European Network of
Transmission System Operators
for Electricity

Hydropower modelling – New database complementing PECD

V.1.0

12 September 2019

Contents

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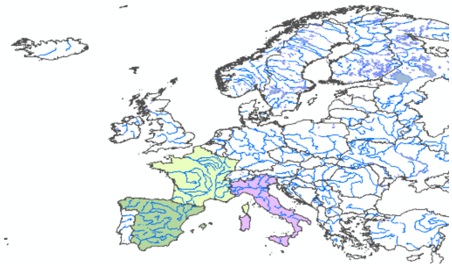
1. Introduction



Available hydropower generation is an important factor in adequacy assessments, as it can have significant impacts on results. Therefore, choosing the appropriate level of detail, evaluating distinct hydrological conditions, and better reflecting the interdependence of hydro generation and climatic conditions, including with other Renewable Energy Sources (RES), is of great importance. More specifically, adequacy modelling requires the use of historical (or synthetic) hydrological profiles for each considered zone, and coherence with other climatic parameters for each scenario increases the quality of the assessment. Unfortunately, the availability of historical/statistical data is not uniform between different regions, being spread and often subject to confidential restrictions.

In previous market modelling studies performed at ENTSO-E (e.g. Ten Year Network Development Plan – TYNDP, Mid-term Adequacy Forecast – MAF), hydro generation data was a simplified, yet representative, collection of the available hydro resources in each market node. Hydropower plants were aggregated in 5 different groups, and data was collected in weekly time resolution. Due to the limited availability in historical data regarding hydro, a simplified way was adopted in order to account for the correlation between hydro inflows and other meteorological variables (e.g. wind, irradiance, temperatures); each year from 1982 to 2015 was classified as being wet, normal, or dry for countries with significant hydro resources. This approach had some limitations, one being that as only 3 different profiles were possible, all climate years had to be rounded to one of the three possibilities. For example, even in a "wet" year, the "rainy season" could start later, and this type of event could not be captured. Furthermore, the database relied on assessments individually made by each country. Methodologies were not aligned and estimations were performed utilizing different data sources, with varying availability and quality.

In order to address the issues mentioned above, a new hydro database has been created, expanding the Pan-European Climate Database (PECD) to include hydropower, using a single source and coherent climatic data.

It is important to note that the hydro database differs from other RES such as wind or solar, where energy production can be directly derived from climatic conditions. For hydro, considering energy storage in the form of water reservoirs is widely present, the efforts in creating the database are focused on determining the energy inflows into the power plants. The inflows, along with reservoir levels, express energy availability at the power plant. Actual energy production is then a decision variable for the optimization problem, which highlights hydropower as an outstanding source of flexibility for power systems.

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2. Objective

The new database aims to advance hydro modelling to support the improvement of market models, tackling existing limitations and creating a platform for further improvements in the future.

The main objectives of the new database are the following:

- Full ENTSO-E perimeter coverage – all members and observer members at the time of its development.
- Provide a comprehensive range of historical data (1982 – 2017) so that distinct hydrological conditions are available and alignment of coverage with Pan-European Climate Database (PECD wind and solar) can be ensured – As data becomes available for more years (e.g. 2018, 2019…), the database will be updated.
- Better correlation between hydrological conditions and other climatic variables, resulting in better historical alignment between hydro and other RES (Wind and Solar) energy availability and production – use the same origin of climatic data as inputs to derive energy availability and production.
- Improve modelling of hydro behavior (e.g. avoiding overestimation of the flexibility of pumping cycles, avoiding closed-loop plants from having access to Natural Inflows of other plants…), more flexible constraints and harmonize assumptions and interpretation of the database.
- More homogeneous quality in the database, centralizing procurement of data and applying the same methodology for the perimeter covered.

3. Hydro technologies - aggregation

In order to model and optimize hydropower generation at a European scale, second order effects need to be taken into account. Due to hydraulic coupling between hydropower plants, operational decisions taken by one plant can affect several others, and at different times. Modelling all individual plants leads then to a need for modelling the full hydro circuit, considering cascade, water travel time and coupling between basins amongst other parameters. Furthermore, inflows would have to be calculated for each individual plant. The data needed for this level of sophistication is simply not available at a Pan-European level for various reasons, including confidentiality restrictions, and this complexity would significantly increase computational requirements of the optimization problem.

To reduce the complexity and overcome data availability issues, aggregation of hydropower plants is key. Careful consideration is needed though, to guarantee main characteristics of hydropower resources are respected, minimizing the loss of information and avoiding severely overestimating or underestimating capabilities.

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Hydropower plants have been aggregated in 4 different categories, according to the following criteria:

a) **Run-of-River and Pondage:** Plants that do not have pumping capacity, do not have reservoirs, or have small reservoirs with a maximum of 24 hours of storage. (Reservoir Capacity / Net Generating Capacity ≤ 24 hours).
b) **Reservoir:** This category contains hydro plants that have reservoirs, but do not have pumping capacity. They are pure generation plants with reservoirs with a storage capacity higher than 24 hours. (Reservoir Capacity / Net Generating Capacity > 24 hours).
c) **Open-loop Pump Storage:** This category contains hydro plants that have Pumping capacity/technology in place, irrespectively of reservoir size, and that have Natural Inflows.
d) **Closed-loop Pump Storage:** This category contains hydro plants that have Pumping capacity/technology in place, irrespectively of reservoir size, and that do not have Natural Inflows.

A brief description of the rationale for such aggregation is presented below:

- Aggregating Reservoir with Pump-Storage plants can lead to an overestimation of the flexibility of pumping cycles (pumps being able to pump and 'overfill' their reservoirs). It is also easier to understand and analyze results by having them separate.

- Within the Pump Storage group, it is important to separate Open Loop (with Natural Inflows) and Closed Loop (no Natural Inflows) plants. Closed-Loop plants add noise and severely reduce the quality of the reanalysis, as their production is not related to inflows.

- Closed-Loop and Open-Loop plants are very likely to present different timewise dynamics. Most of Closed Loop plants will have a daily cycle, while Open Loop plants might have longer cycles. Even considering one less category compared to previous modelling, this new aggregation, to some extent, naturally includes and respects the old "Daily storage" plants, with added benefits of not mixing technologies (Reservoir and Pump-Storages).

- Run-of-River and Pondage – bringing together two, previously separate, categories. Pondage types of plants were not widely used, and the aggregation of them can bring benefits of the modulation capacity within the day. By setting appropriate constraints, it is possible to avoid overestimating such capacity.

- Hydropower plants were aggregated based on the ratio between storage capacity and generation capacity, focusing on respecting timewise dynamics (e.g. daily, weekly and seasonal Reservoirs), but no distinction was made between plants with or without pumping capacity. In the new database, even if not explicitly considered, such timewise dynamics are respected or have reduced need.

- Better alignment with ENTSO-E's Transparency Platform – similar categorization and aggregation of hydro plants.

- Better alignment with hydro modelling done for CORESO's Short-Term Adequacy studies.

4. Construction of the new database

4.1. General Methodology

4.1.1. Energy representation – Natural Inflows

In the context of the database, Natural Inflow is a measure of the energy that can be produced at the hydropower plant by water inflows naturally coming into the plant. In other words, it is a way of translating water volumes (m^3/day) flowing in the rivers/basins into energy (GWh).

4.1.2. Calculation of Natural Inflows

Objectively, the construction of the database consists in calculating Natural Inflows for each plant based on hydrological/climatic conditions of each specific period to be covered. For this database, the chosen period covers the years from 1982 until 2017.

The calculation of Natural Inflows from past climatic conditions was done based on statistical reanalysis correlating historical water volumes (m^3/day) flowing in rivers with the corresponding hydropower production (GWh) for a number of sample years. The transfer function resulting from this process could then be applied to historical water volumes (m^3/day) for other years, inferring the corresponding GWh.

More details about the input data and the statistical reanalysis methodology are given in the rest of this section.

4.2. Input data

4.2.1. Climatic data

For the purpose of building the hydro database, the most interesting variable is the “total unregulated inflow”, and this was procured from SMHI (Swedish Meteorological and Hydrological Institute). SMHI calculated this variable using their E-HYPE[1] (European Hydrological Predictions for the Environment and consists of high resolution) model, developed by SMHI, that calculates a number of different variables based on reanalysis of climatic data originated from Clim4Energy – Copernicus Project. The climatic data used by SMHI are coherent with data used in the development of Wind and Solar databases, ensuring a good correlation between all meteorological variables and consequently RES outputs (wind and solar) included in PECD.

The water volumes inflow data in summary:

- Origin from Clim4Energy – Copernicus;
- Modelled hydrological data for European countries ;
- Period covered 1981-2017;

[1] More information about SMHI’s E-HYPE model can be found at http://hypeweb.smhi.se/

- Selected result variable is ***total unregulated inflow*** catchment by catchment (see also Figure 1 with an example for Italy);
- Computed by hydrological modelling with the E-HYPE model ;
- **m^3/d** delivered as time series with daily resolution, catchment by catchment.

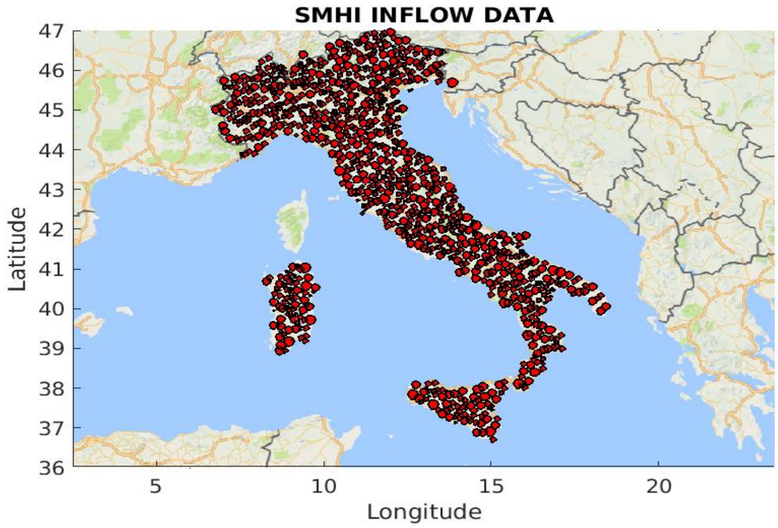

Figure 1 Example of catchment coverage in Italy (more than 1000 catchments - each red circle represents a different catchment)

4.2.2. Hydropower plants – Technical information and historical production data

An extensive data collection was performed, covering technical information about each hydropower unit (including its technology type as defined in the aggregation criteria), their hourly production (MW), hourly pumping (MW) and unit availability status (e.g. maintenance) covering 8 years.

Data collected – 8 years of statistics:

- Unit-by-unit generation and pumping capacities, as well as other technical parameter – aggregation when more granular information not available;
- Reservoir capacities;
- Time series of Generation/Production (MW) – same granularity as provided in the first item;
- Time series of Pumping (MW) whenever applicable – same granularity as provided in the first item;
- Time series of unit availability status – same granularity as provided in the first item.

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4.3. Statistical Reanalysis

In order to calculate/infer Natural Inflows from past climatic conditions, a new methodology was developed. In simple terms, it is based on statistical analysis with the following idea:

- Building, using machine learning/neural networks, a transfer function between SMHI E-HYPE reanalysis data (unregulated inflows data (m^3/d), 1982 – 2017) and the water inflow at the powerplants inferred from their production (statistical data from 2010 to 2017)
- Using this transfer function to infer what the Natural Inflows (GWh) would have been since 1982;

The methodology to implement this idea can be described in some steps, as follows:

1. *SMHI's Inflow data Normalization*

SMHI inflow time series were normalized to obtain zero-mean and unit standard deviation distributions. The normalization step ensures an optimal data decomposition in the dimensionality reduction phase.

$$\hat{F}(t) = \frac{F(t) - \text{mean}(F(t))}{std(F(t))}$$

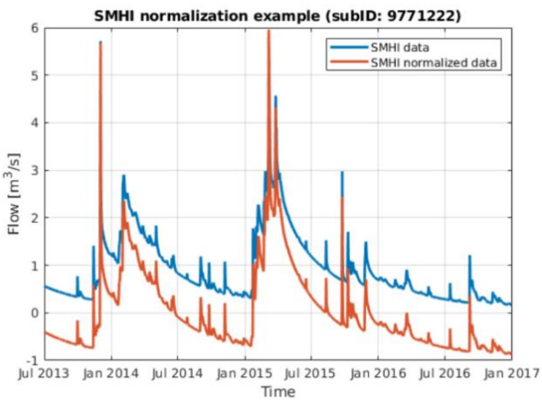

Figure 2 Normalization of inflow data

2. *Singular-value decomposition*

Dimensionality reduction: Proper orthogonal decomposition of SMHI inflow data. The reduction of the input dimensionality from ~1000 to ~50-150 variables leads to a drastic reduction of CPU requirement and avoids regression overfitting.
Derivation of a reduced set of input variables as a linear combination of original SMHI inflows.

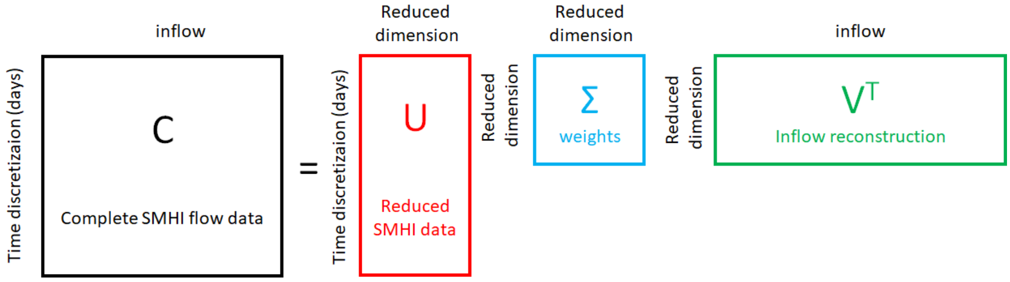

Figure 3 Proper orthogonal decomposition of Inflow data

3. *Statistical/historical data analysis*

Quality checks are performed on the statistical production data. In general (but customizable to account for country specificities):

- For each plant, data must be available for at least 10% of the period covered by the reanalysis – otherwise, the plant is discarded;
- For each plant, data has to be "non-zero" for at least 10% of the period covered by the reanalysis – otherwise, the plant is discarded;
- Data is mean-resampled with frequency *D*, and groups with more than four consecutive maintenances (1 for unavailable data) are discarded.

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4. *Transfer function derivation*

The transfer function is estimated by a plant by plant SMHI/hydropower regression by least squares minimization. Least significant regressors are eliminated based on “p-value” and followed by a verification phase for overfitting.

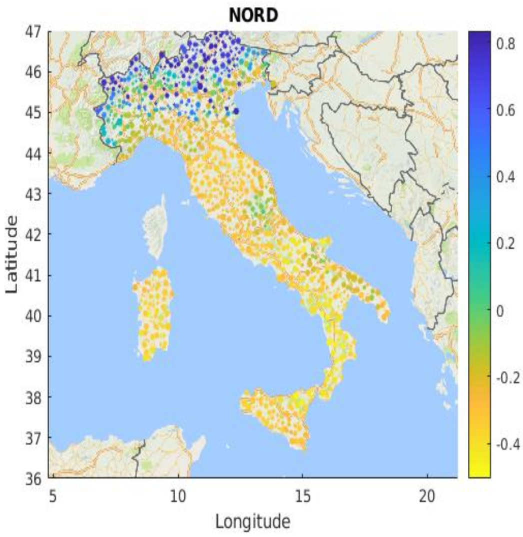

Figure 4 Correlation: Inflows per catchment and plant production

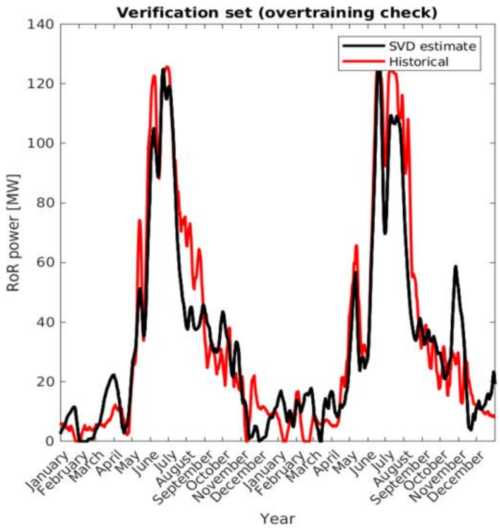

Figure 5 Overtraining check

5. *Post-Processing and analysis in the frequency domain*

The production data has been analysed with a Fourier transform to show its spectrum, indicating yearly, seasonal and/or weekly dynamics, which are expected for regulated plants but not so for pure Run-of-Rivers. Form this analysis, it is possible to identify spurious Run-of-River, influenced by other regulated hydro plants.

$$\overline{P_n} = \sum_{k=0}^{K-1} P_k e^{-\frac{2\pi \cdot i \cdot n \cdot k}{K}}$$

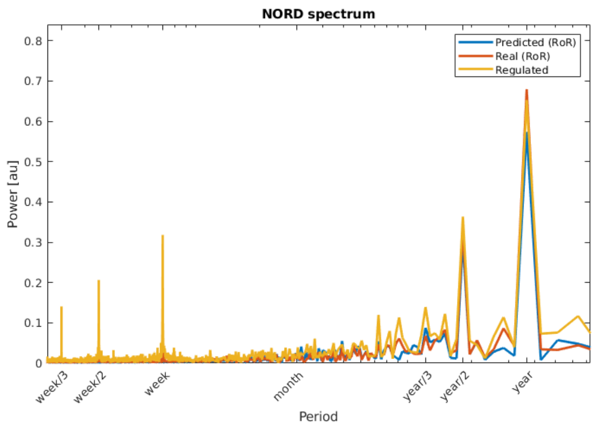

Figure 6 Analysis on the frequency domain

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6. *Zone-wise aggregation of results*

Reaggregation of power plant by power plant estimated inflow:

- Daily (GWh) for RoR & Pondage;
- Weekly (GWh) for Reservoir and Open Loop – Pumped Storages.

The regression is validated with an independent input dataset – part of the statistical/historical data is not used in the regressor training. This also allows checking the presence of overfitting.

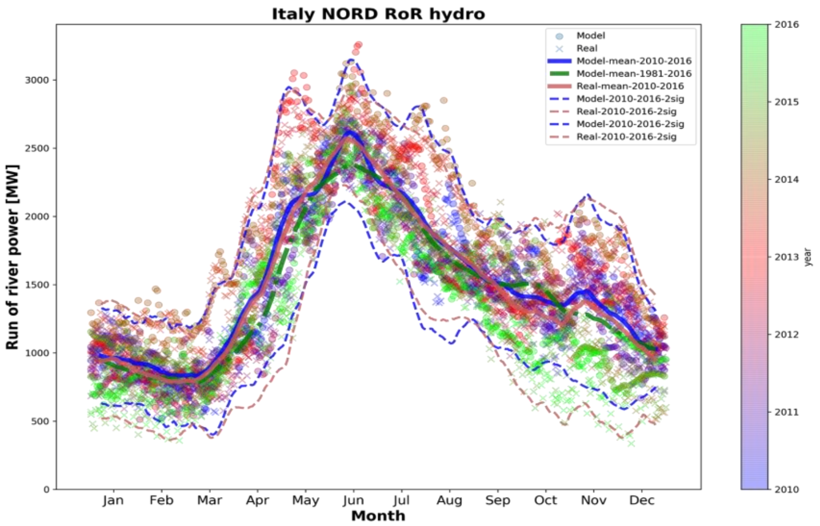

Figure 7 Overview of aggregated results for a region

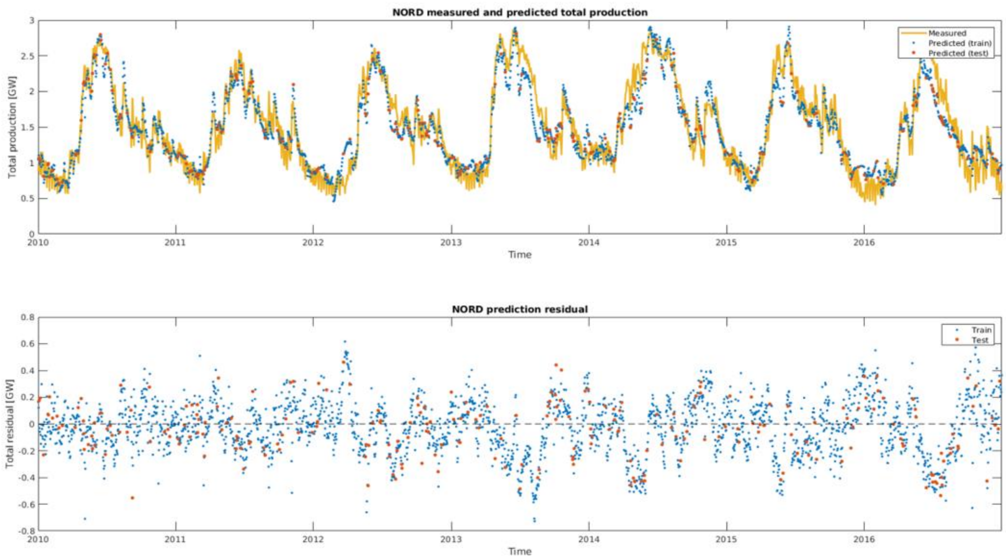

Figure 8 Model verification

7. Population of target template and reporting on results

For each market node to which this methodology was applied, a report is generated indicating overall quality, specific issues that might have been found and plants for which the data could not be used (plants removed from the reanalysis).

The target template is populated with the Natural Inflows resulting from the reanalysis and the reference capacity (MW) of the power plants that were considered in the reanalysis (historical data met the criteria).

8. Post-processing of aggregated results – accounting for "missing generation"

Historical data is not always available for the entire hydro fleet of the country. For example, it might be extremely difficult to obtain in good quality and even to treat historical data from very small plants scattered around the country, even if their total capacity can be significant compared to the rest of the fleet. It is therefore not possible to include them directly in the regression/reanalysis, but it is still necessary to take into account their contribution to the GWh energy availability/production in the country.

In some other cases, as mentioned in step 3, it might be the case that the quality of data provided for some plants (whatever the size of the plant) is not of enough quality to be included in the reanalysis. As in the previous case, it is still necessary to take their energy contribution into account, so something needs to be done.

To account for this "missing generation", a simple approach was taken. Natural Inflows were rescaled linearly, taking as base weighing criteria the Net Generating Capacity. The reference capacity (MW) – mentioned in step 7 – was compared to the total capacity communicated by the TSO in PEMMDB data collection, for each technology type in the country/market node, and inflows were rescaled up with (generally) the same ratio. This assumes that the missing plants would have a very similar behaviour/productivity to the average plant in the same category. While this might not be the most accurate assessment, it is indeed a relatively good approximation, and definitely better than simply not rescaling and ignoring the potential from the "missing" plants.

The resulting Natural Inflows were compared to previous hydro data to make sure they are in a similar statistical range, and some minor adjustments were applied in a limited number of market nodes to account for geographical and technological specificities.

4.4. Temporal granularity of outputs

The inflow input data used (from SMHI) had daily granularity and historical data was provided hourly.

The reanalysis could then be performed to output results in daily granularity, which was the case for the "Run-of-River and Pondage" category. For the other categories, since they involve storage, it is more difficult to directly correlate inflows and production at such fine granularity. It increases noise without bringing much added value to the simulations, since some water is "always" available at the reservoirs and peaks of inflow during a week will not significantly affect the decision process of using/storing water. For that reason, for the other categories (Reservoir and Open Loop Pump Storages) the inflows have been calculated with weekly granularity, while Closed Loop Pump Storages do not have Natural Inflows by definition.

Constraints, in general, follow the same granularity as the category they refer to. For Closed-Loop Pump Storages, constraints follow the same granularity as Open-Loop Pump Storages for ease of understanding.

In a nutshell:

- Run-of-River and Pondage: Inflows and constraints with daily resolution;
- Reservoirs: Inflows and constraints with weekly resolution;
- Open Loop Pump Storages: Inflows and constraints with weekly resolution;
- Closed Loop Pump Storages: No inflows, constraints with weekly resolution;

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4.5. Constraints

Environmental restrictions, cascading, seasonality and climatic conditions amongst other factors, especially when considering aggregation of plants, can impact the real capabilities and behavior of hydro plants. Constraints are an extremely important tool to capture such behaviors and restrictions. As an example, in reality, the maximum generating capacity of the aggregated virtual plant is not simply the sum of the capacities of each individual plant, and it can change throughout the year.

TSOs were asked to provide all relevant constraints for their country, and these can be Climate Year dependent so that they can correctly represent constraints/behaviors of specific climatic conditions.

In some cases, constraints were centrally proposed based on the statistical data provided. Even in these cases, TSOs were asked to check and inform/adjust whenever needed.

Constraints are defined in the same time-granularity as the Natural Inflows for the category they represent.

Below there is a table with the type of constraints, what they mean, and how they were calculated (if centrally proposed).

Constraint	Meaning/implementation in models	ENTSO-E centrally proposed
Minimum Generated Energy (GWh/time granularity)	This means a minimum amount of energy that Market Models will have to dispatch in the concerned period (time granularity in its definition), regardless of inflows – reservoir levels could be decreased. It can, for example, represent minimum water releases required due to environmental reasons.	Not centrally proposed. Country-specific type of constraints.
Maximum Generated Energy (GWh/time granularity)	This means a maximum amount of energy that Market Models will have to dispatch in the concerned period (time granularity in its definition), regardless of inflows – water could be spilled if inflows are too high. It can, for example, represent maximum water release restrictions due to environmental reasons.	Not centrally proposed. Country-specific type of constraints.
Minimum Pumped Energy (GWh/time granularity)	This means a minimum amount of energy that Market Models will have to pump in the concerned period (time granularity in its definition). This can be used, for example, to model known pump storage behaviours.	Not centrally proposed. Country/Plants specific type of constraints.

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Maximum Pumped Energy (GWh/time granularity)	This means a maximum amount of energy that Market Models will have to pump in the concerned period (time granularity in its definition). This can be used, for example, to model known pump storage behaviours.	Not centrally proposed. Country/Plants specific type of constraints.
Minimum Generation (MW)	This is a minimum generation (MW) to be applied at every hour of the simulation (for the time granularity it refers to). It is not the same as a “minimum stable level”. It can be used for example to model RoR & Pondage output, to prevent Market Models from storing all the water during some hours (generation = 0 MW) to generate at maximum for prolonged periods later. If some true RoR (no reservoir at all) are present in the mix, there will always be some production.	This constraint was centrally proposed for RoR and Pondage category, using the following methodology: 1. Consult the statistics for each day (day 1 of each year, day 2 of each year, day 3 of each year, and so on) what was the minimum production (MW) of all RoR and Pondage together. 2. Then, calculate what was the proportion of this minimum production on the corresponding Natural Inflow from the reanalysis. 3. Apply this proportion on the Natural Inflows from the reanalysis for all years to calculate what would be the minimum generation and apply that as Min. Gen. constraint - so we have a Min. Gen. constraint which is Climate Year Dependent, varying according to the inflows of each particular year.
Maximum Generation (MW)	This is a maximum generation constraint to be applied at every hour of the simulation (for the time granularity it refers to). It can be used to represent, for example, cascade and environmental restrictions that limit the total output. As another example, it can represent the loss of power capability due to lower reservoir levels (loss of head).	This constraint was centrally proposed for Reservoir and Open Loop categories, using the following methodology: To define the constraint to be applied at each week, check all years in the historical data to find the maximum production, looking at week, week+1 and week -1. This maximum production encountered in the statistics is then proposed as Maximum Generation constraint. Concretely, to define the constraint for week 10, historical data from weeks 9, 10 and 11 were checked.

Minimum Pumping (MW)	This is a minimum pumping constraint to be applied at every hour of the concerned period (time granularity in its definition). It is not the same as a "minimum stable level". It can represent known behaviour of pumping plants. In any case, it is unlikely this will be of use given the definition, and some further developments are needed to best use this constraint.	Not centrally proposed. Most likely will not be of use under its current definition.
Maximum Pumping (MW)	This is a maximum pumping constraint to be applied at every hour of the concerned period (time granularity in its definition). It can be used to represent limitations due to water availability and other restrictions.	Not centrally proposed. Country/Plants specific type of constraints.
Reservoir level at beginning of week (GWh)	This represents the level of the reservoir at the beginning of each week. This constraint is not imposed throughout the week, only for the first hour. It can be used to define trajectories of reservoirs, using country specific knowledge of the water usage policy and market conditions. The value for the first week is of particular importance, as it can set the initial reservoir level for the Market/Adequacy simulations. It is preferred that Reservoir trajectory boundaries are defined (as in the next two constraints) compared to a strict reservoir trajectory definition imposed by this constraint.	Not centrally proposed. Country/Plants specific type of constraints.
Minimum Reservoir levels at beginning of each week (ratio 0<=x<=1.0)	This constraint, combined with the "Maximum Reservoir levels at beginning of each week", set boundaries for the reservoir level trajectory. This type of modelling allows some degree of freedom for Market Tools to optimize the use of water when compared to strict reservoir trajectories otherwise imposed by the "Reservoir level at	Not centrally proposed. Country/Plants specific type of constraints.

	beginning of week", hence being the preferred option. This constraint imposes the minimum level the reservoir must comply with at the beginning of each week.	
Maximum Reservoir levels at beginning of each week (ratio 0<=x<=1.0)	This constraint, combined with the "Minimum Reservoir levels at beginning of each week", set boundaries for the reservoir level trajectory. This type of modelling allows some degree of freedom for Market Tools to optimize the use of water when compared to strict reservoir trajectories otherwise imposed by the "Reservoir level at beginning of week", hence being the preferred option. This constraint imposes the maximum level the reservoir must comply with at the beginning of each week.	Not centrally proposed. Country/Plants specific type of constraints.

5. Overcoming issues and data limitations

Ideally, data was collected at unit-by-unit level, for the entire hydro fleet of each country. Due to unavailability of data, confidentiality constraints, and in some cases even due to the sheer number of very small plants, this was not possible for all countries.
In the table below there is a summary of issues encountered and actions taken to resolve/mitigate them.

Issue	Impact	Action
Data not available at unit-by-unit level – aggregated by powerplant/dam	Minor, a little bit more difficult to report and take into account effects of maintenance – Maintenance of 1 unit in a plant may not result in any change for the aggregated production/pumping.	None needed.
Very small hydro plants - not feasible to collect/provide individual data. Data provided aggregated for all such plants (e.g. all small RoR in the country reported as 1 plant.)	The quality of the reanalysis can be reduced, due to the fact it is not possible to "locate" them and properly correlate inflows of certain catchments with the production – plants can be all over the country. If they comprise a reasonably small share of the capacity, the impact is minor.	No action taken for the reanalysis. Quality checks on results, and some post-processing needed in some cases
Data aggregated by region. Many plants represented as only one, covering big geographic areas.	Quality of reanalysis severely impacted. It is not possible to "locate" the plants and properly correlate inflows of certain catchments with the production – plants can be all over the region.	Engage with TSO to get more granular data. In case not possible, post-processing of reanalysis – results are not good anyway, but with post-processing, it was possible to bring annual Natural Inflows to realistic numbers.
Production/Pumping data not available at all	Part of the capacity in the country could not be reanalysed. The resulting GWh refers only to what could be calculated from the plants for which data was provided. Database would have missing GWh, as the energy produced by such plants is not being considered.	Post-processing rescaling GWh calculated by the reanalysis. In most cases, a simple linear rescaling of the GWh based on MW capacity.
Data about unit/plant availability (maintenance, plant disconnected, fully available, no data) not provided	Knowing maintenance status helps the reanalysis to better understand the correlation between inflows and production. For example, it can explain why in some instance you may have high inflows and still zero production. Not knowing can reduce the quality of the reanalysis, but not to a big extent.	A methodology was developed to detect at least the most obvious maintenances. This avoids the more extreme cases of misalignment between inflow and production, which is good enough to ensure

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		the quality of the reanalysis is not significantly impacted.
Technology type does not necessarily match the real behaviour of some plants. (e.g. a RoR plant just below a Reservoir plant, with no new natural inflows between the two, behaves exactly like the Reservoir plant)	This can reduce the quality of the reanalysis, as statistical production does not match the expected behaviour for that technology.	Liaison with TSO. When such cases were identified, technology types were adjusted to ensure energy is allocated to the correct category.
Historical data not available for the target of 8 years of statistics	The quality of the reanalysis generally increases with the number of observations, so having fewer data can lower its quality.	It is difficult to tell exactly by how much the quality would be reduced, but even in the cases where only 3 years of statistics were available, post-processing and quality checks have shown results are still aligned with historical data and expectations.

6. Overview of hydropower modelling based in the new database

Run-of-River & Pondage

Plants with very small reservoir: (Reservoir Capacity / Net Generating Capacity ≤ 24 hours)

Daily natural inflows

Max and Min (centrally proposed) generation (MW) Constraints

Reservoir

Plants with bigger reservoir: (Reservoir Capacity / Net Generating Capacity > 24 hours)

No pumps

Weekly natural inflows

Max (centrally proposed) and Min generation (MW) Constraints
Energy and reservoir level constraints

Open Loop Pump Storages

Plants with pumps

Any reservoir size

With Natural Inflows

Weekly natural inflows

Max (centrally proposed) and Min generation (MW) Constraints
Pumping, energy and reservoir level constraints

Closed Loop Pump Storages

Plants with pumps

Any reservoir size

No Natural Inflows

Max and Min generation (MW) Constraints

Constrained by reservoir size and max capacity, but Pumping, energy and reservoir level constraints possible

ENTSO-E AISBL • Avenue de Cortenbergh 100 • 1000 Brussels • Belgium • Tel + 32 2 741 09 50 • Fax + 32 2 741 09 51 • info@entsoe.eu • www. entsoe.eu