\overline{\delta}^{+}_{i,t} \geq \overline{P}_{i,t} - \overline{P}_{i,t-1}}$$

$$\boldsymbol{\overline{\delta}^{-}_{i,t} \geq \overline{P}_{i,t-1} - \overline{P}_{i,t}}$$

$$\boldsymbol{\overline{\delta}^{+}_{i,t} - \overline{\delta}^{-}_{i,t} = \overline{P}_{i,t} - \overline{P}_{i,t-1}}$$

- Minimum off-state duration

$$\boldsymbol{\widetilde{P}_{i,t} = \widetilde{P}_{i,t-1} - \overline{\delta}^{+}_{i,t} + \overline{\delta}^{-}_{i,t+1-T_{Off_i}} + Pmax_i \cdot (Avail_{i,t} - Avail_{i,t-1})}$$

### 3.1.4. ***FLEET MODELS***

When it is not necessary to represent the dynamic constraints of a given asset, one might decide to use a **fleet model** instead of cluster model. The fleet model is a simplification of a cluster model, as the only variable of the asset is the generation level at each hour. The only remaining costs and constraints are:

- $\boldsymbol{P_{i,t} \leq Pmax_i \cdot Avail_{i,t}}$
- $\boldsymbol{fleetCost_{i,t} = C_i \cdot P_{i,t}}$

If relevant, it is also possible to set a minimum generation constraint, e.g. to force an asset to be in must-run throughout the year, or gradient constraint to limit the variation of generation between two consecutive time steps.

### 3.1.5. ***FLEXIBLE ASSETS TECHNICAL PARAMETERS***

A literature review [3-16] resulted in the technical characterization of the different fleets shown below. Characteristics include minimum stable generation $Pmin$ (in % of $Pmax$), minimum off-state duration $T_{Off}$ (also used as minimum start-up time in Intraday models (c.f. *Technical Note T2*), maximum gradient, start-up costs.

Efficiency values at several operating points, and an average value were also provided by [14]. Moreover, for each fleet, the article provides a function which adjusts efficiency to the building year of the unit.

In the following Table, "oldest" corresponds to units built before 2000[5], "prevailing" before 2015 and "state of the art" after 2015.

| Parameters \ Type of unit | Minimal generation level (% of Pmax) | Positive load gradient (% of Pmax) | Negative load gradient (% of Pmax) | Starting cost (€/MW) | Off-state minimal duration (h)[6] | Efficiency (%) @Pmin/@Pmax |
|---|---|---|---|---|---|---|
| **OCGT - prevailing** | 50% | 8%/min | 8%/min | 30 | <1 | 27% / 36% |
| **OCGT- state of the art** | 40% | 12%/min | 12%/min | 21 | <1 | 32% / 42% |
| **Oil fired** | 50% | 8%/min | 8%/min | 30 | 1 | 26% / 35% |
| **CCGT - oldest** | 50% | 2%/min | 5%/min | 45 | 2 | 40 / 49% |
| **CCGT - prevailing** | 50% | 2%/min | 5%/min | 41 | 2 | 48% / 57% |
| **CCGT – state of the art** | 40% | 4%/min | 5%/min | 33 | 2 | 52% / 61% |
| **Hard Coal Power Plant – prevailing** | 40% | 2%/min | 5%/min | 65 | 6 | 36% / 42% |
| **Hard Coal Power Plant – state of the art** | 25% | 4%/min | 5%/min | 50 | 4 | 41% / 46% |
| **Lignite Power Plant – prevailing** | 50% | 2%/min | 5%/min | 25 | 6 | 34% / 38% |
| **Lignite Power Plant – state of the art** | 50% | 2%/min | 5%/min | 25 | 4 | 38% / 42% |
| **Nuclear Power Plant** | 40% | 5%/min<br>7% Rmax | 5%/min<br>7% Rmax | 24 | No off-state modelled | 7,4€/MWh |
| **Hydro turbine (lakes and PHS)** | 60%[7] | Not constrained | Not constrained | 0 | <1 | 90%[8] |
| **Biomass steam turbine** | 20% | 4%/min | 5%/min | 36 | 1 | 33% / 36% |

*Table 1 - Technological data (source: [3-16])*

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[5] Information on unit building dates before 2000 used by PRIMES was not provided. Therefore, the technical characteristics of old units correspond to units built in 1990, which may overestimate the performance of very old units still in operation in 2030.

[6] As on-state minimum duration is 1 hour or less for most units, only the off-state minimum duration is modelled in METIS.

[7] Even if hydro turbines have a very low technical Pmin, the efficiency of most hydro turbines decrease significantly if part-loaded below 60%. As the detailed modelling of the efficiency curves is outside of the scope of METIS, a minimum generation level of 60% is used.

[8] For PHS, pumps are assumed to run at fixed speed and cannot provide balancing services. Pumps have an efficiency of 90%, which leads to a total PHS efficiency of 81%.

## 3.2. HYDRO-POWER AND STORAGE

Run-of-river power plants, inter-seasonal storage dams/reservoirs and pumped hydro storage units are modelled separately.

Run-of-river power plants are represented as uncontrollable (non-dispatchable) generation assets, which means that their generation at all times is determined by a load factor time series.

Hydro-reservoir represents hydraulic dams which have a storage capacity, a natural inflows and extra constraints due to long-term storage management, and an optional pumping capacity.

Pure pumped hydro storage can also be modelled as storage assets, with an overall efficiency of 81% (see next paragraph).

In the paragraphs below, we describe the generic hydro storage model used in METIS, and how are handled long-term storages in typical simulations.

### 3.2.1. *GENERIC HYDRO STORAGE MODEL*

Storage assets are defined by:

- A storage capacity $S_{max}$ which represents the maximal energy volume that can be stored,
- A maximum input capacity $P_{max}^{IN}$ which represents the maximum amount of energy the asset can receive from the power system to store during one hour,
- A maximum output capacity $P_{max}^{OUT}$ which represents the maximum amount of energy the asset can inject into the power system during one hour, using its storage capacity,
- Efficiency rates $\rho^{IN}$ and $\rho^{OUT}$ which represent losses occurring when storing/injecting energy from/to the power system,
- A water inflow time series $waterInflow_t$, which represents the optional water inflow for hydro-reservoir,
- An availability time series $availability_t$, which varies in the [0,1] interval and represents if the production or consumption capacities are unavailable (e.g. in maintenance).

The storage dynamics is given by:

$$\forall\, t, \quad storageLevel_{t+1} = storageLevel_t + waterInflow_t + \rho^{IN} \cdot P_t^{IN} - \frac{1}{\rho^{OUT}} P_t^{OUT}$$

With input and output power being subjected to:

$$0 \leq P_t^{OUT} \leq P_{max}^{\mathrm{OUT}} \cdot availability_t$$
$$0 \leq P_t^{IN} \leq P_{max}^{IN} \cdot availability_t$$

Moreover, the total stored volume at a given date cannot exceed the storage capacity:

$$\forall t, \qquad 0 \leq storageLevel_t \leq S_{max}$$

The storage capacity is often characterized by its discharge duration, which can be computed using the following relation:

$$dischargeDuration = S_{max} \cdot \frac{\rho^{OUT}}{P_{max}^{OUT}}$$

| Member State | Pumping capacities (MW) | | Member State | Pumping capacities (MW) | |
|---|---|---|---|---|---|
| | Mixed | Pure | | Mixed | Pure |
| **Austria** | 5661 | 0 | **Italy** | 3598 | 3957 |
| **Belgium** | 0 | 1310 | **Latvia** | 0 | 0 |
| **Bulgaria** | 149 | 864 | **Lituania** | 0 | 760 |
| **Croatia** | 293 | 0 | **Luxembourg** | 0 | 1300 |
| **Cyprus** | 0 | 0 | **Malta** | 0 | 0 |
| **Czech Republic** | 0 | 1172 | **Netherlands** | 37 | 0 |
| **Denmark** | 0 | 111 | **Poland** | 376 | 1606 |
| **Estonia** | 0 | 46 | **Portugal** | 4004 | 0 |
| **Finland** | 0 | 0 | **Romania** | 269 | 92 |
| **France** | 5393 | 1793 | **Slovakia** | 0 | 916 |
| **Germany** | 1633 | 7448 | **Slovenia** | 0 | 180 |
| **Greece** | 1751 | 0 | **Spain** | 2786 | 3380 |
| **Hungary** | 0 | 0 | **Sweden** | 0 | 235 |
| **Ireland** | 146 | 292 | **United Kingdom** | 0 | 2682 |

*Table 2: Hydro pumping capacities in Europe (source: PRIMES)*

### 3.2.2. *INTER-SEASONAL STORAGE MANAGEMENT*

Storages assets have a limited energy volume that can be injected in the network in a given time range. In the case of hydraulic dams this limit is typically annual and given by the total water inflow over the year. It usually prevents storage plants from constantly generating power at full capacity. As a consequence, the water stored in dams has to be saved when it is not most needed to produce electricity during more demanding periods.

Such an economic-based management, applied to hydro dams at different time scales – from weekly to inter-seasonal, has to be enforced in METIS due to the rolling optimization horizons. It is done in the system module by setting a guide curve[9] which defines, on a weekly basis, the minimal allowed storage level. The storage level time series resulting from METIS Power System Module therefore takes into account both mid-term water management (by satisfying the weekly "guide" curve) and short-term management (through the hourly optimization).

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[9] This curve, based on historical data, actually takes into account non-economic – or non-modelled – considerations (such as tourism or agricultural needs), that affect water management.

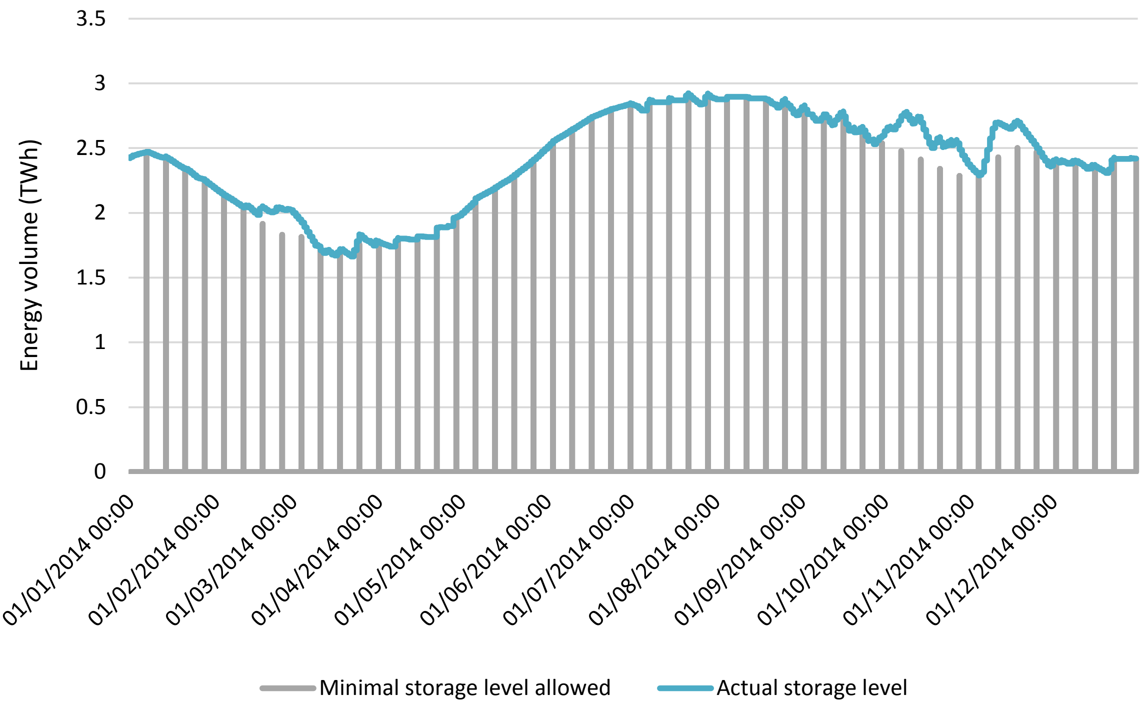

*Figure 4: Illustrative inter-seasonal storage management replicated in METIS (France in standard climate conditions)*

## 3.3. NON-DISPATCHABLE ASSETS

Non-dispatchable generation (Wind, Solar, run-off-river, etc.) are modelled as a single asset by country and by type of technology. Every asset is defined by a variable cost that depends on the technology, and an availability time series. Depending on the market configuration, non-dispatchable assets may be curtailable and may be able to provide upwards and downwards reserves. Biomass is modelled as a wood utility and is either must-run or flexible depending on the market context. More information is available in *Technical Note T2*.

| | **PV** | **Wind onshore** | **Wind offshore** | **Run-of-the-river** | **Waste** | **Derived gasses** | **Geothermal** |
|---|---|---|---|---|---|---|---|
| **Variable cost (€/MWh)** | 0 | 0.5 | 0.5 | 0 | 3.7 | 3.5 | 0.32 |
| **Availability** | Hourly time series | | | Monthly time series | Fixed | Fixed | Fixed |

*Table 3 – Non-dispatchable assets' parameters*

*Source: PRIMES*

CHP units are not modelled per se[10], but are included in the thermal (coal, gas and biomass) capacities.

Ten years of weather data have been used to build a database of hourly generation for PV, onshore and offshore wind. The mean load factors by country for PV, onshore and offshore wind are based on PRIMES EUCO27 data.

EMHIRES[11] datasets of hourly wind and solar power capacity factor have also been integrated in the METIS database.

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[10] METIS Heat Module is planned for 2017-2018 and will include CHP units.

| Zone | year 2001<br>SC8 | year 2002<br>SC9 | year 2003<br>SC10 | year 2004<br>SC1 | year 2005<br>SC2 | year 2006<br>SC3 | year 2007<br>SC4 | year 2008<br>SC5 | year 2009<br>SC6 | year 2010<br>SC7 |
|---|---|---|---|---|---|---|---|---|---|---|
| **AT** | 2 364h | 2 271h | 2 121h | 2 251h | 2 225h | 2 154h | 2 354h | 2 273h | 2 226h | 2 254h |
| **BA** | 2 409h | 2 266h | 2 142h | 2 230h | 2 042h | 1 987h | 2 138h | 2 217h | 2 151h | 2 325h |
| **BE** | 2 456h | 2 513h | 2 157h | 2 401h | 2 268h | 2 483h | 2 558h | 2 520h | 2 364h | 2 165h |
| **BG** | 2 827h | 2 607h | 2 459h | 2 657h | 2 647h | 2 468h | 2 610h | 2 541h | 2 361h | 2 593h |
| **CH** | 1 369h | 1 277h | 1 207h | 1 284h | 1 165h | 1 250h | 1 294h | 1 303h | 1 269h | 1 260h |
| **CZ** | 2 013h | 2 118h | 1 869h | 2 161h | 2 011h | 1 951h | 2 321h | 2 116h | 1 957h | 1 945h |
| **DE** | 1 612h | 1 693h | 1 455h | 1 679h | 1 550h | 1 622h | 1 832h | 1 731h | 1 580h | 1 471h |
| **DK** | 2 464h | 2 642h | 2 399h | 2 697h | 2 646h | 2 494h | 2 876h | 2 791h | 2 586h | 2 487h |
| **EE** | 2 171h | 2 130h | 2 225h | 2 139h | 2 265h | 2 211h | 2 350h | 2 567h | 2 015h | 2 046h |
| **ES** | 2 722h | 2 629h | 2 540h | 2 417h | 2 480h | 2 470h | 2 452h | 2 521h | 2 604h | 2 704h |
| **FI** | 2 638h | 2 408h | 2 690h | 2 519h | 2 773h | 2 603h | 2 754h | 2 764h | 2 447h | 2 402h |
| **FR** | 2 626h | 2 652h | 2 350h | 2 473h | 2 411h | 2 496h | 2 602h | 2 541h | 2 444h | 2 427h |
| **GR** | 2 970h | 2 433h | 2 882h | 2 778h | 2 757h | 2 784h | 2 720h | 2 802h | 2 730h | 2 728h |
| **HR** | 1 919h | 1 778h | 1 779h | 1 765h | 1 703h | 1 653h | 1 716h | 1 776h | 1 789h | 1 795h |
| **HU** | 2 031h | 1 960h | 1 808h | 1 873h | 1 859h | 1 665h | 1 882h | 1 903h | 1 781h | 1 874h |
| **IE** | 2 611h | 3 022h | 2 862h | 2 973h | 2 936h | 2 908h | 2 822h | 3 095h | 2 928h | 2 340h |
| **IT** | 2 241h | 2 035h | 2 097h | 2 145h | 2 045h | 1 946h | 2 120h | 2 105h | 2 203h | 2 235h |
| **LT** | 1 842h | 2 002h | 1 916h | 1 875h | 1 759h | 1 758h | 2 015h | 2 093h | 1 746h | 1 783h |
| **LU** | 1 815h | 1 832h | 1 581h | 1 724h | 1 571h | 1 743h | 1 853h | 1 750h | 1 654h | 1 558h |
| **LV** | 2 379h | 2 510h | 2 473h | 2 424h | 2 392h | 2 383h | 2 643h | 2 800h | 2 328h | 2 300h |
| **ME** | 2 436h | 2 216h | 2 281h | 2 353h | 2 128h | 2 025h | 2 185h | 2 227h | 2 209h | 2 396h |
| **MK** | 1 134h | 1 013h | 1 076h | 1 165h | 1 064h | 938h | 1 044h | 1 073h | 1 035h | 1 163h |
| **NL** | 2 514h | 2 580h | 2 251h | 2 595h | 2 505h | 2 623h | 2 786h | 2 810h | 2 558h | 2 303h |
| **NO** | 2 488h | 2 446h | 2 533h | 2 667h | 2 843h | 2 684h | 2 839h | 2 681h | 2 665h | 2 321h |
| **PL** | 2 100h | 2 252h | 2 045h | 2 213h | 2 038h | 1 953h | 2 359h | 2 261h | 1 986h | 2 093h |
| **PT** | 2 851h | 2 755h | 2 639h | 2 429h | 2 571h | 2 532h | 2 436h | 2 592h | 2 645h | 2 848h |
| **RO** | 2 684h | 2 646h | 2 471h | 2 597h | 2 502h | 2 413h | 2 634h | 2 538h | 2 305h | 2 523h |
| **RS** | 1 558h | 1 522h | 1 346h | 1 501h | 1 389h | 1 262h | 1 393h | 1 464h | 1 349h | 1 550h |
| **SE** | 2 678h | 2 606h | 2 708h | 2 754h | 2 788h | 2 664h | 2 918h | 2 832h | 2 608h | 2 560h |
| **SI** | 1 612h | 1 424h | 1 414h | 1 371h | 1 400h | 1 402h | 1 469h | 1 480h | 1 481h | 1 498h |
| **SK** | 1 439h | 1 434h | 1 315h | 1 390h | 1 351h | 1 212h | 1 430h | 1 428h | 1 280h | 1 345h |
| **UK** | 2 564h | 2 694h | 2 568h | 2 766h | 2 867h | 2 730h | 2 794h | 2 965h | 2 736h | 2 319h |

*Table 4 - Wind onshore generation yearly full load hours (for the different years of weather data)*

| Zone | year 2001<br>SC8 | year 2002<br>SC9 | year 2003<br>SC10 | year 2004<br>SC1 | year 2005<br>SC2 | year 2006<br>SC3 | year 2007<br>SC4 | year 2008<br>SC5 | year 2009<br>SC6 | year 2010<br>SC7 |
|---|---|---|---|---|---|---|---|---|---|---|
| **BE** | 3 501h | 3 505h | 3 114h | 3 342h | 3 305h | 3 535h | 3 585h | 3 630h | 3 359h | 3 158h |
| **DE** | 3 187h | 3 362h | 3 028h | 3 407h | 3 412h | 3 265h | 3 640h | 3 643h | 3 351h | 3 160h |
| **DK** | 4 129h | 4 355h | 4 047h | 4 389h | 4 282h | 4 145h | 4 480h | 4 379h | 4 331h | 4 190h |
| **EE** | 2 131h | 2 031h | 2 157h | 2 078h | 2 182h | 2 162h | 2 309h | 2 525h | 1 946h | 2 001h |
| **ES** | 2 998h | 2 946h | 2 604h | 2 641h | 2 902h | 2 759h | 2 655h | 2 509h | 2 753h | 3 052h |
| **FI** | 2 990h | 2 583h | 2 952h | 2 834h | 3 018h | 2 866h | 3 022h | 2 988h | 2 711h | 2 626h |
| **FR** | 3 255h | 3 357h | 3 011h | 3 051h | 3 016h | 3 151h | 3 225h | 3 228h | 3 025h | 3 002h |
| **IE** | 3 037h | 3 466h | 3 320h | 3 423h | 3 462h | 3 374h | 3 262h | 3 546h | 3 435h | 2 787h |
| **IT** | 3 466h | 3 067h | 3 117h | 3 182h | 3 066h | 2 827h | 3 099h | 3 176h | 3 215h | 3 473h |
| **LV** | 3 001h | 3 306h | 3 071h | 3 266h | 3 076h | 3 048h | 3 332h | 3 461h | 3 064h | 3 037h |
| **NL** | 3 614h | 3 578h | 3 256h | 3 601h | 3 588h | 3 699h | 3 852h | 3 920h | 3 649h | 3 355h |
| **PL** | 2 989h | 3 201h | 2 970h | 3 237h | 2 942h | 2 843h | 3 327h | 3 272h | 2 936h | 3 013h |
| **PT** | 2 859h | 2 936h | 2 591h | 2 480h | 2 776h | 2 690h | 2 528h | 2 447h | 2 633h | 2 977h |
| **SE** | 2 813h | 3 036h | 2 848h | 3 068h | 2 939h | 2 811h | 3 195h | 3 148h | 2 952h | 2 890h |
| **UK** | 2 968h | 3 064h | 2 931h | 3 038h | 3 112h | 3 103h | 3 116h | 3 322h | 3 020h | 2 722h |

*Table 5 - Wind offshore generation yearly full load hours (for the different years of weather data)*

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[11] EMHIRES datasets are an initiative from the Joint Research Centre of the European Commission. More information is available in [25].

| Zone | year 2001 | year 2002 | year 2003 | year 2004 | year 2005 | year 2006 | year 2007 | year 2008 | year 2009 | year 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| | SC8 | SC9 | SC10 | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 | SC7 |
| **AT** | 1 102h | 1 100h | 1 231h | 1 128h | 1 150h | 1 139h | 1 144h | 1 105h | 1 114h | 1 069h |
| **BE** | 1 022h | 1 038h | 1 157h | 1 073h | 1 080h | 1 062h | 1 033h | 1 023h | 1 072h | 1 065h |
| **BG** | 1 327h | 1 302h | 1 353h | 1 324h | 1 271h | 1 305h | 1 343h | 1 335h | 1 302h | 1 255h |
| **CH** | 800h | 785h | 898h | 850h | 837h | 844h | 839h | 807h | 839h | 782h |
| **CZ** | 895h | 934h | 1 056h | 971h | 994h | 987h | 967h | 950h | 955h | 923h |
| **DE** | 919h | 931h | 1 058h | 967h | 987h | 977h | 938h | 951h | 969h | 947h |
| **DK** | 894h | 916h | 947h | 915h | 922h | 918h | 893h | 930h | 933h | 905h |
| **EE** | 821h | 913h | 824h | 816h | 866h | 876h | 840h | 797h | 825h | 818h |
| **ES** | 1 965h | 1 936h | 1 936h | 1 973h | 2 018h | 1 955h | 1 955h | 1 911h | 1 966h | 1 900h |
| **FI** | 733h | 808h | 745h | 729h | 768h | 785h | 734h | 714h | 757h | 728h |
| **FR** | 1 566h | 1 554h | 1 680h | 1 621h | 1 640h | 1 605h | 1 582h | 1 551h | 1 624h | 1 582h |
| **GR** | 1 635h | 1 586h | 1 603h | 1 616h | 1 594h | 1 586h | 1 623h | 1 610h | 1 563h | 1 557h |
| **HR** | 1 447h | 1 409h | 1 523h | 1 398h | 1 435h | 1 438h | 1 453h | 1 429h | 1 431h | 1 363h |
| **HU** | 880h | 901h | 974h | 893h | 909h | 902h | 929h | 900h | 914h | 856h |
| **IE** | 876h | 843h | 893h | 873h | 858h | 865h | 860h | 831h | 835h | 893h |
| **IT** | 1 428h | 1 356h | 1 458h | 1 402h | 1 410h | 1 427h | 1 435h | 1 385h | 1 398h | 1 336h |
| **LT** | 842h | 895h | 881h | 855h | 890h | 888h | 855h | 833h | 862h | 846h |
| **LU** | 862h | 883h | 986h | 916h | 916h | 893h | 873h | 863h | 902h | 896h |
| **LV** | 840h | 898h | 872h | 851h | 892h | 896h | 852h | 829h | 846h | 838h |
| **MK** | 1 298h | 1 266h | 1 307h | 1 285h | 1 283h | 1 288h | 1 300h | 1 297h | 1 244h | 1 209h |
| **NL** | 871h | 872h | 962h | 898h | 912h | 901h | 870h | 881h | 903h | 895h |
| **PL** | 803h | 851h | 921h | 868h | 897h | 885h | 858h | 852h | 867h | 834h |
| **PT** | 1 820h | 1 792h | 1 807h | 1 876h | 1 900h | 1 837h | 1 881h | 1 829h | 1 852h | 1 800h |
| **RO** | 1 333h | 1 337h | 1 402h | 1 344h | 1 302h | 1 332h | 1 385h | 1 361h | 1 366h | 1 283h |
| **RS** | 1 076h | 1 088h | 1 149h | 1 081h | 1 090h | 1 092h | 1 116h | 1 109h | 1 093h | 1 028h |
| **SE** | 837h | 883h | 873h | 857h | 873h | 863h | 840h | 854h | 852h | 835h |
| **SI** | 1 089h | 1 064h | 1 177h | 1 056h | 1 089h | 1 083h | 1 108h | 1 061h | 1 074h | 1 018h |
| **SK** | 869h | 903h | 981h | 908h | 919h | 923h | 928h | 902h | 916h | 864h |
| **UK** | 808h | 796h | 873h | 801h | 816h | 827h | 801h | 798h | 803h | 811h |

*Table 6 - PV generation yearly full load hours (for the different years of weather data)*

More details on the methodology are given in the appendix in section 6.

## 3.4. RESERVE SUPPLY MODELS

### 3.4.1. *RESERVE PROCUREMENT METHODOLOGY*

It is possible to take into account reserve allocation in METIS models. In this case new variables and constraints are added to the model presented in the previous sections. The reserve allocation and power dispatch are then obtained simultaneously by solving an optimisation problem minimizing costs to ensure a reserve and power supply/demand equilibrium.

Note that in itself, the reserve allocation does not incur any direct costs as there is usually no variable costs for allocating reserve capacity (since reserve activation is not simulated). However, the additional constraints on assets to provide reserve might force them to run at a less efficient generation level, incur additional start-up costs, or trigger opportunity costs.

### 3.4.2. *RESERVE TYPES*

Unpredicted events, such as unplanned outages of power plants or forecast errors of load or renewable energy generation, can result in imbalances of the power grid on different time horizons. Different types of reserve, characterized by their activation delay, are therefore procured in advance and then activated to restore balance on the power grid.

The Frequency Containment Reserve (FCR) aims at securing the grid’s security in case of instantaneous power deviation (power plant outages, sharp load deviation, line section, etc.). It is dimensioned by the maximum expected instantaneous power deviation and must be available within 30 seconds (see section 7), meaning that only synchronised units (i.e. units that are currently running) can participate in FCR.

The Automatic Frequency Restoration Reserve (aFRR) and the Manual Frequency Restauration Reserve (mFRR) have different activation times - 5 and 15 minutes will be considered as standard for the aFRR and mFRR respectively. They can be called upon to compensate load fluctuations or forecast errors. Only synchronised units can participate in aFRR procurement. However, due to their low activation time, hydro assets, OCGTs and Oil fleets can participate in mFRR procurement from standstill.

In METIS models, FCR and aFRR are aggregated into "synchronised reserve". One may refer to the appendix – Reserve Sizing Methodology for more information and justification.

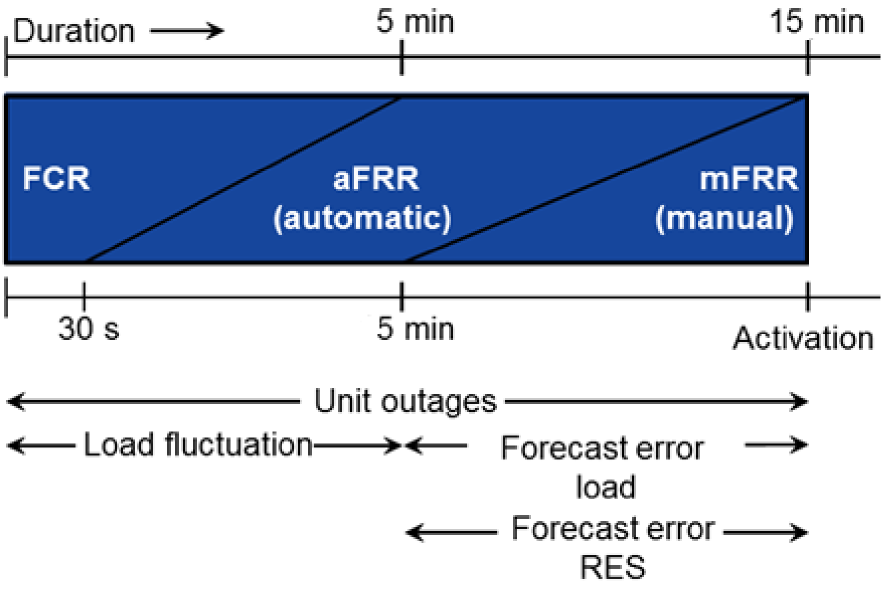

*Figure 5: Reserve types and usages*

For the standard METIS simulations, rules for reserve dimensioning have been standardised and provide as output an hourly requirement for reserve, based on demand and RES generation forecasts[12]. More details are given on section 7.

### 3.4.3. NOTATIONS

The indexes i, j and t respectively refer to generation assets, reserve types and time steps.
The notation $j' \leq j$ is used to indicate that reserve $j'$ has a shorter activation delay than reserve $j$.

- $\boldsymbol{reserve^{UP}_{i,j,t}}$ [MW]: participation of generation cluster $i$ in the upward reserve $j$, at time step $t$
- $\boldsymbol{reserve^{DOWN}_{i,j,t}}$[MW]: participation of generation cluster $i$ in the downward reserve $j$, at time step $t$
- $\boldsymbol{reserveRequirement^{UP}_{j,t}}$ [MW]: upward reserve $j$ requirement at time step $t$
- $\boldsymbol{reserveRequirement^{DOWN}_{j,t}}$ [MW]: downward reserve $j$ requirement at time step $t$
- $\boldsymbol{\Delta T_j}$: activation delay characterizing reserve $j$
- $\boldsymbol{gradient^{UP}_{i}}$ [MW/h]: maximum generation increase rate per hour (in % of running capacity)

---

[12] Forecast generation is described in detail in *METIS Technical Note T2.*

- $\boldsymbol{gradient_i^{DOWN}}$ [MW/h]: maximum generation decrease rate per hour (in % of running capacity)
- $\boldsymbol{Rmax_{i,j}^{UP}}$ [%]: maximum acceptable share of running capacity to be allocated to upward reserves[13]. The value is zero if the asset is banned from upward reserve procurement.
- $\boldsymbol{Rmax_{i,j}^{DOWN}}$ [%]: maximum acceptable share of running capacity to be allocated to downward reserves[14]. The value is zero if the asset is banned from downward reserve procurement.

### 3.4.4. *CONSTRAINTS*

- **Supply/demand constraint at all time for reserve**

$$\forall j,t, \qquad \sum_i reserve_{i,j,t}^{DOWN} = reserveRequirement_{j,t}^{DOWN}$$

$$\forall j,t, \qquad \sum_i reserve_{i,j,t}^{UP} = reserveRequirement_{j,t}^{UP}$$

- **Maximal participation in the primary and secondary reserves**

A given cluster can only allocate a part of its running capacity to reserves, since starting up more capacity would take longer than the available delay. The following constraints apply to all clusters for primary and secondary reserves:

$$P_{i,t} + \sum_j reserve_{i,j,t}^{UP} \leq \bar{P}_{i,t}$$ [15]

$$Pmin_i \cdot \bar{P}_{i,t} \leq P_{i,t} - \sum_j reserve_{i,j,t}^{DOWN}$$ [16]

$$\forall\, i,j,t, \qquad \sum_{j' \leq j} reserve_{i,j',t}^{UP} \leq \bar{P}_{i,t} \cdot\ Rmax_{i,j}^{UP}$$

$$\forall\, i,j,t, \qquad \sum_{j' \leq j} reserve_{i,j',t}^{DOWN} \leq \bar{P}_{i,t} \cdot\ Rmax_{i,j}^{DOWN}$$

- **Maximal participation in the tertiary reserve**

The tertiary reserve's activation time may be long enough for peaking or hydro units to start up and generate power within this delay[17]. The following equations would then apply **to such clusters only**:

$$P_{i,t} + \sum_j reserve_{i,j,t}^{UP} \leq Pmax_i \cdot Avail_{i,t}$$

$$0 \leq P_{i,t} - \sum_j reserve_{i,j,t}^{DOWN}$$

$$\forall\, i,j,t, \qquad \sum_{j' \leq j} reserve_{i,j',t}^{UP} \leq Rmax_{i,j}^{UP} \cdot Pmax_i \cdot Avail_{i,t}$$

---

[13] For most thermal assets and for aFRR/mFRR, $Rmax_{i,j}^{UP} = gradient_i^{UP} \cdot \Delta T_j$

[14] For most thermal assets and for aFRR/mFRR, $Rmax_{i,j}^{DOWN} = gradient_i^{DOWN} \cdot \Delta T_j$

[15] Note that this is a generalization of the constraint $P_{i,t} \leq \bar{P}_{i,t}$ presented in the cluster model, which is implied by the constraint presented here

[16] Note that this is a generalization of the constraint $minLoad \cdot \bar{P}_{i,t} \leq P_{i,t}$ presented in the cluster model, which is implied by the constraint presented here

[17] A penalty is added to assets which supply tertiary reserve from standstill, to compensate start-up costs which may occur if the asset is called for balancing services.

$$\forall\, i,j,t, \qquad \sum_{j'\leq j} reserve_{i,j',t}^{DOWN} \leq Rmax_{i,j}^{DOWN} \cdot Pmax_i \cdot Avail_{i,t}$$

Other clusters (that is, clusters of which units which cannot start up fast enough) are subject to the same maximal participation constraints for tertiary reserve as for the primary and secondary reserves.

- **Specific constraints for hydro storage plants**

Storage clusters are subject to available energy constraints, in addition to generation capacity constraints. The storage level of each storage asset is driven by the following dynamics:

$$\forall i,t, \qquad storageLevel_{i,t} = storageLevel_{i,t-1} + waterInflow_{i,t} + \rho^{IN} \cdot\ P_{i,t}^{IN} - \frac{1}{\rho^{OUT}} P_{i,t}^{OUT}$$

Where $\rho^{IN}$ (or $\rho^{OUT}$) stands for input (or output) efficiency

Note that

- $P_{i,t}^{IN} = 0$ for hydro dams without mixed pumping, which cannot consume electricity to fill their storage tanks,
- $waterInflow_{i,t} = 0$ for pure pumped hydro storage assets, which can only fill their reservoirs by activating their pumps.

Such dynamics imply that a storage plant cannot produce more energy than what is stored (since the storage level has to be positive at all times):

$$\frac{1}{\rho^{OUT}} \cdot {P_{i,t}}^{OUT} \leq storageLevel_{i,t-1}$$

Storages can participate in reserve procurement with their production component[18] as long as the storage level is sufficient to generate reserve for $\Delta T$:

$$\forall i,t, \qquad \Delta T\ *\ \frac{1}{\rho^{OUT}} \sum_j reserve_{i,j,t}^{UP}\ \leq storageLevel_{i,t}$$

$$\forall i,t, \qquad \Delta T\ *\ \frac{1}{\rho^{OUT}} \sum_j reserve_{i,j,t}^{DOWN} \leq \left(Smax_i - storageLevel_{i,t}\right)$$

In practice, the value of $\Delta T$ depends on TSOs rules for storages' reserve participation and can vary from one TSO to the other. In METIS, we assume a value of 1h, thus allowing the storage to participate in reserve as long as its storage level is enough to cover one hour of reserve procurement.

- **Reserve procurement from variable RES**

Depending on the market configuration, variable renewable energy may participate in reserve procurement. As variable RES and in particular wind energy have very high load gradients and low minimum stable generation, the only constraints modelled are:

$$P_{i,t} + \sum_j reserve_{i,j,t}^{UP}\ \leq Pmax_i \cdot Avail_{i,t}$$

$$0 \leq P_{i,t} - \sum_j reserve_{i,j,t}^{DOWN}$$

---

[18] It is assumed that pumped storages can only participate to reserve with their production component as their consumption component (pump) usually runs at a fixed power level and thus cannot provide reserve.

# 4. MAIN OUTPUTS AND VISUALIZATION IN THE INTERFACE

## 4.1. MAIN KEY PERFORMANCE INDICATORS

In addition to raw inputs and optimization results such as generation and running capacities time series for each asset or flow of interconnection, the Crystal Super Grid platform provides functionalities to display model parameters and aggregated results of different assets in an ergonomic view using tables, charts or geographical display functions. The main way to display this aggregated data are the Key Performance Indicators whose full list and equations are detailed in the *METIS KPI documentation*.

The following KPIs are among the most useful (non-exhaustive list):

- Based on input data: Demand, reserve sizing, installed capacities, import capacity, import capacity over net demand,
- Based on optimisation results: Production and production costs by asset or aggregated at zone level, annual flows and congestion rent for interconnections, production curtailment and loss of load in each zone, marginal costs by zone and price divergence between zones, consumer, producer surplus and total welfare by zone,

KPIs can be displayed in tables or directly on the map view as shown in the following figure:

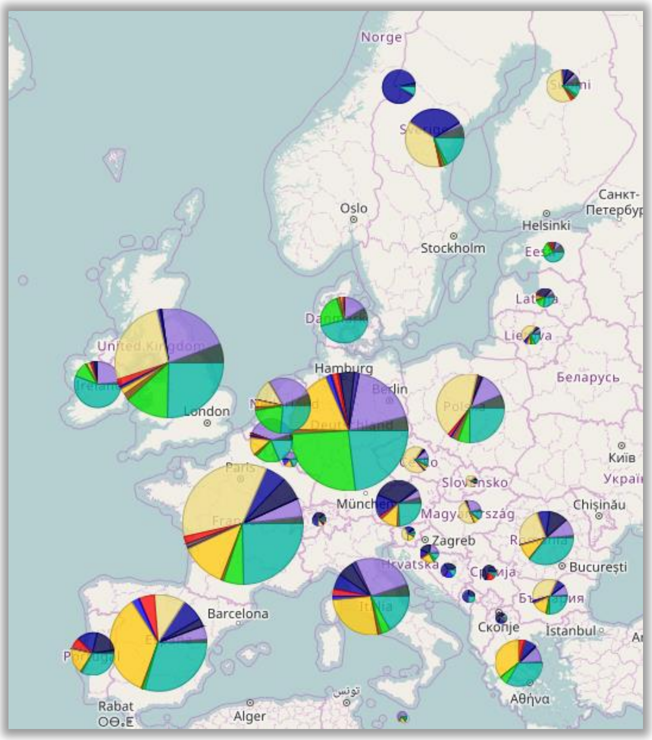

*Figure 6: Production by asset and by country, displayed directly on the European map in Artelys Crystal Super Grid*

## 4.2. MAIN OTHER DISPLAY FEATURES

In addition to aggregated yearly figures (KPIs), it is possible to display time series in a synthetized view to better understand the functioning of the system. In particular, marginal costs and cumulative generation curve are of the most useful features.

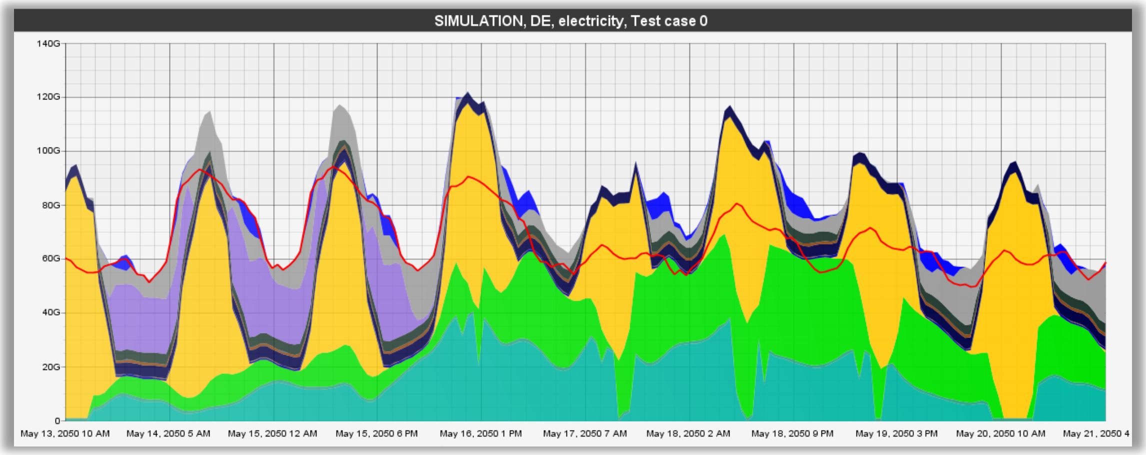

*Figure 7: Cumulative generation curve for several days in Germany in 2050, simulated using METIS models and displayed in Artelys Crystal Super Grid*

*Productions - wind power (in turquoise and green), solar (in yellow), CCGTs (in purple) - are displayed on top of each other, while demand is displayed with a red curve. Here, the production exceeds demand during the whole period, meaning that the country exports electricity.*

It is also possible to go more in depth of the functioning of a specific asset in the production view, which is especially useful for cluster and reserve models, as it allows to display in one chart the running capacity, generation level, minimal power and the 4 reserve allocations at each time step.

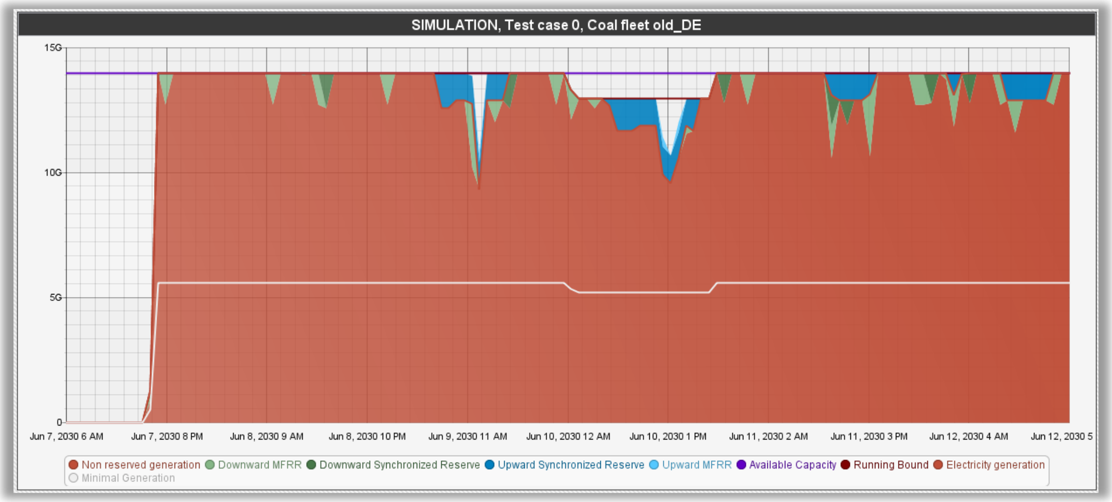

*Figure 8: Zoom on a coal fleet using METIS cluster and reserve model, in the production view of Artelys Crystal Super Grid*

# 5. SCENARIOS USED IN METIS POWER SYSTEM MODELS

## 5.1. SCENARIOS AVAILABLE IN METIS

In the version delivered to the European Commission, a METIS version of the PRIMES scenarios has been implemented[19]:

- European Commission **REF16 scenario** (reference scenario published in 2016) for year 2020 and 2030
- European Commission **EUCO30 scenario** for year 2030 and 2050
- European Commission **EUCO27 scenario** for year 2030, used in particular for METIS S12 study on market design,

In addition to EU Member States, METIS scenarios include Switzerland, Bosnia, Serbia, Macedonia, Montenegro and Norway to model the impact of power imports and exports on the MS.

METIS versions of PRIMES scenarios include refinements on the time resolution (hourly) and unit representation (explicit modelling of reserve supply at cluster and MS level). Data provided by the PRIMES scenarios include: demand at MS-level, primary energy costs, $CO_2$ costs, installed capacities at MS-level, interconnection capacities. These scenarios are complemented with METIS data such as consumption and RES generation time series, availability time series for thermal fleets, unit technical data and constraints, etc.

For that purpose, a specific document has been written on the integration of PRIMES data into METIS for the construction of EUCO27 (*METIS Technical Note T1*). A similar approach has been used for Ref16 and EUCO30 scenarios. Additionally, some details on Demand and RES data generation are also available in the appendices (section 6).

## 5.2. STANDARD CONFIGURATION OF METIS

The scenarios delivered to the European Commission share by default the same modelling options that are described briefly below:

- EU28 + 6 ENTSO-E non-EU countries are represented in the models, at a national granularity,
- Simulations are performed over a year, at an hourly time step, with an operational horizon of seven days and a tactical horizon of fifteen days,
- Models include reserve, with separated products for downwards and upwards reserve, a hourly reserve sizing[20] done with a probabilistic approach and assuming a regional cooperation of countries,
- Reserve procurement is optimised jointly to the power dispatch,
- Thermal fleets are modelled as clusters with reserve,
- Biomass fleet is not considered as must-run, renewable fleets (Run-off-river, Biomass, Wind, Solar, Waste) can participate in reserve procurement, and there is no penalty for RES curtailment.

While these options correspond to the standard for these scenarios, the user can chose to use other modelling options depending on the needs of the study.

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[19] More information at https://ec.europa.eu/energy/en/data-analysis/energy-modelling

[20] More details in section 7 and *METIS Technical Note T3.*

# 6. APPENDIX – DEMAND AND RES DATA GENERATION

## 6.1. OVERALL APPROACH FOR CLIMATIC SCENARIOS

To assess the benefits of regional cooperation, it is crucial to use consistent weather data through Europe. For this reason, correlated RES generation data were integrated in METIS, as represented in Figure 9.

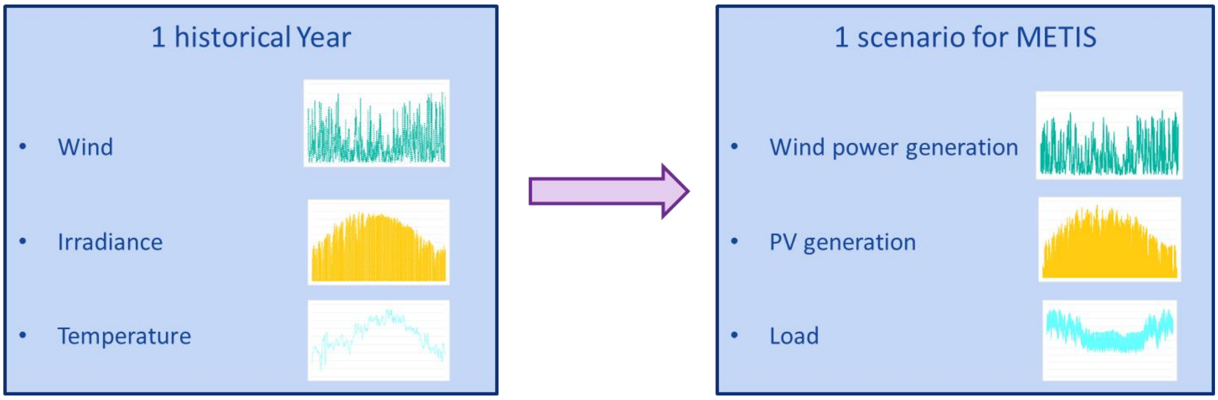


*Figure 9: Correlated RES generation in METIS: for each year of weather data, one corresponding scenario is built.*

The following paragraphs describe the methodology which was used to build the correlated demand time series and RES generation.

RES generation and demand forecasts have also been generated for the Power Market Module and for reserve sizing. The methodology for its computation is described in detail in *METIS Technical Note T2.*

## 6.2. DEMAND PROFILES

### 6.2.1. *TEMPERATURE SENSITIVITY AND DEMAND MODELLING*

The objective is to generate fifty hourly scenarios of demand for each country by means of a statistical model fitted to the following data sources:

- **historical daily temperature** data from years 1965 to 2014 for all countries from the European Climate Assessment & Dataset project (ECA), see [22].
- **hourly demand data** projections for 2030 provided by ENTSO-E TYNDP 2014[21] visions 1 and 3, see [17].

In this regard, each demand scenario is modelled as the sum of a thermo-sensitive component and the non-thermo-sensitive one. The thermo-sensitive component is computed by using a piecewise linear model. This model is set up with one threshold and two slopes[22] and calibrated by getting recourse to a *Multivariate Adaptive Regression Splines* method[23] that involves the computation of temperature gradients (MW of demand increase per °C increase) for each country.

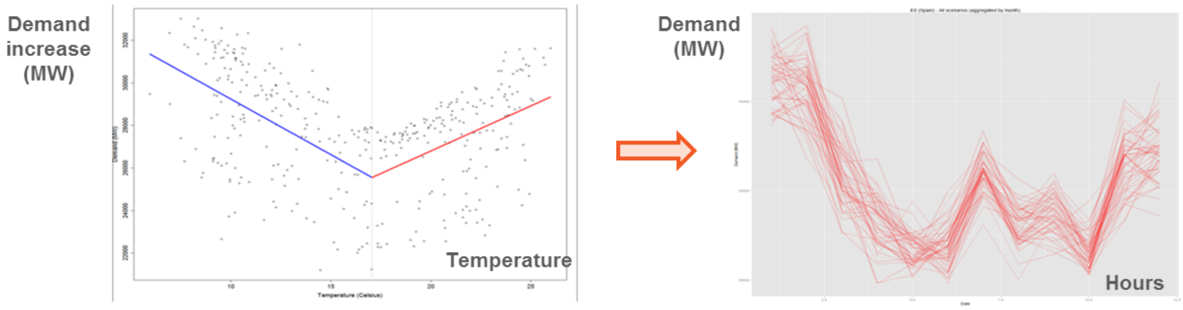
As depicted in Figure 10 for Spain, the temperature scenarios of each country drive its thermo-sensitive demand scenarios by using the country temperature gradients. Then, thermo-sensitive and non-thermo-sensitive demand scenarios are added so as to complete the generation of the country demand scenarios.

---

[21] Data is given as hourly time series for one year and average seasonal temperatures.

[22] The use of two slopes - one slope associated to low temperatures and one slope associated to high temperatures allows for applying the same approach for each country, with the same number of parameters, although three slopes could have been used for countries with both heating and cooling gradients.

[23] See [23] for the method and [24] for its R implementation.



Sensitivity to temperature in Spain

50 load scenarios in Spain

*Figure 10: Two gradients and one threshold accounting for heating and cooling effects on Spain demand*

## 6.3. RES GENERATION PROFILES

### 6.3.1. *GENERATION OF SOLAR AND ONSHORE WIND POWER PROFILES*

Generation of ten historical yearly profiles for wind power and solar power has been performed by a model developed by IAEW. The model uses historical meteorological data, units' power curves and historical generation data as input parameters to determine RES generation profiles and calibrate the results for each region in the models scope.

The methodology is depicted in Figure 11.

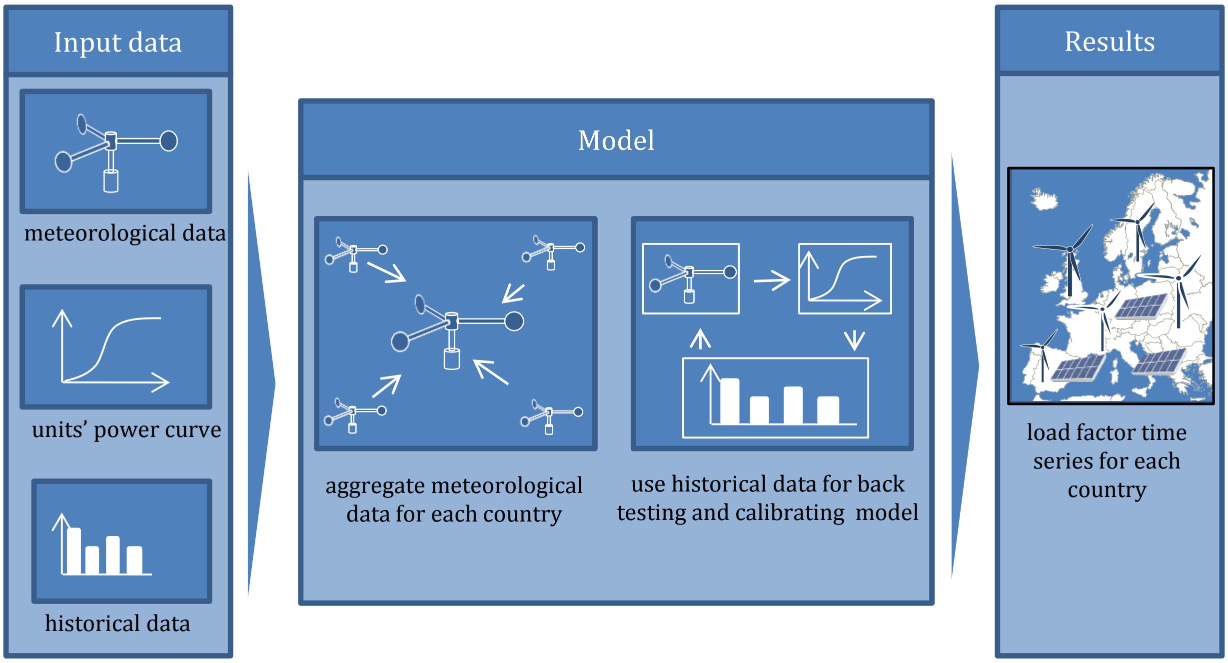


*Figure 11: Methodology*

**Input Data**

*Meteorological Data*

The delivered time series of renewable feed-ins are based on fundamental wind, solar and temperature time series for 10 years (2001 to 2010) on a detailed regional level derived from the ERA-Interim data provided by Meteo Group Germany GmbH. From ERA-Interim's model, values for wind speed (m/s), global irradiation (W/m2) and temperature (°C) are derived for every third hour and interpolated to hourly values by Meteo Group. The regional resolution of the data is one hourly input series (wind, solar, temperature) on a 0.75° (longitude) times 0.75° (latitude) grid model, which ensures an adequate modeling accuracy. The regional resolution is shown in Figure 12, in which each blue dot represents one data point.

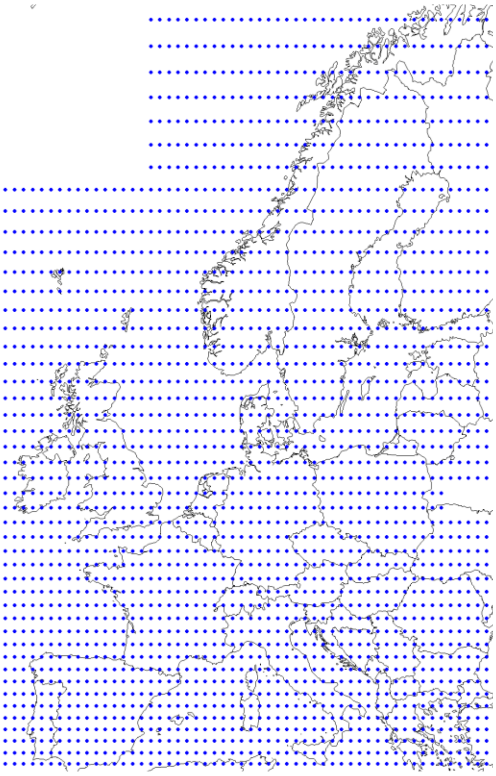


Figure 12: Regional resolution of meteorological data

*Historical Data*

To generate realistic time series, a calibration of the models is inevitable. Therefore information regarding the yearly full load hours for wind and PV generation in each country is necessary. To derive the yearly number of full load hours the installed capacities of wind and PV generation as well as the yearly energy production have been investigated for each country.

In case of unavailable data the full load hours were derived based on the data of a neighboring country. As the availability for data regarding installed wind generation capacities and generated energy is satisfying in almost every country it is rather low for information regarding PV power. Only for a few countries reasonable full load hours could be derived from historical published data. For the other country data from the Photovoltaic Geographical Information System was used instead.

### Model

In first step the high-resolution meteorological data are aggregated for each country and NUTS2 region. The aggregation is thereby based on the regional distribution of wind and PV capacities. The required distribution of wind and PV generation capacities is extracted from different databases and is aggregated at high voltage network nodes. In countries with no available information a uniform distribution is assumed.

Each high voltage network node gets the nearest meteorological data point assigned to and the data is weighted with the installed capacity at the network node. Thereby the wind-speed is weighted by the installed wind generation capacity whereas global irradiation and temperature are weighted with the installed PV generation capacity. The weighted time series for all nodes in each region are aggregated and divided by the overall installed wind respectively PV capacities. Subsequently, it is necessary to calibrate the generation models for each country by scaling the meteorological data accordingly. The process of calibration is display in Figure 13.

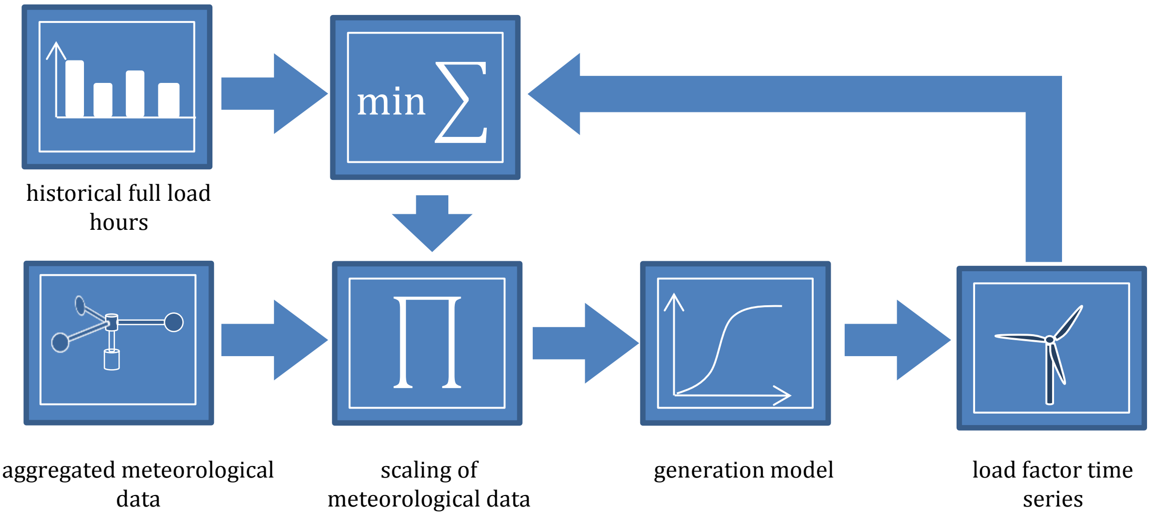


*Figure 13: Model calibration*

The meteorological data is fed into generation models for PV and wind generation. The resulting load factor time series are compared with the historical full load hours for the specific country and the deviation between load factor time series and the historic full load hours in each year *i* is to be minimized by scaling the meteorological data accordingly. In this minimization the yearly deviation between time series full load hours (*FLH*) and historical data is weighted with the installed capacity (*IC*) in the specific year according to formula 1.

$$\min \sum_{i=1}^{10} (FLH_{i,time\ series} - FLH_{i,historical\ data}) \cdot IC_i \qquad (1)$$

The scaling factors are chosen independently for wind speed and global irradiation and are individual for each country.

### Calibration to PRIMES load factors

In order to generate RES generation profiles for the METIS EuCo27 2030 scenario, the installed capacities and full load hours for each country from PRIMES were used. From these data each NUTS2 region was assigned a share of the country's installed generation capacities for PV, onshore wind and offshore wind (if applicable) according to the region's average global irradiation and wind speed in comparison to the countries average global irradiation and wind speed, respectively. The model was then calibrated by minimizing the deviation between time series full load hours and PRIMES full load hours in 2030.

The resulting full load hours for both wind and PV for exemplary countries are shown in Figure 14.

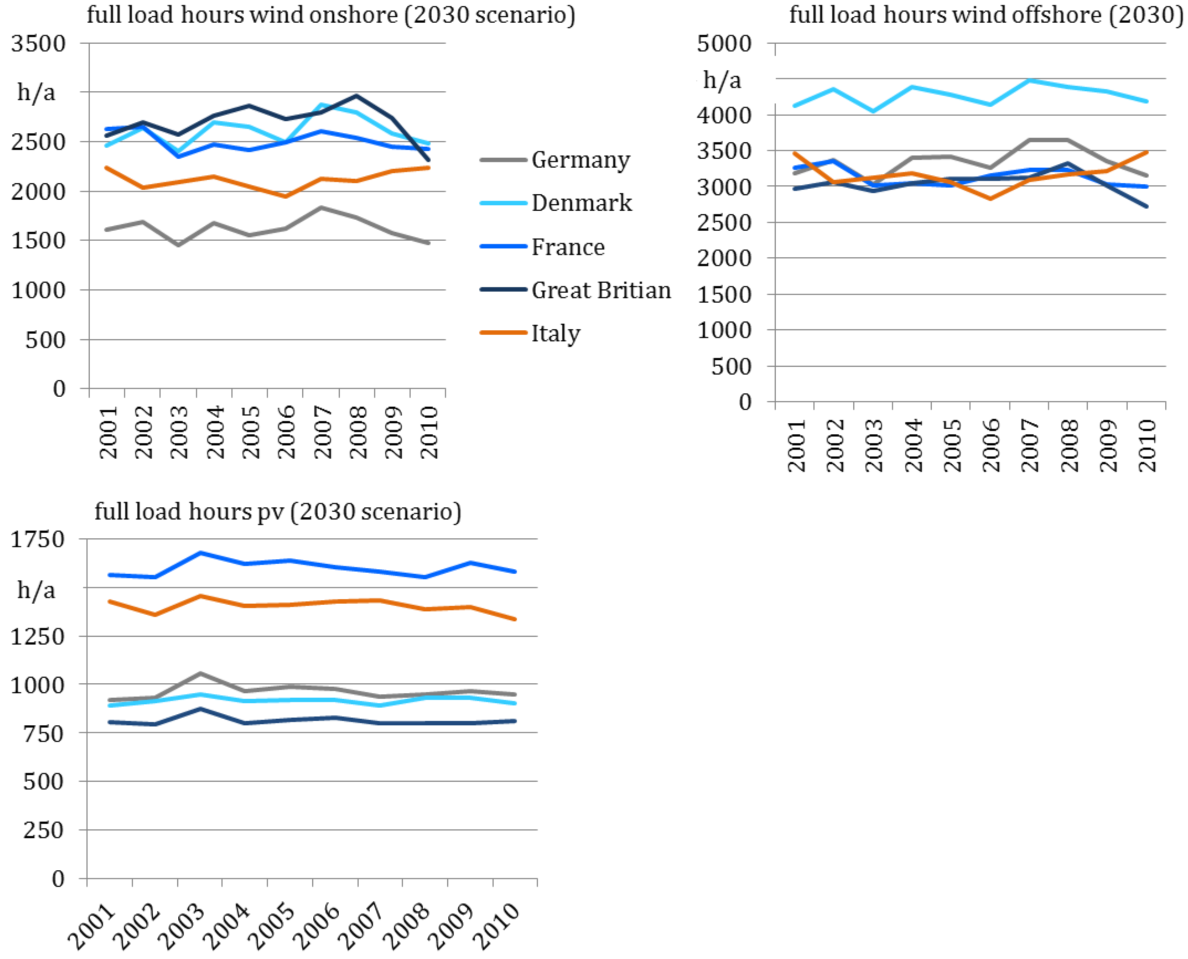


*Figure 14 - Wind and PV full load hours per year*

Whereas the PV full load hours per year are not changing significantly from one year to the next, the resulting full load hours from wind generation vary considerably.

# 7. APPENDIX – RESERVE SIZING METHODOLOGY

## 7.1. MAIN ASSUMPTIONS

One important assumption behind METIS modelling is that all markets are supposed to be liquid. As such, the variations in net demand linked to the RES or demand forecast errors up to t-1 are supposed to be met by the offers done on the intraday market. In reality, TSOs use Replacement Reserves (RR), which are not explicitly modelled in the system module[24], to make sure that enough capacity is available and running (or ready to be running) for the next 1 to 4 hours. Hence, only variations/events occurring in a time horizon smaller than 1 hour are taken into account and used for the sizing of the FCR, aFRR and mFRR.

Besides, METIS functions at an hourly granularity by default. As a consequence, 15 or 30 minutes intraday gateways are not modelled and all variations occurring inside the hour have to be dealt with by the FRR.

Finally, FCR and aFRR are simulated as a single synchronized reserve and the specific constraints of FCR are not integrated by default. FCR and aFRR sizing are added to define the required synchronized reserve.

The main evolution in FRR needs that is to be assessed when comparing to today's situation is the growing share of renewables in the production mix. The immediate impact will be that both empirical and deterministic methods (c.f. 7.3.2) which are currently used in some countries will prove to be insufficient in the near/longer term, when renewables account for an important part of the hourly/daily electricity production. Reserve sizing is thus bound to evolve towards a more probabilistic approach.

In order to compute the FRR sizing following a probabilistic methodology, a TSO point of view is used. It means a forecast state of the system, with a 5min granularity, is compared to an actual state of the system, also with a 5min granularity. Reserves (aFRR and mFRR) are called upon to take care of the resulting imbalances (difference between what was forecast by the TSO and what actually happened). aFRR and mFRR sizings are computed based on the 0.1% and 99.9% centiles of imbalances.

The whole simulation process and FRR sizing for typical METIS models is explained in more details in the following parts.

Note that several options for reserve dimensioning are available and have been used for the S12 study. They are described in details in *Technical Note T3*.

## 7.2. FREQUENCY CONTAINMENT RESERVE

FCR is shared between ENTSO-E continental members with a total sizing of 3GW which is split among MS proportionally to their annual power generation. FCR sizing for each Member State is assumed to follow the same rule up to 2030.

The FCR values used in METIS are presented below (FCR is assumed to be symmetrical for each country).

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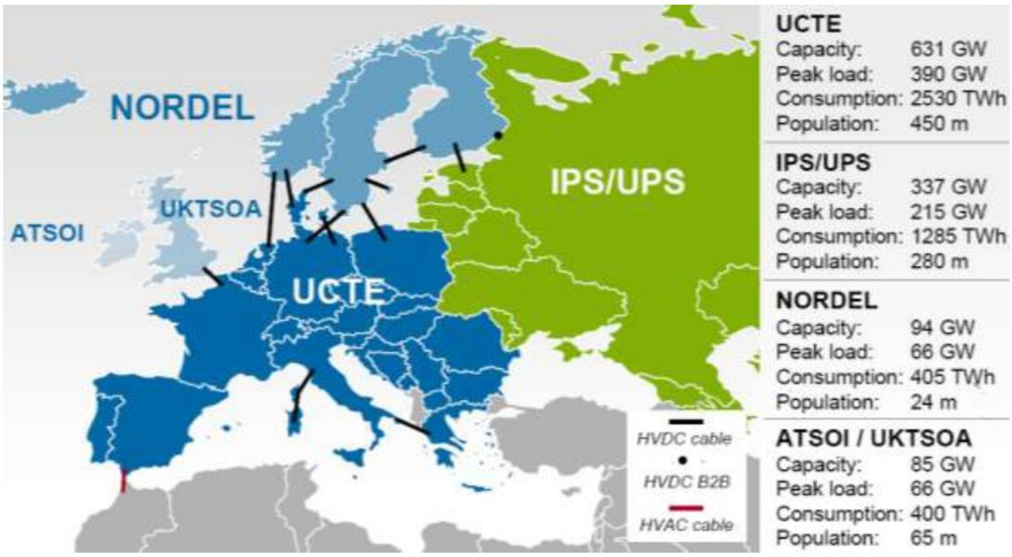
[24] A proxy for RR is used in the Power Market Module, as is described in *Technical Note T2*.

| Country | FCR (MW) | Country | FCR (MW) | Country | FCR (MW) | Country | FCR (MW) |
|---|---|---|---|---|---|---|---|
| **AT** | 65 | **EE** | 45 | **IT** | 535 | **PL** | 171 |
| **BA** | 14 | **ES** | 421 | **LT** | 57 | **PT** | 51 |
| **BE** | 100 | **FI** | 931 | **LU** | 6 | **RO** | 57 |
| **BG** | 44 | **FR** | 650 | **LV** | 42 | **RS** | 46 |
| **CH** | 71 | **GB** | 900 | **ME** | 25 | **SE** | 644 |
| **CY** | | **GR** | 60 | **MK** | 9 | **SI** | 16 |
| **CZ** | 75 | **HR** | 10 | **MT** | | **SK** | 29 |
| **DE** | 583 | **HU** | 75 | **NL** | 102 | | |
| **DK** | 50 | **IE** | 90 | **NO** | 352 | | |

*Table 7– FCR sizing by member state*



## 7.3. Automatic Frequency Restoration Reserve (aFRR) and Manual Frequency Restoration Reserve (mFRR)

### 7.3.1. *Units participating to the reserve*

Only synchronized units can participate in the aFRR because the Full Activation Time (FAT), i.e. the time required for the reserve to be fully activated, is too low for the non-synchronized units to start-up.

FAT varies a lot between Member States as can be seen on the following figure.

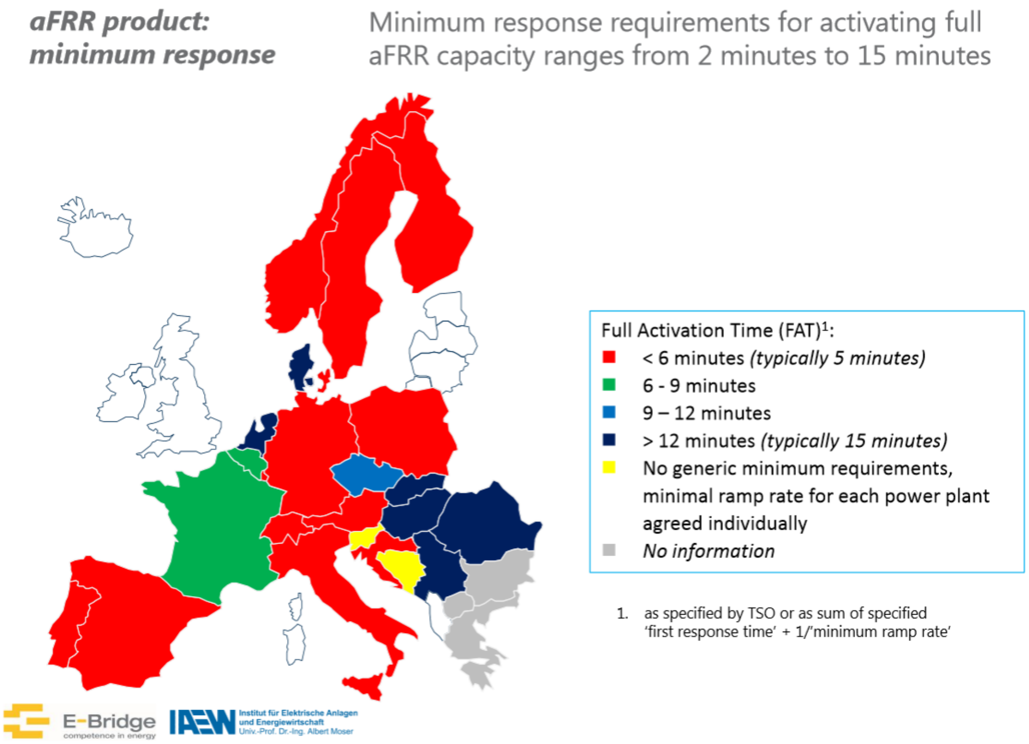


*Figure 15: Diversity of aFRR products across continental Europe*

By default, the FAT chosen for the aFRR in METIS is 5 minutes.

As for the mFRR, because its FAT is set to 15 minutes, assets which can start-up in less than 15 minutes (OCGT and hydro power plants) can also participate, even if they were not running at the beginning of the event.

### 7.3.2. *SIZING APPROACH*

Three approaches are described in the ENTSO-E Operation handbook for aFRR and mFRR reserves sizing, referred to as *empiric, probabilistic* or *deterministic* [18]:

- **Empirical approach** (currently used in France in case of low demand gradient. A margin, computed as the 5-min forecast gradient of the demand, is used whenever the demand gradient is high).
  Variable hourly sizing, based on the maximum anticipated demand level D (expressed in MW).
  $$aFRR\ requirements = \sqrt{10\ D + 22500} - 150$$

- **Probabilistic approach** (currently used in Germany).
  Based on load fluctuations standard deviation, RES generation forecasts and outage statistics, this methodology consists in applying convolution techniques to Normal probability distributions, in order to get the maximum upward / downward balancing requirements for a given probability.
  It results in hourly reserve requirements that could be aggregated to get a fixed-valued sizing over longer time-spans.

  The following figure illustrates the probabilistic reserve sizing with a 99% probability (i.e. that 99% of the time there is no reserve shortage):

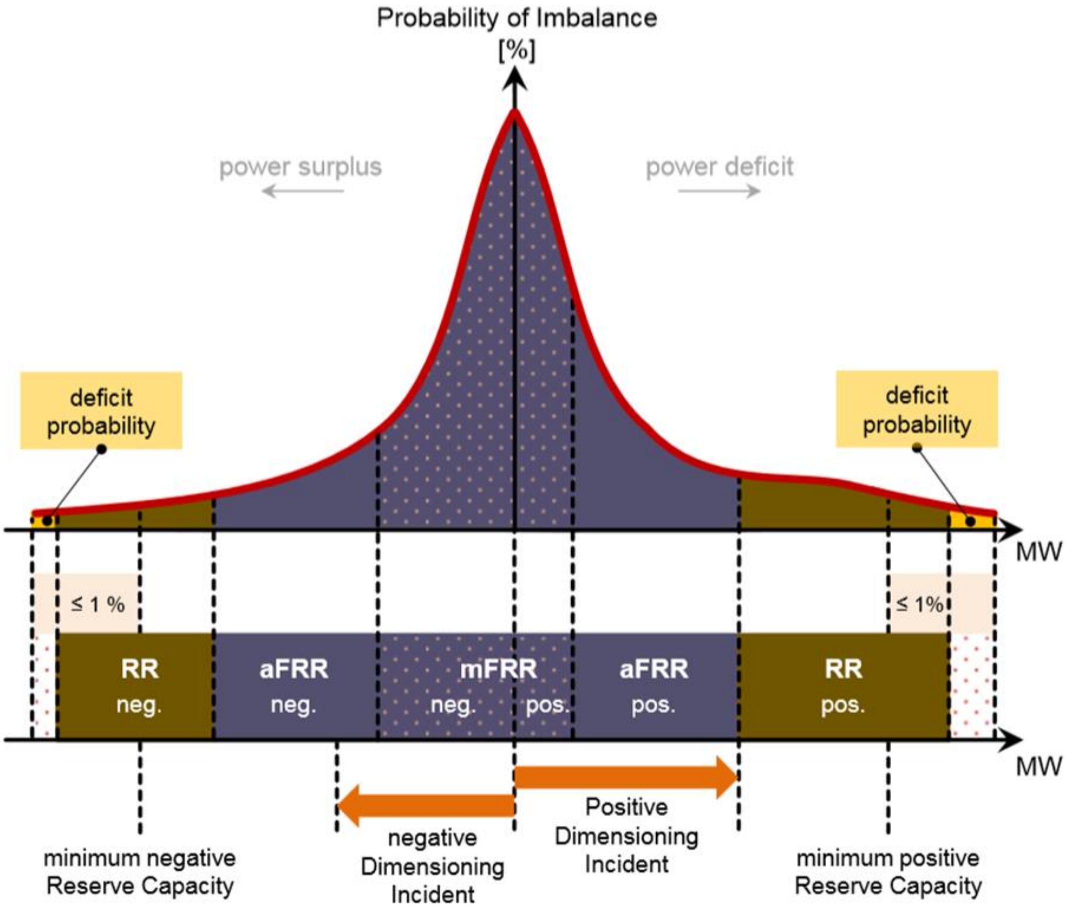


*Figure 16: Probabilistic reserve sizing illustration*
*Source: ENTSO-E's Supporting Document for the Network Code on Load-Frequency Control and Reserves*

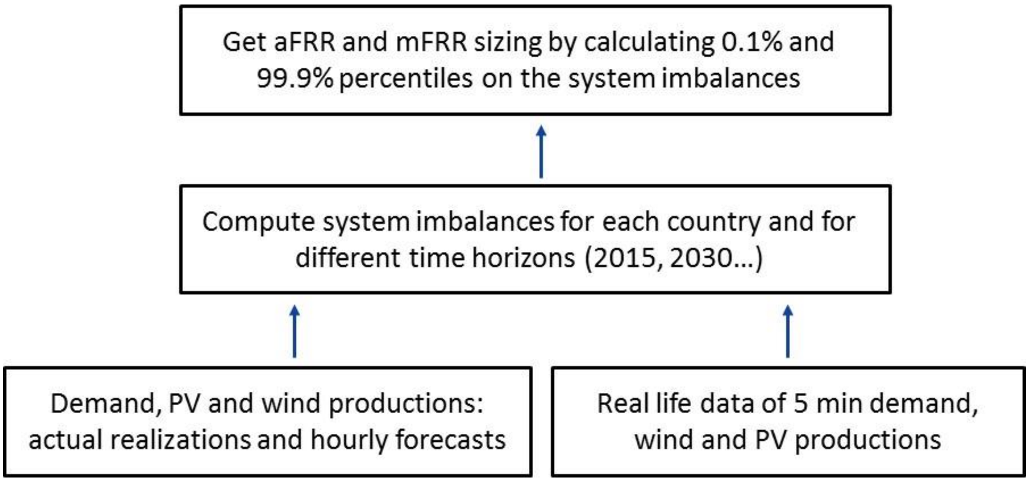
- **Deterministic approach** (currently used in Ireland and United-Kingdom)
  Consists in setting reserves' size to the value of the biggest expected generation incident. It is mentioned as "Dimensioning incident" on the previous illustration.

Both empirical and probabilistic approaches can be implemented in METIS. The following paragraphs will provide a more detailed description of the way the probabilistic approach is done for the FRR reserves.

#### 7.3.2.1. *PROBABILISTIC APPROACH*

A TSO's point of view was adopted for the market simulations: imbalances (difference between the forecast and the actual states of the system) with a 5min granularity are computed, and it is then assumed that these imbalances must be dealt with by the aFRR and mFRR.

In our approach, FRR reserves must be able to cope with imbalances 99.9% of the time.



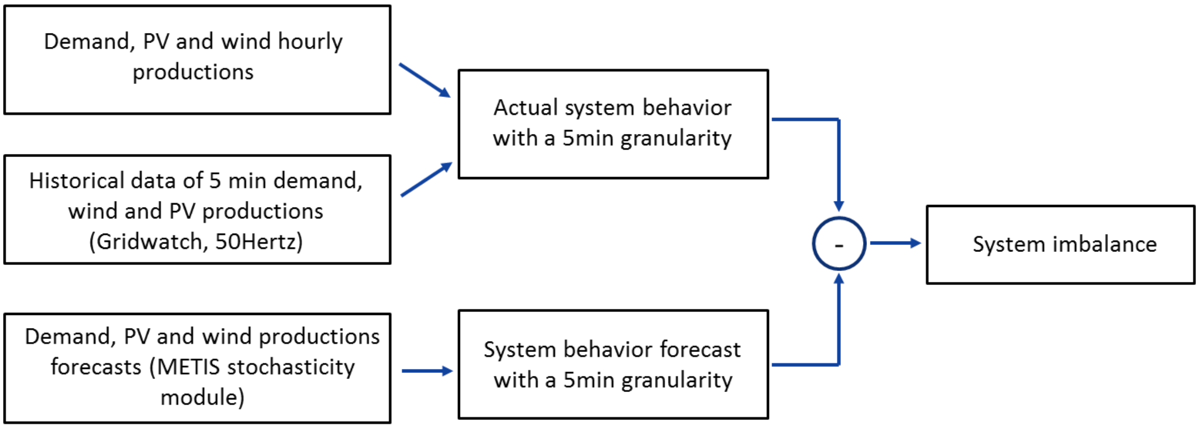
Imbalances are the results of variable RES units, typically wind and solar power plants, and non-flexible loads' forecast errors. In order to simulate a 5min system from data with 1h granularity as it is usually the case in METIS, additional data was needed.

The "actual" state of the system was thus simulated using real 5min data of demand and wind for UK in 2015 extracted from Gridwatch, and 15min PV production data from a German TSO, 50Hertz, which was linearized to go down to the 5min granularity. These datasets were used to compute sub-hourly patterns (series of twelve 5-min data-points) for classes of generation/demand level and hourly gradient. These patterns are then applied to other countries for hours with similar gradient and level characteristics.

In order to model the imbalances that will trigger the call to aFRR and mFRR, the actual state of the system is compared to forecasts. Hence, h-1 forecasts of demand and PV generation (30min for wind[25]) have been collected from METIS forecast database and linearized in order to get 5min data.

Subtracting the actual values from the forecasts gives access to the imbalance levels with a 5min granularity and for 10 years of weather data. These imbalances are finally scaled (using the square root of the mean demand or installed capacities) to mimic how imbalances evolve depending on demand and RES integration scenarios.

The imbalance generation process can be summed up as follows:



FRR activation is modelled using the following process

- For deviations that are not too large compared to the aFRR sizing (imbalances < aFRR sizing * 0.9), only aFRR is triggered
- For large deviations, aFRR is automatically activated the first 5 minutes, then replaced by mFRR. mFRR activation ends when imbalances come back below a

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[25] The use of 30min forecasts for wind resulted from comparisons between modelled imbalances, using today wind and PV installed capacities, and historical values published by ENTSO-E.

second threshold (imbalances < aFRR sizing * 0.5 ) thanks to updated forecasts and intraday market.

Therefore, as commonly practiced by TSO, aFRR is dimensioned to compensate for the variation of imbalances during a 5min interval[26], excluding outages, while the mFRR is sized to cope with total imbalances[27] including outages[28].

Depending on the studied market designs[29], the imbalances used for the probabilistic approach can be computed on groups of countries (for regional cooperation within ROCs) or aggregated in time (if the reserve sizing is constant over time, over a year for instance).

So the reserve can be sized for each country separately or for a group of country and can be fixed over the year or change depending on the time of the day.

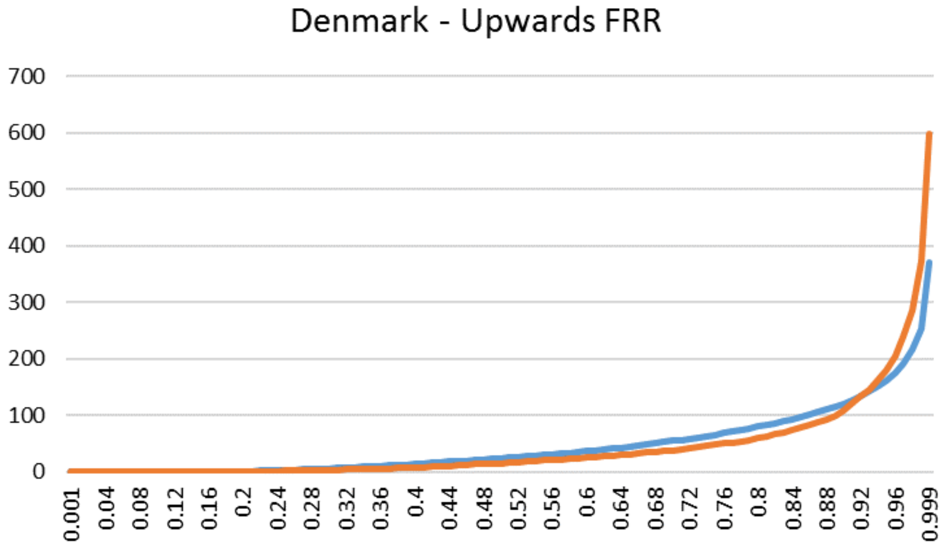
Model validation

The way the FRR reserves are calculated in METIS in order to take into account the demand/RES variations is similar to what is done by various TSOs around the world:

- In Belgium, Elia used a similar methodology in 2013 in order to assess the need for ancillary services in the country in 2018 and based its calculation on the convolution of different events. See [19]
- In France, in case of high demand gradient, RTE bases its calculation of the aFRR on the 5-minute gradient. See [20]
- In the US, the Eastern Wind Integration and Transmission Study (EWITS) aimed at assessing the impact of wind power on the need for reserves. The forecast error and the resulting standard deviation were assumed to be dependent upon the production level. See [21]

The following graphs show the distribution of the simulated imbalances (blue), which thus corresponds to the FRR calls, with actual data taken from the ENTSOE website (orange).

The graphs show the results for Denmark. One can see that the model follows the historical outcome quite closely:



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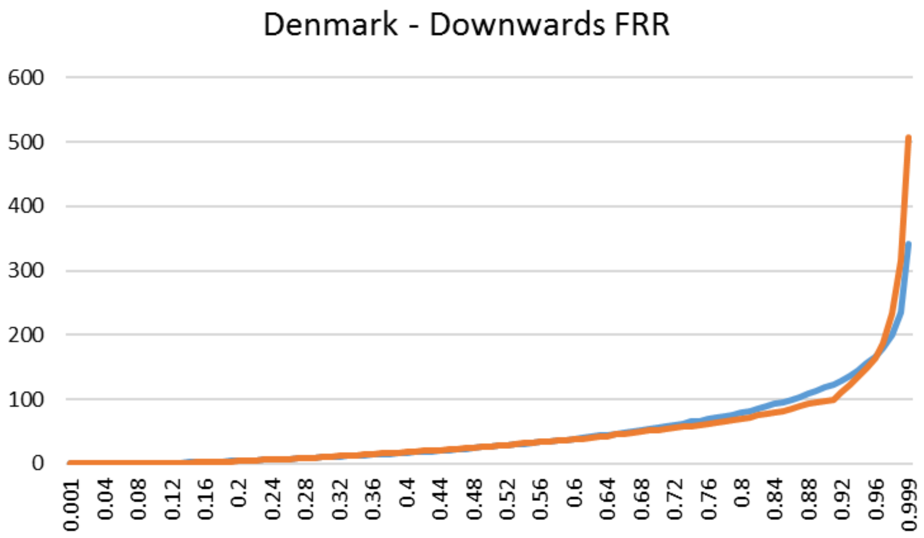
[26] The 0.1% and 99.9% percentiles of imbalance variations are used to compute the downward and upward aFRR size.

[27] The 0.1% and 99.9% percentiles of total imbalances are used to compute downward and upward FRR sizes. mFRR sizes are then calculated by substracting aFRR to FRR sizes

[28] See *METIS Technical Note T2* for more details about the generation of outages

[29] See *METIS Technical Note T3* and *METIS Study S12* for more details on policy options.



The following table shows the comparison between the actual 2015 aFRR and mFRR sizes and the ones simulated with METIS (the figures displayed are the sum of the national sizing of each country).

| **GW** | | **2015 – historical data** | **2015 - METIS** |
|---|---|---|---|
| **aFRR** | Upwards | 8.6 | 9.9 |
| | Downwards | 7.2 | 8.8 |
| **mFRR** | Upwards | 19.1 | 15.1 |
| | Downwards | 16.6 | 11.7 |
| **Total** | | **51.5** | **44.2** |

aFRR values are a bit overestimated, but the difference is smaller than 20% of the historical value. mFRR sizes are much smaller in METIS: while historical and simulated imbalances are consistent, several countries currently use a deterministic approach for reserve sizing which may overestimate the reserve needs.

The table below shows the evolution of the aFRR and mFRR sizes as calculated with METIS, between 2015 and 2030. Total FRR sizes will increase by 20% in 2030, mostly due to higher shares of wind energy.

| **GW** | | **2015** | **2030** |
|---|---|---|---|
| **aFRR** | Upwards | 9.9 | 10.5 |
| | Downwards | 8.8 | 10.0 |
| **mFRR** | Upwards | 15.1 | 17.4 |
| | Downwards | 11.7 | 15.6 |
| **Total** | | **44.2** | **53.5** |
| **Increase** | | | **+21%** |

The assessed impact of wind power capacity on the reserve needs is consistent with available publications on the subject. It was found that 1MW of additional wind power increases the aFRR size by 4.3kW. A study from NREL found around 3.5kW additional regulating reserve per MW of wind power [21].

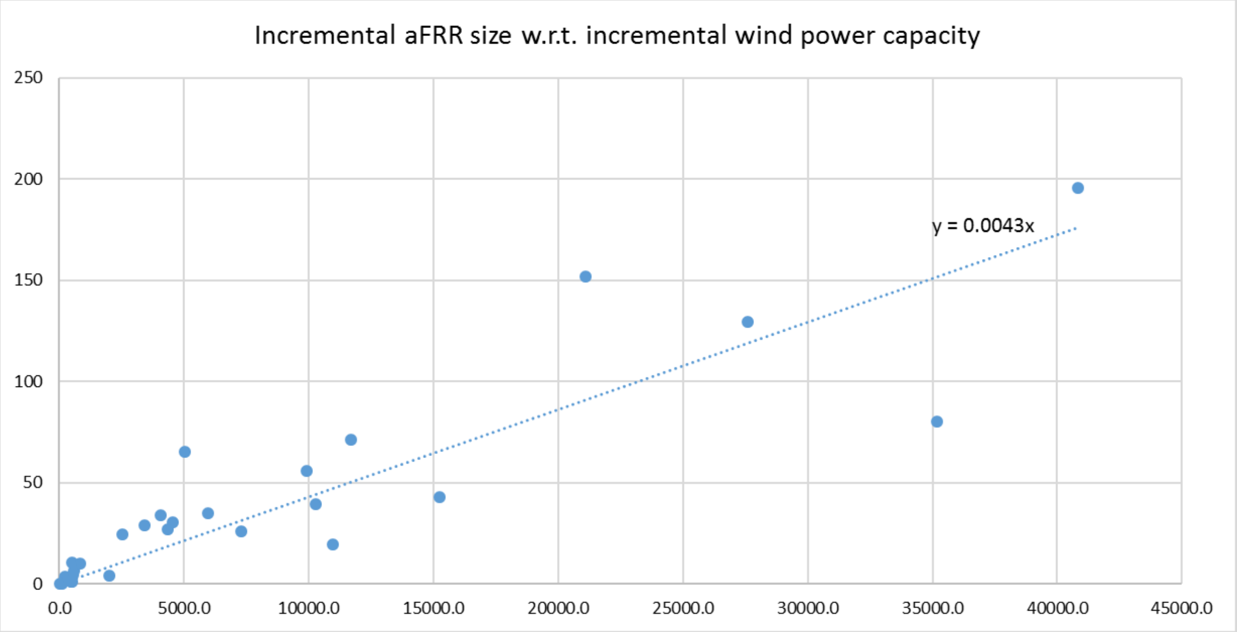


*Figure 17: Linear regression of additional aFRR needs (2030 compared to 2015) and additional installed wind power capacity, for the 30 countries*

### 7.3.3. ***RESERVE SHARING***

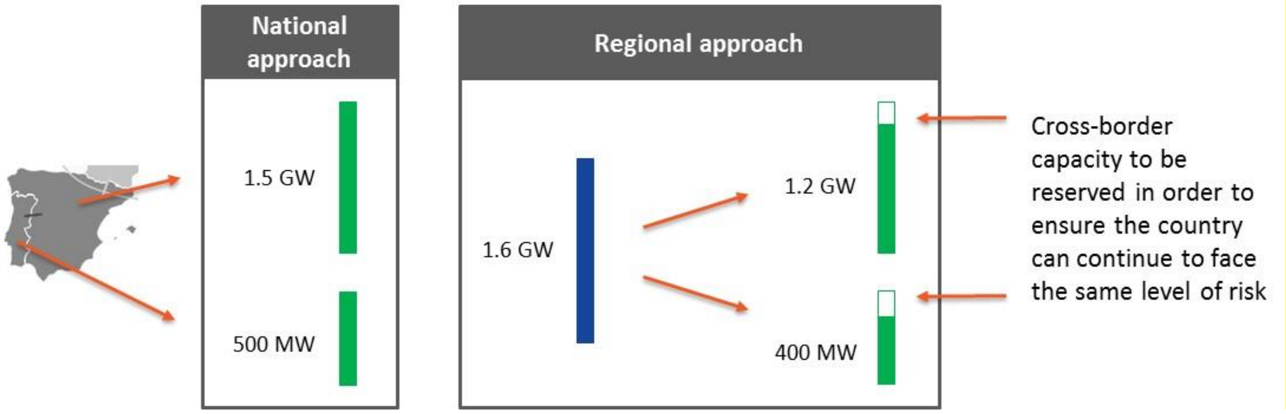
With regional cooperation, countries can share their imbalance risks to decrease overall reserve sizing requirements by pooling part of it. Indeed, for a given level of security of supply, the total regional reserve requirement is lower.

METIS can implement the following methodology to simulate reserve sharing:

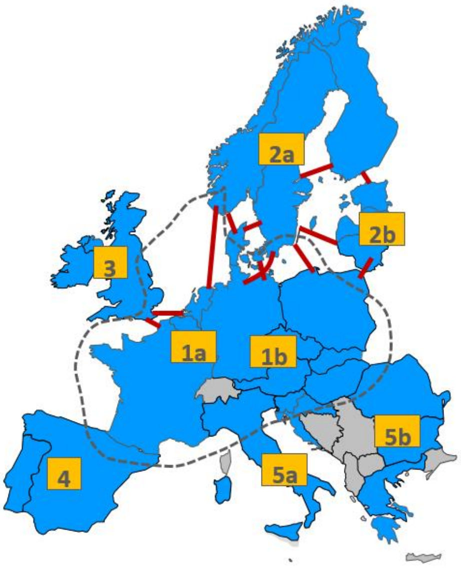
- First the probabilistic approach is used to assess the size of the reserve for each country,
- Then the probabilistic approach is used to compute the regional reserve sizing, by calculating the imbalances over the whole region (i.e. by adding the imbalances of each individual country within the region) and calculating the aFRR and mFRR sizes based on those regional imbalances,

- The regional reserve is assigned to each country in proportion of their individual levels of electricity demand,
- Finally, reserve procurement is optimized so that:
    - Each country procures an amount of reserve at least equal to its share of the regional reserve sizing
    - Local reserve procurement plus cross-border capacity reservation[30] is equal to national reserve sizing. Hence, each country can face its own imbalances with locally procured reserve and imports.

This method guarantees that the level of security of supply is similar for both national and regional reserve sizing.



The following map defines regions used in METIS.



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[30] Reserved cross-border capacity cannot be used for day-ahead and intraday exchanges and are kept for the balancing market. Hence, cross-border capacity reservation is computed as the optimal trade-off between interconnection use for arbitrages and reserve sharing.

| Region 1 |
|---|
| Austria |
| Belgium |
| Czech Republic |
| Denmark |
| France |
| Germany |
| Hungary |
| Luxembourg |
| Netherlands |
| Poland |
| Slovakia |
| Slovenia |
| Switzerland |

| Region 2 |
|---|
| Estonia |
| Finland |
| Latvia |
| Lithuania |
| Norway |
| Sweden |

| Region 3 |
|---|
| United Kingdom |
| Ireland |

| Region 4 |
|---|
| Portugal |
| Spain |

| Region 5 |
|---|
| Bosnia and Herzegovina |
| Bulgaria |
| Croatia |
| Cyprus |
| FYR of Macedonia |
| Greece |
| Italy |
| Malta |
| Montenegro |
| Romania |
| Serbia |

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