Mainstreaming RES

Objectives, methodology, and data sources

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Summary

The purpose of this document is to present the objectives and methodology of Task 3 of the study "Study on the impact assessment for a new Directive mainstreaming deployment of renewable energy and ensuring that the EU meets its 2030 renewable energy target", which is led by Artelys.

TABLE OF CONTENTS

1 Objectives

In order to cost-efficiently reach the 2030 objectives set out in its Energy and Climate Framework (COM(2014) 15 final) and to promote a transparent and reliable governance system (COM(2015) 572 final), the European Commission requires Member States to draft **National Energy and Climate Plans** by 2018, which not only have to set out the Member States' objectives in terms of share of renewables, but also have to include the way Member States propose to adapt their power systems in order to integrate renewables in a cost-efficient manner.

Power systems have to embed a higher level of flexibility as the share of renewables increases in order to continue delivering power when consumers need it. Flexibility can be provided by a number of technologies: flexible thermal generation (incl. retrofitting existing power plants to decrease their ramping times and minimum stable generation power), demand-side management, storage, and interconnectors. Identifying the optimal portfolio of flexibility options for a given deployment of RES is the objective of this project.

The Commission has therefore commissioned this study in order to provide Member States with evidence-based analysis of the optimal deployment of flexibility options.

The objectives of the work undertaken by Artelys is to optimise the 2020-2030 deployment flexibility options in the context of high shares of RES. To perform these tasks, Artelys will use Artelys Crystal, which jointly optimises the investments (flexibility options) and the operations of the power system (hourly time resolution, 8760 consecutive time-steps per year). The following tables present the flexibility needs for different time-scales, and associated the flexibility solutions.

Occurrence	Yearly	Weekly
Historical stakes	Peak demand due to temperature (heating in winter or cooling in summer)	Higher demand during working days compared to week-end
New stakes with high RES shares	Needs to back-up renewable variable energy with firm capacity	Variation of wind energy generation (at national level) over periods of a few days
How it is modeled?	10 years of hourly weather data which impact the demand, PV and wind energy generation	Hourly time series of demand, PV and wind energy generation
Modeled flexibility solutions	Interconnectors, CCGT, reciprocating engines, PHS (48h), CAES (48h)	Interconnectors, CCGT, reciprocating engines, PHS (48h), CAES (48h), system-friendly wind onshore

Occurrence	Daily	Intra-hour
Historical stakes	Demand variation between peak and off peak hours	Unit outages and demand forecast errors
New stakes with high RES shares	Daily cycle of PV generation. RES surplus.	RES generation forecast errors
How it is modeled?	Hourly time series of demand, PV and wind energy generation	Optimal procurement of synchronized and tertiary reserves
Modeled flexibility solutions	Interconnectors, CCGT and coal units retrofitting, DSR, batteries (3h), system-friendly PV	CCGT and coal units retrofitting, DSR, batteries (1h)

Conventional hydro also contributes to the flexibility of the power system, but is not mentioned in the above table since its capacity will be considered as being fixed.

The technologies that are capable of providing flexibility to the power system and the main data sources are presented in the following sections.

2 Model description

This section describes the way Artelys Crystal Super Grid will be used to provide robust pathways of flexibility deployment that help integrating renewables cost-efficiently. The model may be slightly revised in case of data unavailability.

2.1 Optimised deployment

In order to assess the optimal deployment flexibility options between the base year (2015) and 2030, we will proceed in two steps: we will first optimise the 2030 power system, and then determine how to get there cost-efficiently. The remainder of this Section is devoted to the presentation of the capacity expansion planning model.

The following procedure will be followed to optimise investments between 2015 and 2030:

- Assumptions regarding plant closures, decommissioning, phase-out, etc. between 2015 and 2030 are used to constrain the minimum capacities of the 2030 power system,
- The installed capacities of the assets listed below are no longer considered as input parameters, but as variables[1],
- The model finds the investments and operations of the whole power system that minimise the total cost (CAPEX + OPEX)

The capacities of the following categories of assets will be optimised:

- Interconnectors
- Demand response
- Flexible thermal power plants
- Storage
- System-friendly RES

The deployment of all other assets will be scenario-based. The categories of assets that will be optimised are described below.

2.1.1 Interconnectors

The capacity of each interconnection is considered as a variable. The minimum capacity is given by the 2015 capacity to which we add the projects that will be online in 2030 (“Under construction” and “Design and permitting” status).

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[1] The 2015 capacities that are still online in 2030 (residual capacities) will be considered as the lower bounds on the 2030 installed capacities.

The model will be able to invest in interconnectors that appear in the TYNDP 2016 (the capacity can be different). The costs will be based on the costs of the corresponding PCI.

2.1.2 Demand-response

In the same manner as for interconnectors, the capacity of demand response is considered as a variable and is constrained between its base year value and a maximum value (corresponding to the maximum flexibility). Demand response is modelled as peak-shaving capacity.

2.1.3 Flexible thermal power plants

Two kinds of investments in flexible thermal power plants are considered: installing new power plants and retrofitting existing power plants.

The following technologies are eligible:

- New investments: OCGTs, CCGTs
- Retrofitting: coal plants, CCGTs

The following paragraphs describe how the model takes the retrofit and new investment options into account.

OCGTs

We assume these technologies are flexible by design and are not eligible for retrofitting.

Coal plants

The deployment of coal power capacity is not optimised (scenario-based deployment). However, one can imagine that a share of the 2015 coal plants that are still present in 2030 are retrofitted.

CCGTs

The deployment of CCGTs is optimised. The upper bound of the capacity that can be retrofitted is given by the residual capacity of 2015 assets still existing in 2030.

2.1.4 Storage

The new storage capacities are modelled as new assets with different efficiencies, discharge times, and CAPEXs representing different storage categories:

- Pumped Storage Hydro (with discharge time of 48 hours, subject to available potential)
- Compressed Air Energy Storage (with discharge time of 48 hours, subject to available potential)
- Hourly flexibility (technical characteristics of Li-Ion batteries with discharge time of one hour are used)

Their installed capacities are considered as variables which are constrained to be greater than the capacity that is remaining from 2015 and smaller than a country and technology-specific maximum value.

2.2 Scenario-based deployment

The deployment of the following technologies will be based on a scenario[2]:

- Must-run units:
    - Onshore wind (optimisation of the share of system-friendly installations)
    - Offshore wind
    - Photovoltaics
    - Run-of-the-river
    - Waste
    - Other renewable sources
    - Must-run thermal sources
- Reservoir units
    - Hydro turbines
- Conventional units
    - Biomass plants
    - Coal power plants
    - Lignite power plants
    - Nuclear power plants

2.2.1 Focus on system-friendly RES

This study concentrates on the deployment of flexibility options. However, we propose to consider the deployment of system-friendly RES as a mean to ease the integration of renewables. These technologies therefore lessen the need for flexibility and should be considered when designing flexibility roadmaps. One example of such technology is next generation wind turbines, which have a greater economic value because of a higher capacity factor attained at lower wind speed than conventional wind turbines (see figure below).

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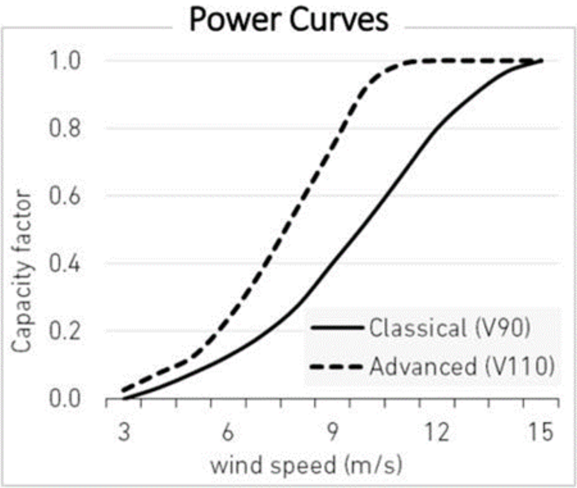
[2] The foreseen scenario is EuCo30.



The total capacity of RES technology i will be fixed (by the deployment scenario). This total capacity will be shared between conventional RES and system friendly RES, the latest having a better load factor and a higher cost.

2.2.2 Focus on conventional hydropower

As mentioned earlier, conventional hydropower also provides flexibility to the power system. In order to take this flexibility into account, we adopt the following model:

- A stock model is used: the storage level depends on the water inflow and the production
- The water inflow is based on observations
- The operations of the system is subject to a minimum storage constraint (based on observations). This constraint ensures that the system does not adopt an overly optimistic management of its water resources, and that the seasonal management is well described.

2.3 Cluster Model

Modelling dynamic constraints and binary states of units (to take into account starting costs and dynamic constraints associated with thermal units) induces computational difficulties, especially when dealing with a significant number of variables. “Clustering” is an alternative modelling solution that allows to take into account dynamic constraints and starting costs without having to include any binary variables. It consists of a continuous representation, in which units with similar technical characteristics are bundled together into clusters. A continuous variable represents the capacity of running units of each cluster. The generation of a cluster is also bounded by its running capacity.

Two different clusters are defined for CCGT, coal fleet and lignite fleet, corresponding respectively to conventional and state of the art units.

Asset parameters are, for each cluster i, at each time step t:

- C_i : generation cost (€/MWh)

- $\bar{C}_i$: running cost (€/MW.h)
- γ_i: start-up cost (€/MW)
- $Pmax_i$: Maximum generation (MW) (= installed capacity for a cluster)
- $Pmin_i$: Minimum stable generation (%), as a proportion of running capacity
- $Avail_{i,t}$: Availability (%), proportion of maximum generation that can be available at time t. Note that the actual availability can be lower due to minimum off-state constraints.
- $CAPEX_i$: Capital cost (€/MW)

Variables to describe each cluster, at each time step t are:

- Generation variable $P_{i,t} \geq 0$
- Running capacity variable $\bar{P}_{i,t} \geq 0$
- Difference variables:
  - Positive part of difference in running capacity between t-1 and t : $\bar{\delta}_{i,t}^{+} \geq 0$
  - Positive part of the difference in shutdown power between t-1 and t : $\bar{\delta}_{i,t}^{-} \geq 0$
- Amount of power from off-state units which could be started-up $\tilde{P}_{i,t} \geq 0$

The difference variable $\bar{\delta}_{i,t}^{+}$ represents the amount of power that has been started at time step t. Start-up costs for time-step t will be proportional to this variable. Similarly $\bar{\delta}_{i,t}^{-}$ represents the amount of power that has been shut down at time step t. It will in particular be used to determine the amount of power $\tilde{P}_{i,t}$ that could be started at time t. Indeed, $\tilde{P}_{i,t}$ is the power which is off at time step t.

The objective is to minimise total cost, written as the sum of:

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

And constraints are:

- Satisfying demand
- Generation bounded by running capacity: $P_{i,t} \leq \bar{P}_{i,t}$
- Running capacity bounded by installed capacity: $\bar{P}_{i,t} \leq Pmax_i \cdot Avail_{i,t}$
- Generation greater than a part of running capacity: $P_{i,t} \geq Pmin_i \cdot \bar{P}_{i,t}$
- Difference variables meaning :
  - $\bar{\delta}_{i,t}^{+} \geq \bar{P}_{i,t} - \bar{P}_{i,t-1}$
  - $\bar{\delta}_{i,t}^{-} \geq \bar{P}_{i,t-1} - \bar{P}_{i,t}$
  - $\bar{\delta}_{i,t}^{+} - \bar{\delta}_{i,t}^{-} = \bar{P}_{i,t} - \bar{P}_{i,t-1}$
- Minimum off-state duration
  $\tilde{P}_{i,t} = \tilde{P}_{i,t-1} - \bar{\delta}_{i,t}^{+} + \bar{\delta}_{i,t+1}^{-} + Pmax_i \cdot (Avail_{i,t} - Avail_{i,t-1})$

2.4 Reserves

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

The Automatic Frequency Restoration Reserve (aFRR) and the Manual Frequency Restauration Reserve (mFRR) have different activation times, depending on countries - 5 minutes (respectively 15 minutes) will be considered as standard for the aFRR (respectively mFRR). They can be called to compensate load fluctuations or forecast errors.

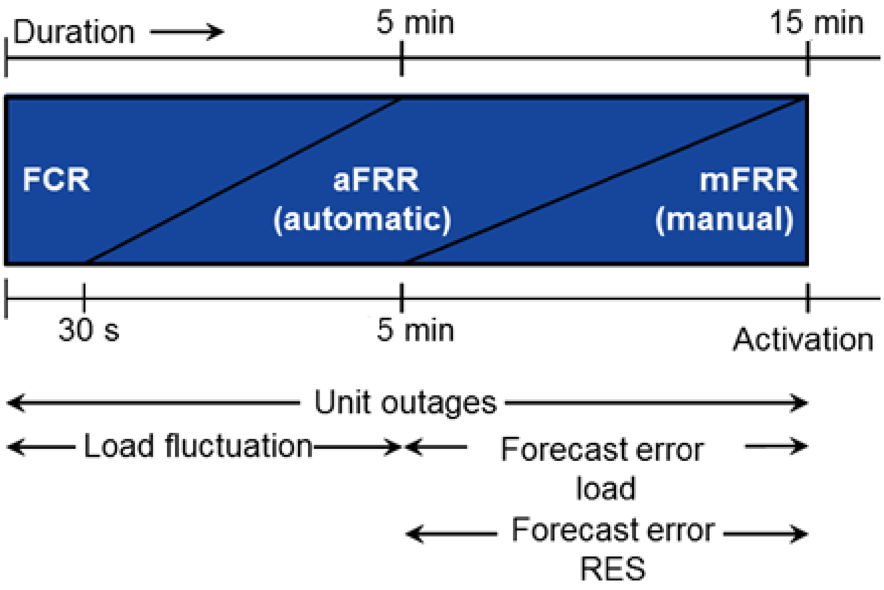


Figure 1 : Reserve types and usages

Balancing reserves are dimensioned endogenously so as to be able to cover imbalances. The reserve needs therefore depend on the characteristics of the energy system such as the share of intermittent RES in the national energy mixes.

To dimension reserves, we generate imbalances (5-minute time steps) and require that reserves should be able to cover 99.9% of all deviations. More precisely, aFRR should be able to cover 99.9% of 5-min gradients, while aFRR + mFRR should cover 99.9% of 5-min gradient + forecasts errors + outages.

3 Assets' description

The model's assets are divided in the following categories:

- Must-run units:
    - Offshore wind
    - Onshore wind
    - Photovoltaics
    - Run-of-river
    - Waste
    - Other renewable sources
    - Must-run thermal sources
- Reservoir units
    - Hydro turbines
    - Pumped storage plants
- Conventional units
    - Biomass plants
    - Coal power plants
    - Lignite power plants
    - OCGT
    - CCGT
    - Nuclear power plants
- Demand-response
- Interconnectors
- Storage (other than PSH)
- Demand

Must-run units are modelled as a single asset by zone and by type of technology. They generate at each time step as much electricity that their availability enables them to, until curtailment is needed. 10 years of weather data have been used to build a database of hourly generation at country level for onshore wind, offshore wind and PV (we are doing our best so as to be able to use 50 years of observed temperature data).

A short description of each of the technologies mentioned above is provided in the following. Data sources for each of these are provided in Section 4.

3.1 Must-run units

All the units below are considered to be non-dispatchable: their production is given by the installed capacity multiplied by the availability. All RES technologies are assumed to be curtailed at 0€/MWh, and to be able to participate in the reserve procurement exercise.

3.1.1 Offshore wind

Parameters:

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation

3.1.2 Onshore wind

Different technologies and different CAPEX

- Conventional onshore
- State of the art, i.e. with a higher and less erratic load factor

Parameters:

- $Pmaxmax_i$: Maximum capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum capacity (MW) that has to be installed
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $CAPEX_i$: Capital cost (€/MW)
- FOC_i: Fixed operation costs (€/MW)
- $Lifetime_i$: Asset lifetime (years)

3.1.3 Photovoltaics

Parameters:

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation

3.1.4 Run-of-river

Parameters:

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation

3.1.5 Waste

Parameters:

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation

3.1.6 Other renewable sources

Parameters:

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation

3.1.7 Must-run thermal sources

Parameters:

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $CO2Content_i$: CO2 Emissions (t/MWh)

3.2 Reservoir units

3.2.1 Hydro turbines

Parameters:

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_i$: Availability (%), as a proportion of maximum generation (independent of t)
- $minStorageLevel_{i,t}$: Guide sketch of annual energy storage (MWh)
- $initialStorageLevel_i$: Initial level of energy storage (MWh)
- $maxStorageLevel_i$: Maximum level of energy storage (MWh)
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)

3.2.2 Pumped storage plants

Different technologies and different CAPEX

- Pumped storage with 1 existing reservoir
- Pumped storage with 2 existing reservoirs

Parameters:

- $Pmaxmax_i$: Maximum capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum capacity (MW) that has to be installed
- $Avail_i$: Availability (%), as a proportion of maximum generation (independent of t)
- $CAPEX_i$: Capital cost (€/MW)
- FOC_i: Fixed operation costs (€/MW)
- $inputEfficiency_i$: Efficiency of storing electricity ([0,1])
- $outputEfficiency_i$: Efficiency of releasing stored energy ([0,1])
- $dischargeTime_i$: Duration for full storage discharge at full power (h)
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)
- $Lifetime_i$: Asset lifetime (years)

3.3 Conventional units

3.3.1 Biomass plants

Parameters:

- $productionHeatRate_i$: production heat rate (MWh$_{PCS}$/MWh)
- $runningCapacityFuelCons_i$: Running capacity fuel consumption per hour (MWh$_{PCS}$/MW.h)
- γ_i: start-up cost (€/MW)
- $Pmax_i$: Installed capacity (MW)
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)
- $CO2Content_i$: CO2 Emissions (t/MWh$_{PCS}$)

3.3.2 Coal power plants

Coal power plants are divided in three different assets:

- Conventional plants
- Retrofitted conventional plants
- State-of-the-art plants

Conventional and retrofitted conventional plant have the following parameters:

- $productionHeatRate_i$: production heat rate (MWh$_{PCS}$/MWh)
- $runningCapacityFuelCons_i$: Running capacity fuel consumption per hour (MWh$_{PCS}$/MW.h)
- γ_i: start-up cost (€/MW)
- $Pmaxmax_i$: Maximum capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum capacity (MW) that has to be installed
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)
- $CO2Content_i$: CO2 Emissions (t/MWh$_{PCS}$)
- $CAPEX_i$: Capital cost (€/MW)
- FOC_i: Fixed operation costs (€/MW)
- $Lifetime_i$: Asset lifetime (years)

State-of-the-art plant capacities are fixed by the scenario and thus have the following parameters:

- $productionHeatRate_i$: production heat rate (MWh$_{PCS}$/MWh)
- $runningCapacityFuelCons_i$: Running capacity fuel consumption per hour (MWh$_{PCS}$/MW.h)
- γ_i: start-up cost (€/MW)

- $Pmax_i$: Installed capacity (MW)
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)
- $CO2Content_i$: CO2 Emissions (t/MWh$_{PCS}$)
- $Lifetime_i$: Asset lifetime (years)

3.3.3 Lignite power plants

Parameters:

- $productionHeatRate_i$: production heat rate (MWh$_{PCS}$/MWh)
- $runningCapacityFuelCons_i$: Running capacity fuel consumption per hour (MWh$_{PCS}$/MW.h)
- γ_i: start-up cost (€/MW)
- $Pmax_i$: Maximum generation (MW) (= installed capacity for a cluster)
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)
- $CO2Content_i$: CO2 Emissions (t/MWh)
- $Lifetime_i$: Asset lifetime (years)

3.3.4 OCGT

Parameters:

- $productionHeatRate_i$: production heat rate (MWh$_{PCS}$/MWh)
- $runningCapacityFuelCons_i$: Running capacity fuel consumption per hour (MWh$_{PCS}$/MW.h)
- γ_i: start-up cost (€/MW)
- $Pmaxmax_i$: Maximum capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum capacity (MW) that has to be installed
- $CAPEX_i$: Capital cost (€/MW)
- FOC_i: Fixed operation costs (€/MW)
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)
- $CO2Content_i$: CO2 Emissions (t/MWh$_{PCS}$)
- $Lifetime_i$: Asset lifetime (years)

3.3.5 CCGT

CCGT power plants are divided in three different assets:

- Conventional plants
- Retrofitted conventional plants
- State of the art plants

They all have the following parameters:

- $productionHeatRate_i$: production heat rate (MWh$_{PCS}$/MWh)
- $runningCapacityFuelCons_i$: Running capacity fuel consumption per hour (MWh$_{PCS}$/MW.h)
- γ_i: start-up cost (€/MW)
- $Pmaxmax_i$: Maximum capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum capacity (MW) that has to be installed
- $CAPEX_i$: Capital cost (€/MW)
- FOC_i: Fixed operation costs (€/MW)
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $gradUp_i$: maximum generation increase rate per time unit (in % of running capacity)
- $gradDown_i$: maximum generation decrease rate per time unit (in % of running capacity)
- $CO2Content_i$: CO2 Emissions (t/MWh$_{PCS}$)
- $Lifetime_i$: Asset lifetime (years)

3.3.6 Nuclear power plants

The main difference between nuclear plants and the other thermal units is that nuclear power will not be modelled as consuming a fuel. Therefore no heat rate is considered.

- $Pmax_i$: Maximum generation (MW) (= installed capacity)
- $Avail_{i,t}$: Availability (%), as a proportion of maximum generation
- $Rmax_i$: maximum share of the installed capacity available for balancing reserves
- $minLoad_i$: Minimum stable generation (%), as a proportion of running capacity
- $genCost_i$: Generation cost (€/MWh)

3.4 Demand-response

Demand-response is defined as an electricity generator (whose production is subtracted from the demand, representing peak shaving).

- $Pmaxmax_i$: Maximum response capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum response capacity (MW) that has to be installed

3.5 Interconnectors

The power grid model is based on ATC capacities (no grid model). Each direction is modelled as a separate asset so as to be able to represent the fact that congestion may impact the capacity in one direction more than in the other (due to local effects, which have to be specified exogenously).

By construction, interconnection capacities in opposite directions are equal.

Parameter:

- $Pmaxmax_i$: Maximum capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum capacity (MW) that has to be installed
- $CAPEX_i$: Capital cost (€/MW)
- $Lifetime_i$: Asset lifetime (years)

3.6 Storage

Parameters:

- $Pmaxmax_i$: Maximum capacity (MW) that can be installed
- $Pmaxmin_i$: Minimum capacity (MW) that has to be installed
- $Avail_i$: Availability (%), as a proportion of maximum generation (independent of t)
- $CAPEX_i$: Capital cost (€/MW)
- FOC_i: Fixed operation costs (€/MW)
- $inputEfficiency_i$: Efficiency of storing electricity ([0,1])
- $outputEfficiency_i$: Efficiency of releasing stored energy ([0,1])
- $dischargeTime_i$: Duration for full storage discharge at full power (h)
- $Lifetime_i$: Asset lifetime (years)

3.7 Demand

The electricity demand is specified by an hourly time-series at MS level (based on the treatment of hourly load profiles obtained from ENTSO-E). We model the load profiles as a 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[3]

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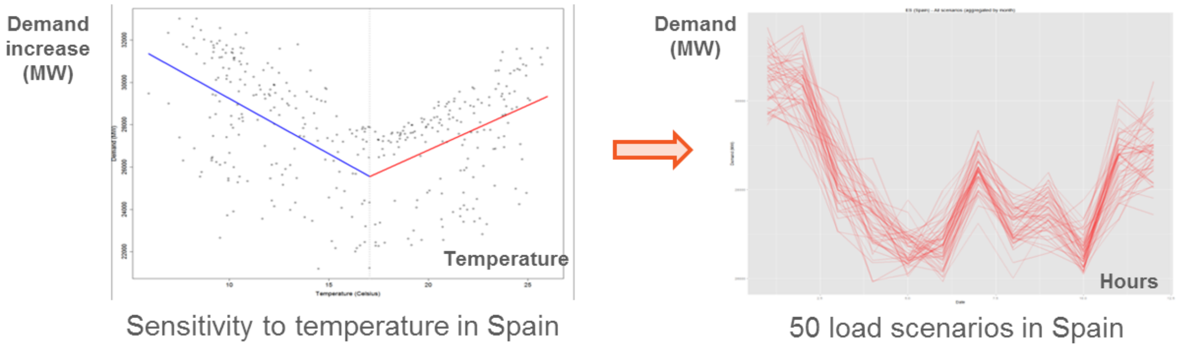
[3] The use of two slopes - one slope associated to low temperatures and one slope associated to high temperatures allows for applying the same approach for each country, with the same number of parameters, although three slopes could have been used for countries with both heating and cooling gradients.

and calibrated by getting recourse to a *Multivariate Adaptive Regression Splines* method[4] that involves the computation of temperature gradients (MW of demand increase per °C increase) for each country.

The calibration is performed by analysing observed country-level demand time-series (source: ENTSO-E). 50 time-series are then generated based on 50 years of temperature statistics (source: ECA, the European Climate Assessment & Dataset project). The time-series are finally rescaled so as to ensure the average over the 50 time-series corresponds to the annual PRIMES EuCo30 demand.

As depicted in Figure 22 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.



Sensitivity to temperature in Spain

50 load scenarios in Spain

Figure 2 - Two gradients and one threshold accounting for heating and cooling effects on Spain demand

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[4] See J. H. Friedman, « *Multivariate Adaptive Regression Splines* », *Annals of Statistics*, vol. 19, nº 1, 1991 for the method and https://cran.r-project.org/web/packages/mda/mda.pdf for its R implementation.

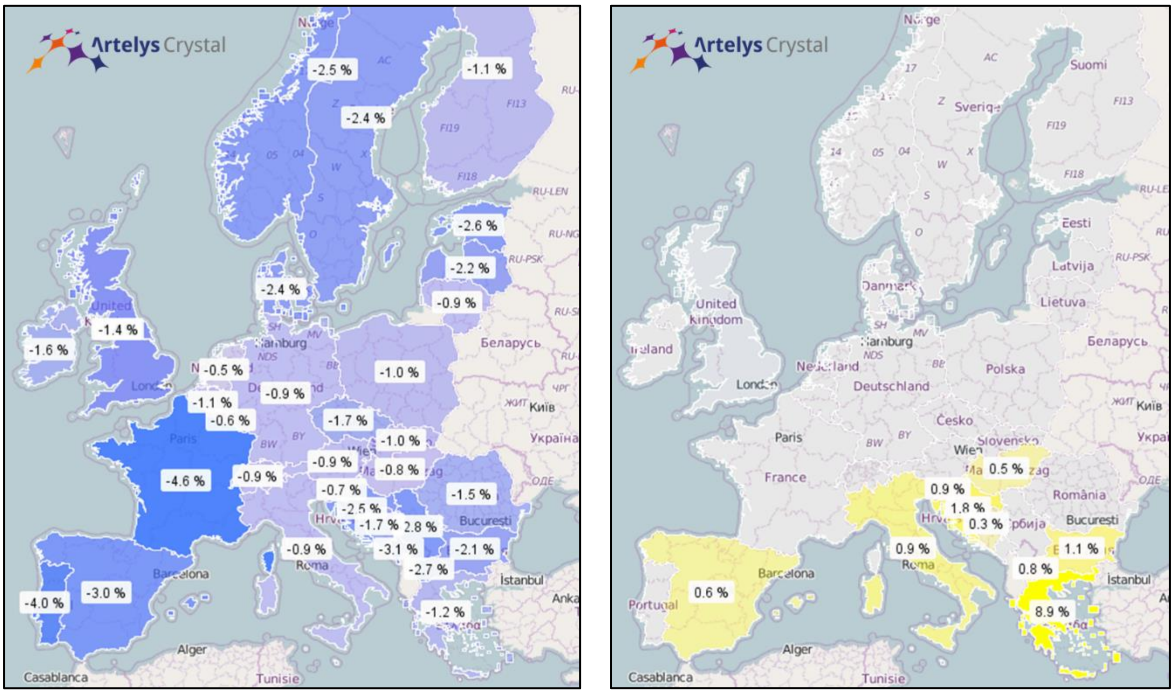

Figure 3: Heating (left) and cooling (right) gradient in % of mean demand per °C, based on ENTSO-E TYNDP vision 1 (2030)

4 Data sources

This Section is devoted to summing up the asset parameters and the data sources that will be used to characterise all assets listed in the previous section. Production costs are assumed to be the same for all countries.

Note that the CAPEX in this table have not been actualised. In practice we will use a discount rate of 4%[5].

Asset	Parameter	Value	Unit	Source
Offshore wind	$Pmax_i$	Country dpdt	MW	Scenario specific
	$Avail_{i,T,t}$	Time series	-	Artelys
Conventional Onshore wind	$Pmaxmax_i$	Country dpdt	MW	Scenario specific
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$Avail_{i,T,t}$	Time series	-	Artelys
	$CAPEX_i$	1 300 000	€/MW	[1]
	FOC_i	28 600	€/MW	[1]
	$Lifetime_i$	25	year	[1]
State of the Art Onshore wind	$Pmaxmax_i$	Country dpdt	MW	Scenario specific
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$Avail_{i,T,t}$	Time series	-	Artelys
	$CAPEX_i$	1 800 000	€/MW	[1]
	FOC_i	39 600	€/MW	[1]
	$Lifetime_i$	25	year	[1]
Photovoltaics	$Pmax_i$	Country dpdt	MW	Scenario specific
	$Avail_{i,T,t}$	Time series	-	Artelys
Run-of-River	$Pmax_i$	Country dpdt	MW	Scenario specific
	$Avail_{i,T,t}$	Time series	-	Artelys
Waste	$Pmax_i$	Country dpdt	MW	Scenario specific
	$Avail_{i,T,t}$	Time series	-	Artelys
	$Pmax_i$	Country dpdt	MW	Scenario specific

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[5] http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm

Must-run renewable sources	$Avail_{i,T,t}$	Time series	-	Artelys
Must-run thermal sources	$Pmax_i$	Country dpdt	MW	Scenario specific
	$Avail_{i,T,t}$	Time series	-	Artelys
	$CO2Content_i$	0	t/MWh	Ademe
Conventional Hydro reservoir	$Pmax_i$	Country dpdt	MW	ESTMAP
	$Avail_{i,T,t}$	Country dpdt	-	Artelys
	$minStorageLevel_{i,t}$	Country dpdt	MWh	ESTMAP
	$initialStorageLevel_i$	Country dpdt	MWh	ESTMAP
	$maxStorageLevel_i$	Country dpdt	MWh	ESTMAP
	$minLoad_i$[6]	60%	%Pmax	Artelys
	$gradUp_i$	-	%Pmax/min	Artelys
	$gradDown_i$	-	%Pmax/min	Artelys
Pumped Storage Plant[7] with 1 existing reservoir	$Pmaxmax_i$	Country dpdt	MW	ESTMAP
	$Pmaxmin_i$	Country dpdt	-	ESTMAP
	$Avail_{i,T,t}$	90%	%Pmax	Artelys
	$CAPEX_i$	3 420 000 + small country dpdt connection cost	€/MW	ESTMAP
	FOC_i	1.5% of $CAPEX_i$	€/MW	ESTMAP
	$inputEfficiency_i$	0.9	MWh	Artelys
	$outputEfficiency_i$	0.9	MWh	Artelys

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[6] 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 this study, a minimum generation level of 60% is used.

[7] 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%.

	$dischargeTime_i$	48	h	Artelys
	$minLoad_i{}^2$	60%	%Pmax	Artelys
	$gradUp_i$	-	%Pmax/min	Artelys
	$gradDown_i$	-	%Pmax/min	Artelys
	$Lifetime_i$	60	year	[1]
Pumped Storage Plant[8] with 2 existing reservoirs	$Pmaxmax_i$	Country dpdt	MW	ESTMAP
	$Pmaxmin_i$	Country dpdt	-	ESTMAP
	$Avail_{i,T,t}$	90%	%Pmax	Artelys
	$CAPEX_i$	1 610 000 + small country dpdt connection cost	€/MW	ESTMAP
	FOC_i	1.5% of $CAPEX_i$	€/MW	ESTMAP
	$inputEfficiency_i$	0.88	MWh	ESTMAP
	$outputEfficiency_i$	0.88	MWh	ESTMAP
	$dischargeTime_i$	48	h	Artelys
	$minLoad_i{}^2$	60%	%Pmax	Artelys
	$gradUp_i$	-	%Pmax/min	Artelys
	$gradDown_i$	-	%Pmax/min	Artelys
	$Lifetime_i$	60	year	[1]
Conventional Coal Power Plants	$productionHeatRate_i$	2.12	MWh$_{PCS}$/MWh	Artelys
	$runningCapacityFuelCons_i$	0.26	MWh$_{PCS}$/MW.h	Artelys
	$startUpCost_i$	65	€/MW	Artelys
	$Pmaxmax_i$	Country dpdt	MW	Scenario specific
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$minLoad_i$	40%	%Pmax	Artelys
	$Avail_{i,T,t}$	Time series	-	Artelys

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[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%.

	$gradUp_i$	2%	%Pmax/min	Artelys
	$gradDown_i$	5%	%Pmax/min	Artelys
	$CO2Content_i$	0.32	t/MWh$_{PCS}$	Ademe
	$CAPEX_i$	0	€/MW	No investment
	FOC_i	0	€/MW	No investment
	$Lifetime_i$	40	year	[1]
Retrofitted conventional coal power plants	$productionHeatRate_i$	2.12	MWh$_{PCS}$/MWh	Artelys
	$runningCapacityFuelCons_i$	0.26	MWh$_{PCS}$/MW.h	Artelys
	$startUpCost_i$	50	€/MW	Artelys
	$Pmaxmax_i$	Country dpdt	MW	Scenario specific
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$minLoad_i$	25%	%Pmax	Artelys
	$Avail_{i,T,t}$	Time series	-	Artelys
	$gradUp_i$	2%	%Pmax/min	Artelys
	$gradDown_i$	5%	%Pmax/min	Artelys
	$CO2Content_i$	0.32	t/MWh$_{PCS}$	Ademe
	$CAPEX_i$	RetrofitCost	€/MW	NREL[9]
	FOC_i	0	€/MW	No investment
	$Lifetime_i$	?	year	[1]
State-of-the-art Coal Power Plants	$productionHeatRate_i$	2.04	MWh$_{PCS}$/MWh	Artelys
	$runningCapacityFuelCons_i$	0.15	MWh$_{PCS}$/MW.h	Artelys
	$startUpCost_i$	50	€/MW	[2]
	$Pmax_i$	Country dpdt	MW	Scenario specific
	$minLoad_i$	25%	%Pmax	[2]
	$Avail_{i,T,t}$	Time series	-	Artelys
	$gradUp_i$	6%	%Pmax/min	[3]
	$gradDown_i$	6%	%Pmax/min	[3]
	$CO2Content_i$	0.32	t/MWh$_{PCS}$	Ademe
	$Lifetime_i$	40	year	[1]

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[9] NREL (2012), "Cost-benefit analysis of flexibility retrofit for coal and gas-fueled power plants"

Lignite Power Plants	$productionHeatRate_i$	2.22	MWh_{PCS}/MWh	Artelys
	$runningCapacityFuelCons_i$	0.16	MWh_{PCS}/MW.h	Artelys
	$startUpCost_i$	25	€/MW	Artelys
	$Pmax_i$	Country dpdt	MW	Scenario specific
	$minLoad_i$	50%	%Pmax	Artelys
	$Avail_{i,T,t}$	Time series	-	Artelys
	$gradUp_i$	2%	%Pmax/min	Artelys
	$gradDown_i$	5%	%Pmax/min	Artelys
	$CO2Content_i$	0.34	t/MWh_{PCS}	Ademe
	$Lifetime_i$	40	year	[1]
Biomass Plants	$productionHeatRate_i$	2.68	MWh_{PCS}/MWh	Artelys
	$runningCapacityFuelCons_i$	0.06	MWh_{PCS}/MW.h	Artelys
	$startUpCost_i$	36	€/MW	Artelys
	$Pmax_i$	Country dpdt	MW	Scenario specific
	$minLoad_i$	20%	%Pmax	Artelys
	$Avail_{i,T,t}$	Time series	-	Artelys
	$gradUp_i$	4%	%Pmax/min	Artelys
	$gradDown_i$	5%	%Pmax/min	Artelys
	$CO2Content_i$	0	t/MWh_{PCS}	Ademe
	$Lifetime_i$	40	year	[1]
OCGT	$productionHeatRate_i$	1.59	MWh_{PCS}/MWh	Artelys
	$runningCapacityFuelCons_i$	0.79	MWh_{PCS}/MW.h	Artelys
	$startUpCost_i$	21	€/MW	Artelys
	$Pmaxmax_i$	Country dpdt	MW	Scenario specific
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$minLoad_i$	40%	%Pmax	Artelys
	$Avail_{i,T,t}$	Time series	-	Artelys
	$gradUp_i$	12%	%Pmax/min	Artelys
	$gradDown_i$	12%	%Pmax/min	Artelys
	$CAPEX_i$	550 000	€/MW	[1]
	FOC_i	16 500	€/MW	[1]

	$CO2Content_i$	0.18	t/MWh$_{PCS}$	Ademe
	$Lifetime_i$	30	year	[1]
Conventional CCGT	$productionHeatRate_i$	1.58	MWh$_{PCS}$/MWh	Artelys
	$runningCapacityFuelCons_i$	0.46	MWh$_{PCS}$/MW.h	Artelys
	$startUpCost_i$	45	€/MW	Artelys
	$Pmaxmax_i$	Country dpdt	MW	Scenario specific
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$minLoad_i$	50%	%Pmax	Artelys
	$Avail_{i,t}$	Time series	-	Artelys
	$gradUp_i$	2%	%Pmax/min	[3]
	$gradDown_i$	5%	%Pmax/min	[3]
	$CAPEX_i$	0	€/MW	No investment
	FOC_i	0	€/MW	No investment
	$CO2Content_i$	0.18	t/MWh$_{PCS}$	Ademe
	$Lifetime_i$	30	year	[1]
Retrofitted Conventional CCGT	$productionHeatRate_i$	1.58	MWh$_{PCS}$/MWh	Artelys
	$runningCapacityFuelCons_i$	0.46	MWh$_{PCS}$/MW.h	Artelys
	$startUpCost_i$	33	€/MW	Artelys
	$Pmaxmax_i$	Country dpdt	MW	Scenario specific
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$minLoad_i$	40%	%Pmax	Artelys
	$Avail_{i,t}$	Time series	-	Artelys
	$gradUp_i$	2%	%Pmax/min	[3]
	$gradDown_i$	5%	%Pmax/min	[3]
	$CAPEX_i$	RetrofitCost	€/MW	NREL
	FOC_i	0	€/MW	No investment
	$CO2Content_i$	0.18	t/MWh$_{PCS}$	Ademe
	$Lifetime_i$	30	year	[1]
State-of-the-art CCGT	$productionHeatRate_i$	1.35	MWh$_{PCS}$/MWh	Artelys
	$runningCapacityFuelCons_i$	0.29	MWh$_{PCS}$/MW.h	Artelys
	$startUpCost_i$	33	€/MW	Artelys
	$Pmaxmax_i$	Country dpdt	MW	Scenario specific

	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$minLoad_i$	40%	%Pmax	[3]
	$Avail_{i,t}$	Time series	-	Artelys
	$gradUp_i$	4%	%Pmax/min	[3]
	$gradDown_i$	5%	%Pmax/min	[3]
	$minOffTime_i$	2	h	Artelys
	$CAPEX_i$	950 000	€/MW	[1]
	FOC_i	23 750	€/MW	[1]
	$CO2Content_i$	0.18	t/MWh$_{PCS}$	Ademe
	$Lifetime_i$	30	year	[1]
Nuclear Power Plant	$Pmax_i$	Country dpdt	MW	Scenario
	$minLoad_i$	40%	%Pmax	[3]
	$Avail_{i,t}$	Time series	-	Artelys
	$Rmax_i$	7%	%Pmax	Artelys
	$genCost_i$	7.4	€/MWh	Artelys
Demand Response	$Pmaxmax_i$	Country dpdt	MW	COWI
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
Interconnectors	$Pmaxmax_i$	Country dpdt	MW	
	$Pmaxmin_i$	2015 capacity	MW	ENTSO-E
	$CAPEX_i$	Country dpdt	€/MW	ENTSO-E TYNDP2014
	$Lifetime_i$	60	year	[1]
Compressed Air Energy Storage[10]	$Pmaxmax_i$	Country dpdt	MW	ESTMAP
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$availability_i$	90	%	Artelys
	$CAPEX_i$	2 146 000 + small country dpdt connection cost	€/MW	ESTMAP
	FOC_i	1.5% of $CAPEX_i$	€/MW	ESTMAP

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[10] The costs of CAES provided in [1] are for a 15 hour discharge time unit.

	$inputEfficiency_i$	81	%	ESTMAP
	$outputEfficiency_i$	81	%	ESTMAP
	$dischargeTime_i$	48	h	Artelys
	$Lifetime_i$	40	year	ESTMAP
Hourly flexibility	$Pmaxmax_i$	No upper bound	MW	ESTMAP
	$Pmaxmin_i$	Country dpdt	MW	Residual capacity
	$availability_i$	90	%	Artelys
	$CAPEX_i$	200 000	€/MW	ESTMAP
	FOC_i	2 800	€/MW	ESTMAP
	$inputEfficiency_i$	0.95	%	ESTMAP
	$outputEfficiency_i$	0.95	%	ESTMAP
	$dischargeTime_i$	1	h	Artelys
	$Lifetime_i$	10	year	ESTMAP
Power demand	$hourlyLoad_{T,t}$	Time series	MW	Scenario specific

Annex: Artelys Crystal

Artelys Crystal Super Grid is a long-term planning tool for power systems, with a special focus on the analysis of the value brought by investments in infrastructure (storage, power plants, interconnectors, etc.). Its development has been funded through a project led by Artelys, financed by the French Environment & Energy Management Agency (ADEME). Artelys Crystal Super Grid has been developed by experts in the fields of optimisation and software development. Artelys is an independent company.

The following sections present the main characteristics of the model.

Artelys Crystal: an efficient and robust technology

The Artelys Crystal platform is dedicated to the optimisation of investments and operations of energy generation, transmission, demand-response, and storage assets. Artelys Crystal adopts a modular structure and allows for a complete and customizable representation of the energy value chain (production, transmission, consumption, markets).

The graphical user interface allows users to easily describe the structure of the portfolio of assets to be studied and the characteristics of these assets (capacity, efficiency, availability, costs, ramping times, minimum off time, GHG emissions, etc.). Advanced data management capabilities allow the user to create scenarios reflecting the uncertainties to which power systems are confronted (production by renewables, outages). Given the characteristics of the power system and a set of scenarios, Artelys Crystal Super Grid optimises the management of all assets: production assets, consumption, storage, demand-response, and interconnectors.

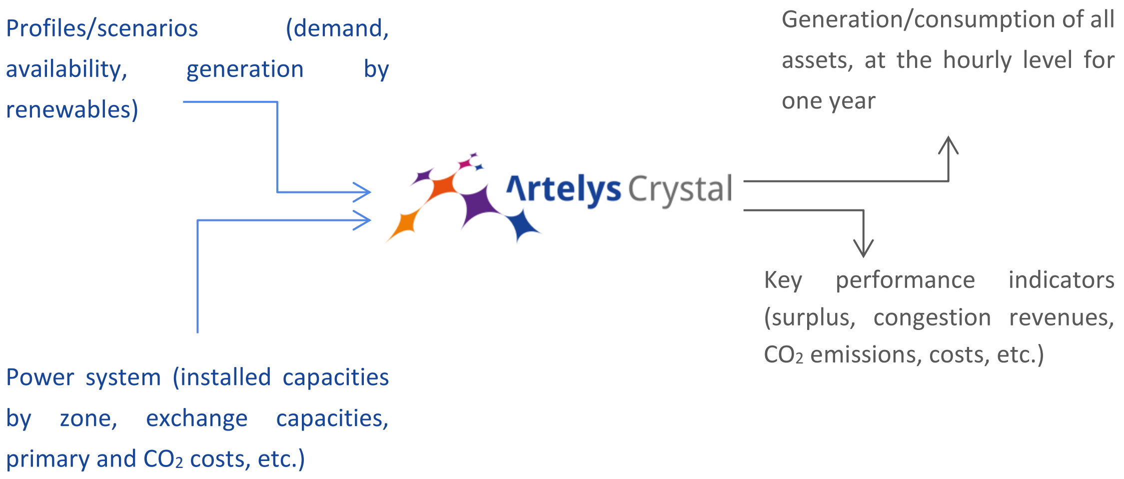
Key performance indicators are then computed from the detailed (generally hourly) optimisation results, allowing analysts to easily and efficiently have access to indicators such as social welfare, consumer and producer surplus, congestion revenues, CO_2 emissions, and more. The consequences of a new build (e.g. an interconnector) on the social welfare, producer surplus, consumer surplus, GHG emissions, etc. can be assessed by selecting two contexts (with and without the interconnector) and selecting the desired indicators (see Figure 4).

Artelys Crystal Super Grid is powered by a detailed bottom-up optimal dispatch model with hourly time resolution (8760 chronological time steps per year) and country-level spatial granularity (finer temporal and spatial granularities can be used depending on the availability of data). In order to produce accurate results a detailed characterisation of the assets is adopted. The following behaviours and constraints can easily be modelled:

- Technical and operational constraints such as:
    - Minimum and maximum on/off time
    - Start-up ramp rates

    - Transmission losses
- Economic characterisation of the system:
    - Primary energy costs
    - Start-up costs
    - Fixed and variable running costs
    - Environmental costs (e.g. CO_2) and costs of not meeting environmental targets
- Environmental constraints
    - GHG emissions
    - Pollutants emissions

The Artelys Crystal platform has been conceived in such a way as to offer Artelys' analysts and advanced users the possibility to modify the way assets are modelled, or to create new kind of assets.



A ready to use cost-benefit analysis tool

Provided with a rich library of physical and financial assets, Artelys Crystal Super Grid is ready for immediate use to quantitatively assess the costs and benefits of infrastructure investments (optimal dispatch mode) and to determine the optimal investments needed to ensure the power system keeps meeting the demand (capacity expansion planning mode).

Powered by the most advanced and reliable optimisation solvers, Artelys Crystal Super Grid simulates the demand-supply equilibrium with an hourly time resolution for a set of interconnected areas (8760 chronological time steps per year). The software optimises the capacity and hourly production of all assets, based on the demand, production costs, technical constraints, and the exchange capacities between areas.

Thanks to the precise implementation of complex constraints such as ramp rates for production and storage assets (e.g. for the modelling of pumped-hydro), Artelys Crystal Super Grid provides a pertinent and reliable analysis of modern power system, and is very well suited to study the integration of renewables, the associated flexibility needs and the role of interconnectors.

The results can be accessed in two forms:

- Hourly production, consumption and flow, on an asset by asset basis (see Figure 1). These results can easily be exported in CSV and Microsoft Excel formats.
- Key performance indicators that facilitate the analysis for a given investment project: surplus by area, congestion revenues, marginal production costs, GHG emissions, etc. (see Figure 2)

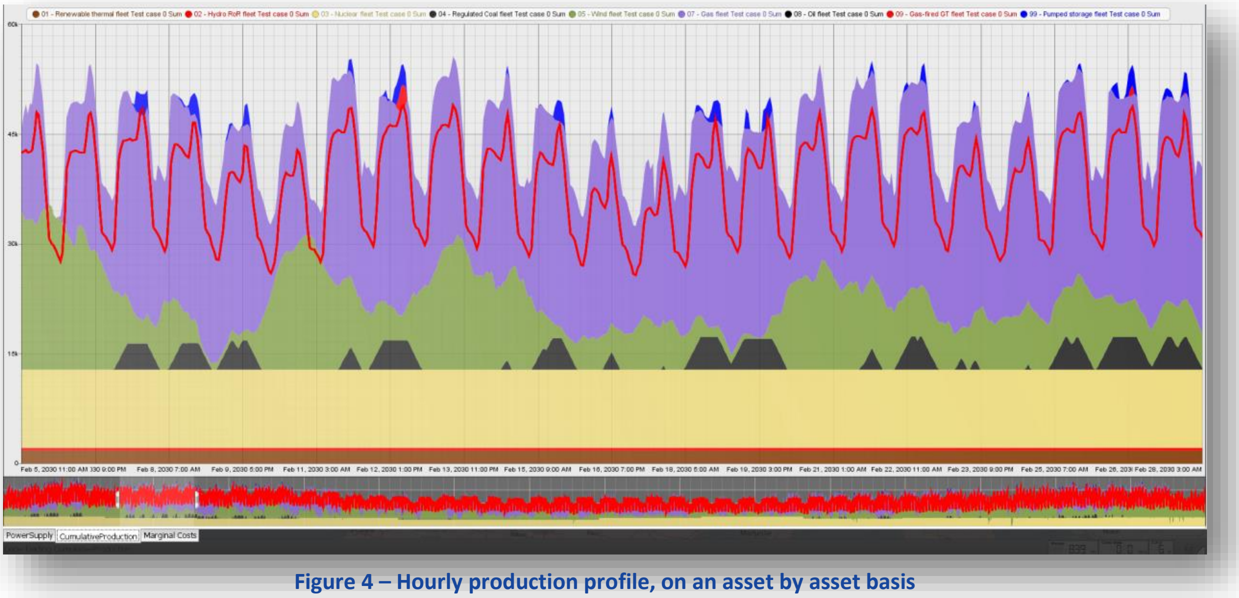


Figure 4 – Hourly production profile, on an asset by asset basis

An intuitive and ergonomic graphical user interface

All Artelys Crystal Super Grid features can be accessed through its graphical user interface (GUI) at all stages: modelling phase, optimisation/simulation phase, and the exploitation of the results. The GUI has been designed to allow analysts to access quantitative indicators that are tailored to the study of interconnector projects, allowing for a rapid and robust exploitation, analysis and valorisation of the results.

Artelys Crystal Super Grid helps analysts manage the complexity of the process of evaluating the value brought by infrastructure development, thanks to:

- Indicators (see Figures 2 and 4)

- Geographical views to easily understand the structure and dynamics of the dispatch and power flows (see Figure 3)
- Cumulated production graphs to understand when the different assets are running (see Figure 1)

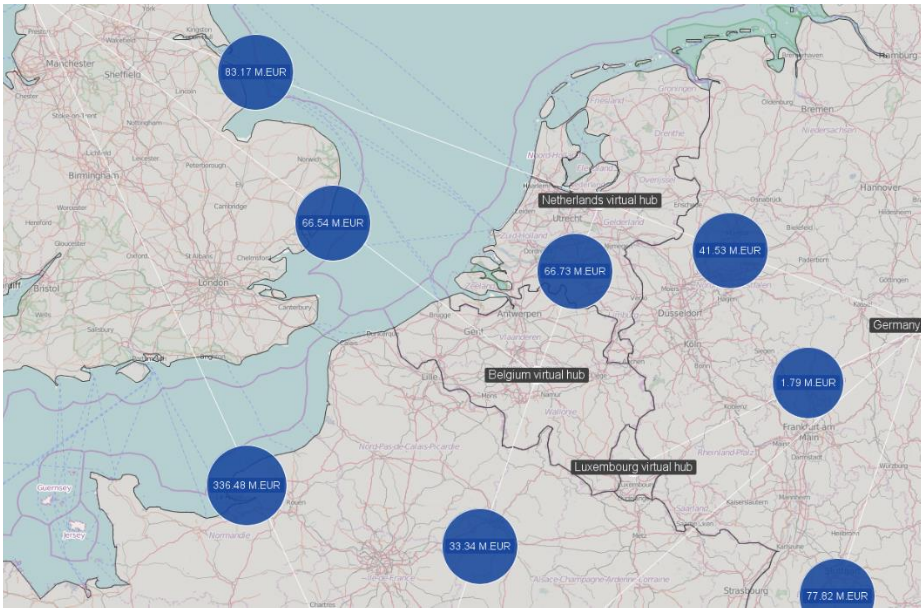


Figure 5 - Example of Key Performance Indicators

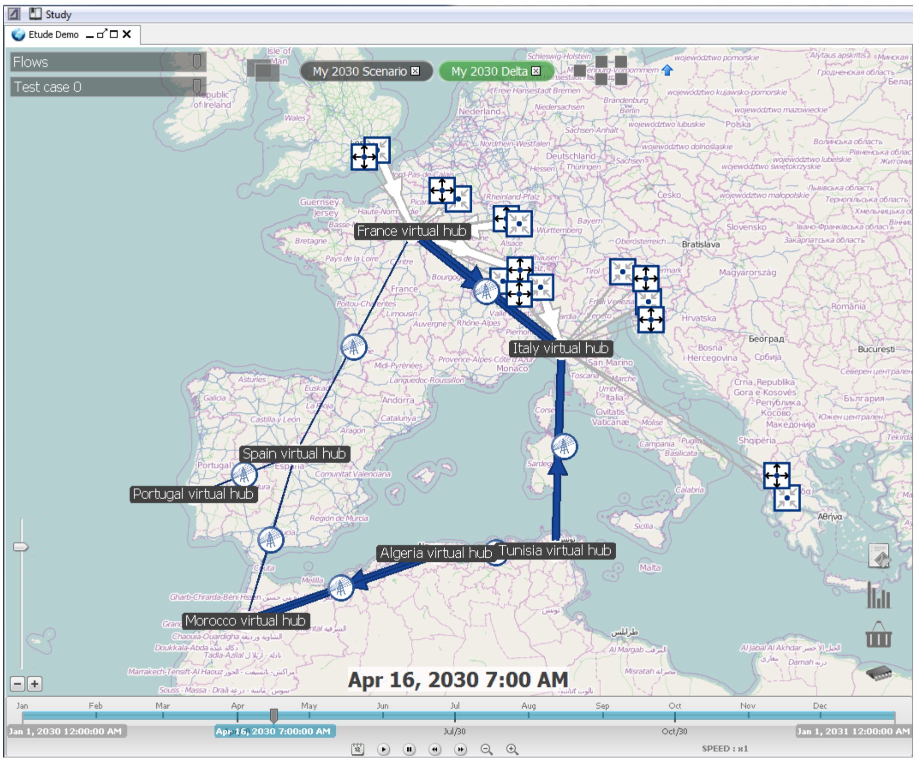


Figure 6 - Power flows

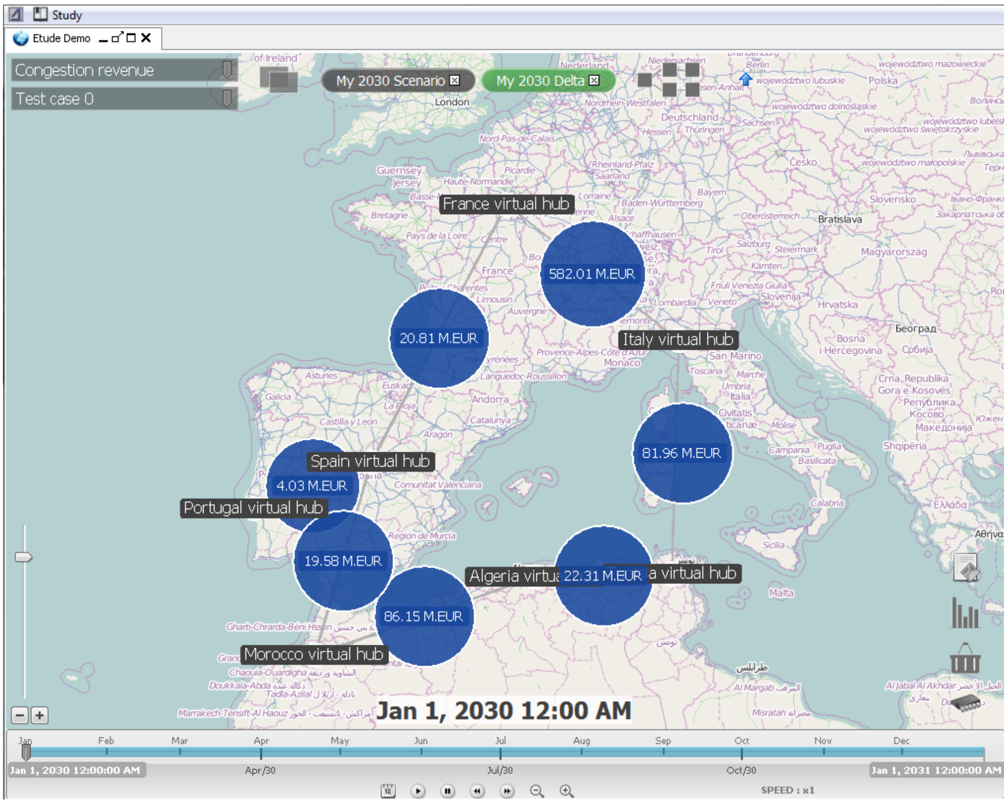
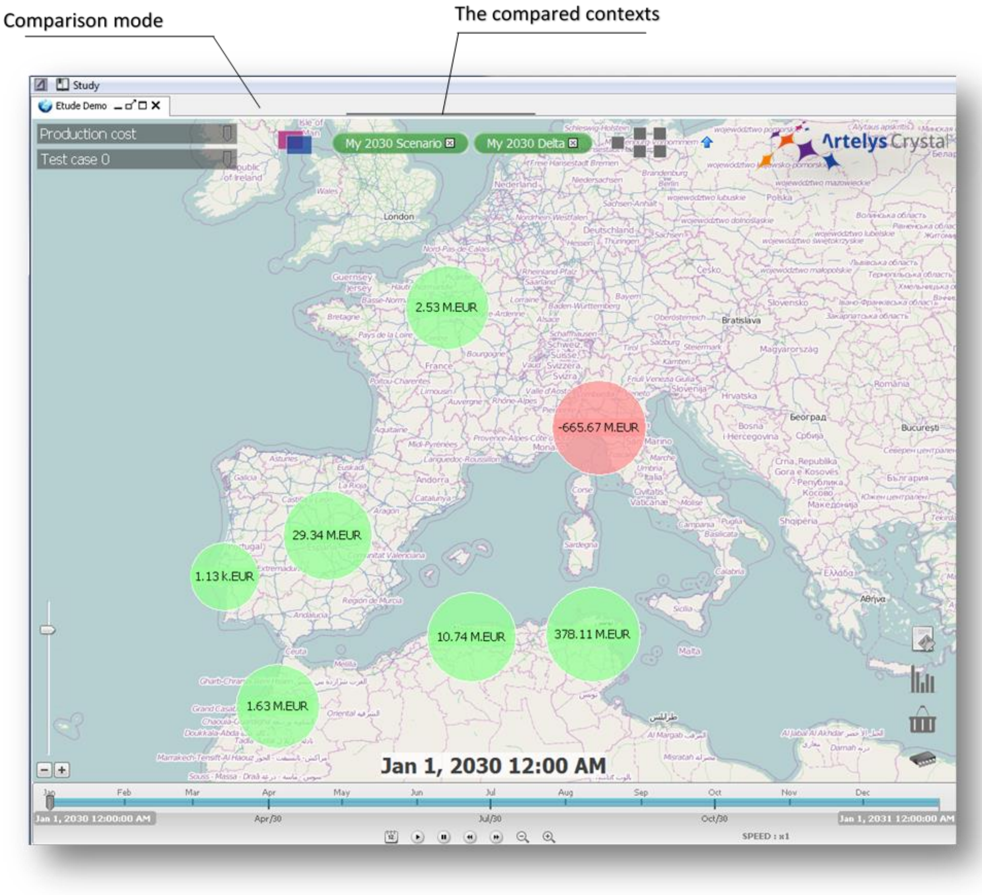


Figure 7 - Congestion revenues

A comparison mode allows Artelys Crystal Super Grid users to quickly and efficiently assess the differences between two contexts (e.g. with and without a given interconnector) for a wide range of metrics: social welfare, producer surplus, consumer surplus, production costs, GHG emissions, etc. (see Figure 5).



Comparison mode

The compared contexts

Figure 8 - Comparison mode

Finally, Artelys Crystal Super Grid allows users to import, create and modify studies very easily, either by duplicating an existing study, or by specifying the characteristics of the power system (installed capacities, availabilities, demand, etc.) in an Excel or CSV file (see Figure 5). All the characteristics of the power system, including profiles such as the hourly demand, can be modified within Artelys Crystal Super Grid.

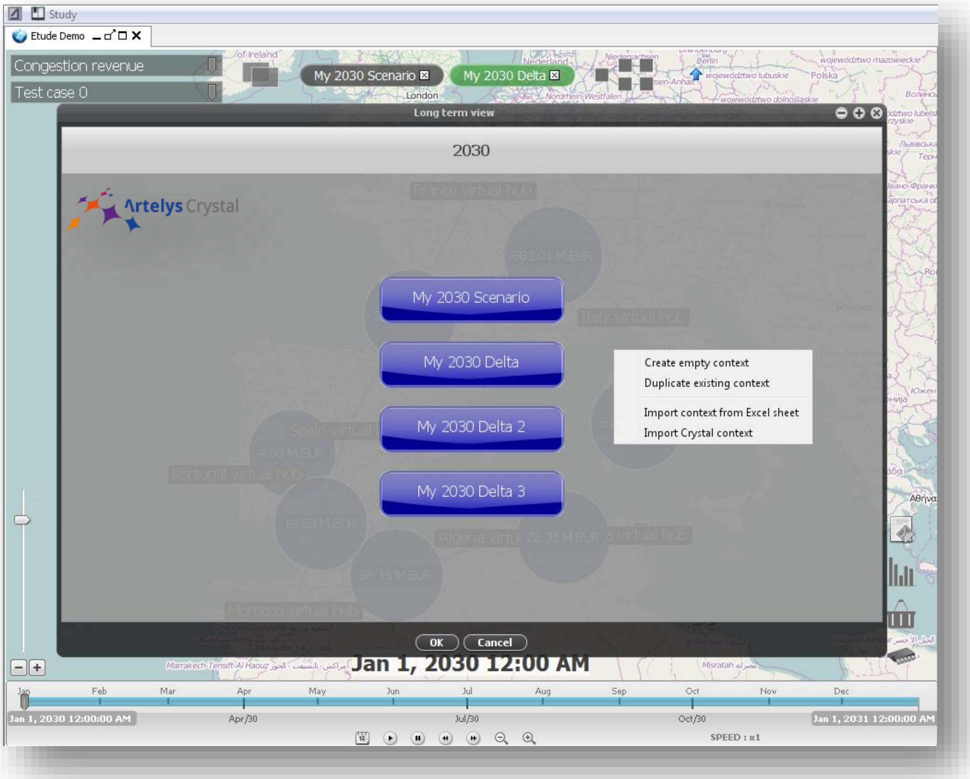


Figure 9 - Creation, duplication, and import/export

A proven performance track record

Artelys Crystal Super Grid is used on a daily basis by Artelys’ engineers to perform studies for its clients. Below is a list of the recent studies performed with Artelys Crystal Super Grid:

- Artelys has been asked by the Medgrid consortium to realise a cost-benefit analysis of trans-Mediterranean interconnectors in a 2030 power system
- Artelys has studied the economic potential and role of storage in France for the French Environment and Energy Management Agency (ADEME). The results of this study have been used by France when designing its energy transition law. Artelys has recently been awarded a study on the role of heat storage, which will be performed with the Artelys Crystal platform.
- Artelys has recently published a study assessing the techno-economic feasibility of a 100% renewable power supply in France at the 2050 horizon. This study was financed by the French Environment and Energy Management Agency (ADEME). During this study, the following investments have been optimised (capacity and location): RES technologies, storage technologies, transmission grid.

- Artelys has recently conducted a study for UFE and BDEW assessing the benefits of adopting a coordinated approach to capacity mechanisms in France and Germany. The impacts of different market design configurations have been assessed on both countries' social welfare, production costs, marginal costs of electricity, and CO2 emissions.
- The French Regulatory Commission of Energy (CRE) has commissioned a number of studies to Artelys in recent years, and has acquired an Artelys Crystal Super Grid licence in order for its team to be able to evaluate the impact on social welfare of interconnectors.
- The Belgian Federal Planning Bureau (FPB) has acquired an Artelys Crystal Super Grid licence to study the impact of policy development (increase of renewable power generation, development of interconnectors, etc.) on the Belgian power system.
- Artelys has been awarded a 3M€ contract by the European Commission to develop a piece of software (Artelys) allowing their analysts to assess the impacts of market design and energy policies.

Bibliography

[1] Joint Research Centre, Energy Technology Reference Indicator, 2014.

[2] “Current and Perspective Costs of Electricity Generation until 2050,” Deutsches Institut fur Wirtschaftsforschung, Berlin, 2013.

[3] “Flexibility options in electricity systems,” ECOFYS, Berlin, 2014.

[4] ESTMAP, Database.