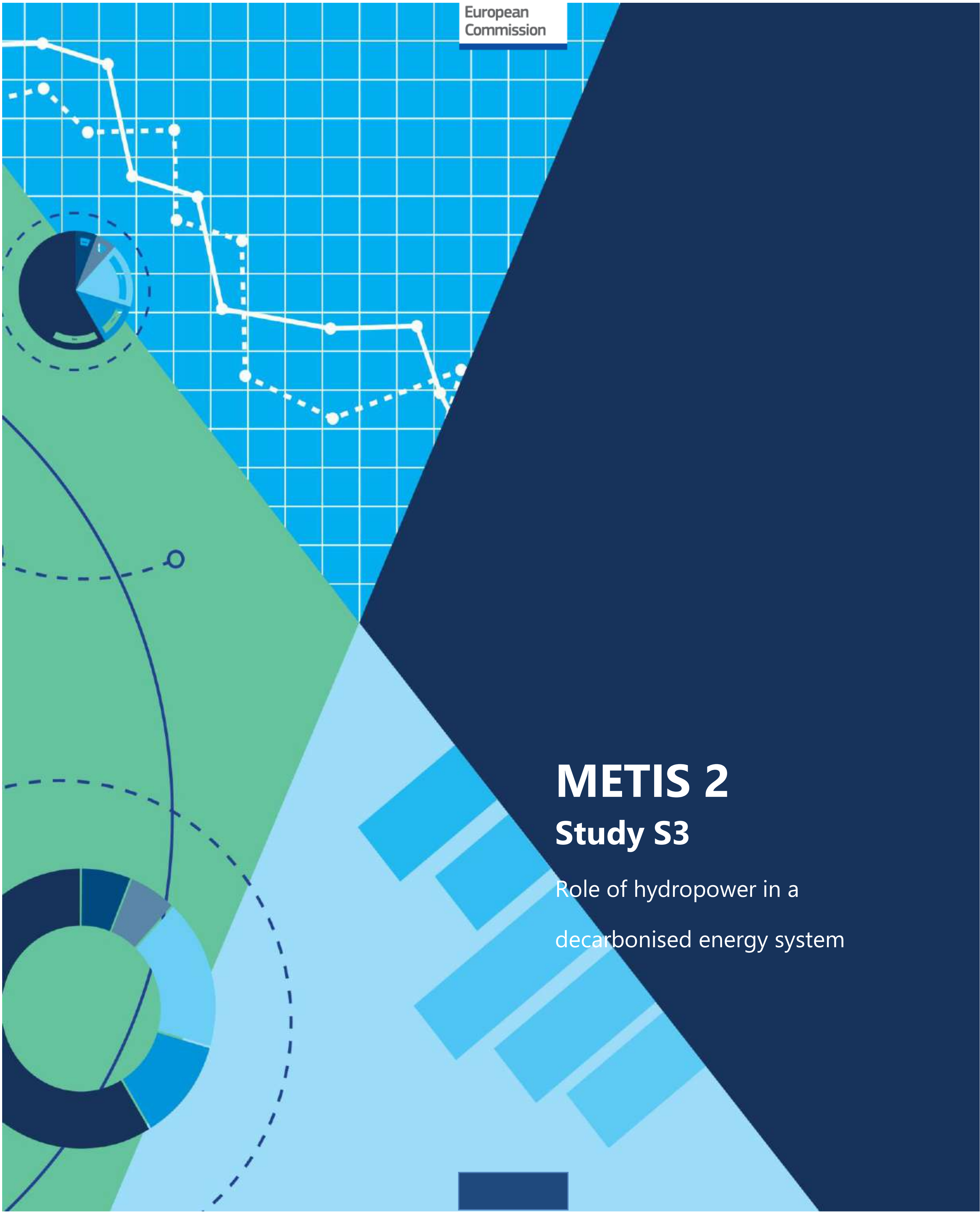

METIS 2

Study S3

Role of hydropower in a

decarbonised energy system

LEGAL NOTICE

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1. ABBREVIATIONS AND DEFINITIONS

1.1. ABBREVIATIONS

Abbreviation	Definition
CAPEX	Capital Expenditures
EFLOH	Equivalent Full Load Operation Hours
ENTSO-E	European Network of Transmission System Operators for Electricity
Eurostat	Statistical office of the European Union
LCOE	Levelised Cost of Electricity
OPEX	Operational Expenditures
RoR	(Hydro) Run-of-River
SDDP	Stochastic Dual Dynamic Programming
SFS	Statistical Factsheet (from ENTSO-E)
SMHI	Swedish Meteorological and Hydrological Institute
TSO	Transmission System Operator

1.2. METIS CONFIGURATION

The configuration of the METIS model used for this study is summarised in Table 1.

Table 1: METIS configuration

METIS Configuration	
Version	METIS v2.0 Beta (non-published)
Modules	Energy system integration module
Scenario	METIS 1.5 scenario from METIS 2 - Study S6
Time resolution	Hourly (8760 consecutive time-steps per year)
Spatial granularity	Member State

2. INTRODUCTION

The initial objective of *Study S3 – Role of hydropower in a decarbonised system* was to improve the hydro dispatch strategy of flexible hydro assets in the METIS model. Instead of relying on guidance curves based on historical data, the idea was to incorporate a forward-looking view, that would reflect the full flexibility offered by hydropower plants and allow modelling a more realistic dispatch of these.

At the start of this study, it became clear that the data source for the initial METIS hydro power model, this is, ENTSO-E's Transparency Platform[1], was inaccurate in terms of *envelope* parameters: both the annual hydro power generation statistics and the installed capacities were not aligned with data reported by Eurostat[2] or national Transmission System Operators (e.g. RTE and REE, the French and Spanish TSO, respectively). Depending on the country, the deviations could be important. To deal with this question, we have updated those parameters and aligned them with historical Statistical Factsheets ("SFS") from ENTSO-E[3]. The SFS have shown to be more reliable, and are consistent with the data published by Eurostat[4]. This results in a more accurate view in terms of installed hydro capacity and annual generation volume, and leads to realistic annual running hours. Given that the goal of the study was to investigate rather delicate effects (fine-tuning of guidance curves, assessing the impact of climate change), it was important to ensure accuracy and thus to deal with data quality first. The details of the update are laid out in the Annex.

Next, in order to improve the dispatch strategy of hydro reservoir assets in METIS, it was necessary to represent the stochastic nature of hydro inflows for both run-of-river and reservoir assets. Not taking uncertainties into account could lead to an overestimation of the flexibility available to the system. We seized the opportunity to perform a second upgrade of the hydro model: we equipped METIS with variable inflow profiles (time series data) for 28 historical weather years, in line with the modelling of other renewable energy sources (solar PV & wind). This upgrade is crucial, since the relative variability of annual generation for hydro power is typically much wider than the variability of other renewable energy sources. Furthermore, in order to quantify the impact of climate change on hydro generation (and the full power system), also a variant of the hydro inflow time series / profiles, impacted by climate change, was created. How those different hydro inflows were constructed for METIS' full geographical perimeter is explained in sections 3 and 4.

Building further on these upgrades, it became possible to update the guidance curves of hydro reservoir assets. To perform this exercise, we resorted to Stochastic Dual Dynamic Programming (SDDP), a state-of-the art modelling approach for hydrothermal power systems. SDDP provides a numerically efficient way to calculate the optimal dispatch of hydro reservoir assets under uncertainty, without incorporating perfect foresight. The full power system model of METIS was transferred to SDDP, which allowed for an offline calculation of the optimal hydro strategy with SDDP. Last but not least, new guidance curves were extracted from the simulation results of SDDP, and fed back to METIS. A detailed explanation of the approach is discussed in section 5. Finally, the result of the guidance curve update is discussed in section 6, including the impact of the climate change variant (section 7).

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[1] (ENTSO-E Transparency, 2020)

[2] (Eurostat, 2020)

[3] (ENTSO-E SFS, 2020)

[4] A dedicated section focusing on the review of the hydropower model parameters and providing details on the discrepancies is available in (Artelys, 2021)

3. REVIEW HYDRO INFLOW PROFILES

In order to characterise the uncertainty of hydro power generation, the first step is the construction of a set of stochastic hydro inflows for the geographical scope covered by the METIS model.

Those hydro inflows will be used in two ways:

1. Create a set of stochastic inflow profiles for the SDDP model, as an input to calibrate guidance curves that integrate a forward-looking view of the power market (see section 5).

2. Create inflow profiles for METIS for 28 historical weather years. This enables the simulation of hydro variability (intra-annual and in terms of annual envelope) in the METIS model. Simulating synchronously the weather years for different variable renewable energy sources ensures consistency because spatial and temporal correlations between risk factors are implicitly reproduced, i.e.:

    - correlations between hydro Run of River (RoR) and reservoir inflows in a given country;

    - any correlations that may exist between (annual) solar PV or wind generation and (annual) hydro production – for instance, correlation with solar PV exists in countries where hydro is driven by precipitation;

    - any correlations that may exist between thermosensitive power demand and hydro production (through temperature) - these effects are expected in countries where hydro is driven by ice melting;

    - correlations between the hydro generation of different countries.

To construct the stochastic hydro inflows, we exploited the E-HYPE database from the Swedish Meteorological and Hydrological Institute[5]. The next paragraphs explain in detail how the inflows were calibrated for Run-of-River and Reservoir assets.

3.1. CONSTRUCTION OF STOCHASTIC RoR HYDRO GENERATION PROFILES

The two main data sources used to construct stochastic RoR hydro generation profiles are:

1. The E-HYPE data: a database consisting of daily naturalised[6] river flows at thousands of measurement stations throughout Europe, over the period 1989-2018 (see Figure 1);

2. ENTSO-E Transparency data: data for aggregated RoR power generation per market zone, at hourly resolution, over 2016-2018.

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[5] (SMHI, 2019)

[6] This term refers to the scientific method to decorelate the observed river flow from other factors (e.g., human influence) and re-create somehow the “natural” river flow

Figure 1: Locations of the SMHI Measurement Stations from E-Hype in Europe

As mentioned earlier, the ENTSO-E Transparency data for aggregated power generation is not suitable to estimate envelope parameters, such as the total annual generation. Nevertheless, the data can still be exploited to characterise the intra-year production profiles. Still, the horizon of available data is rather limited given that the Transparency platform only started operating in 2015, and for some countries, there are data missing in the first months of operation.. Therefore, the adopted strategy was:

1. Rescale the ENTSO-E generation time series data, such that it respects the annual envelope parameters determined from the Statistical Factsheets and Eurostat.

2. Resample the (hourly) ENTSO-E generation time series data at daily granularity to bring it to the same resolution as the inflow data.

3. Per country, calibrate a mathematical relationship between the E-HYPE inflows and the ENTSO-E RoR production data through a regression model. The calibration period is defined by the common data sample (2016-2018). The regression variables are:

    - the instantaneous inflows (expressed in m^3/day) from all the measurement stations of the given country (static relationship, without any time lag);

4. the month of the year in order to capture seasonal effects (through the use of so-called dummy variables). Use the regression model to simulate synthetic RoR production data over the horizon covered by E-HYPE (1989-2018).

Given that there are hundreds to thousands of measurement stations per country, too much regression data is generally available to fit a relationship. Precautions need to be taken to avoid overfitting and spurious relations, especially because the inflow data of the different hydro stations are highly correlated. The challenge is to select the appropriate measurement stations that correctly represent the dynamics of the observed hydro RoR generation.

A machine learning algorithm called *Gradient Boosting for Regression*[7] was used to model the relationship between SMHI river flows, and RoR production. This algorithm automatically selects relevant measurement stations for the prediction, provides options against overfitting, and even accommodates for possibly non-linear relationships.

Figure 2 shows a practical example of which measurements stations are selected by the method for France (i.e., which stations get dominant weights).

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[7] (xgBoost, 2020)

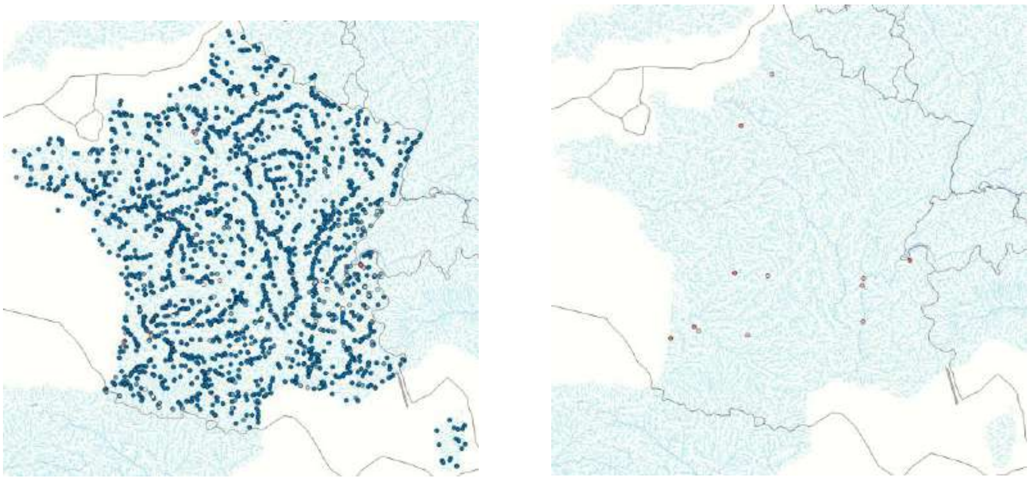

Figure 2: Original and selected measurement stations by the Gradient Boosting method

During the calibration, the data sample is split in two fractions with randomly chosen data points:

- a training data set (80%): these data are used to calibrate the relationship between river flows and power generation;
- a test data set (20%): this is data sample unseen by the calibration, that serves to independently measure the model performance without being subject to overfitting. It allows the gradient boosting method to find the good balance between model complexity, and overfitting.

An example of the performance on both the training set and test set are shown in Figure 3. The first scatterplot shows the performance on the training data set ("in-sample"): there is an excellent match between RoR generation predicted by the model, and the observed one. The second subplot shows the performance on the test set ("out-of-sample"). Although the match is less perfect, the model still reaches an R² value of 97.5%.

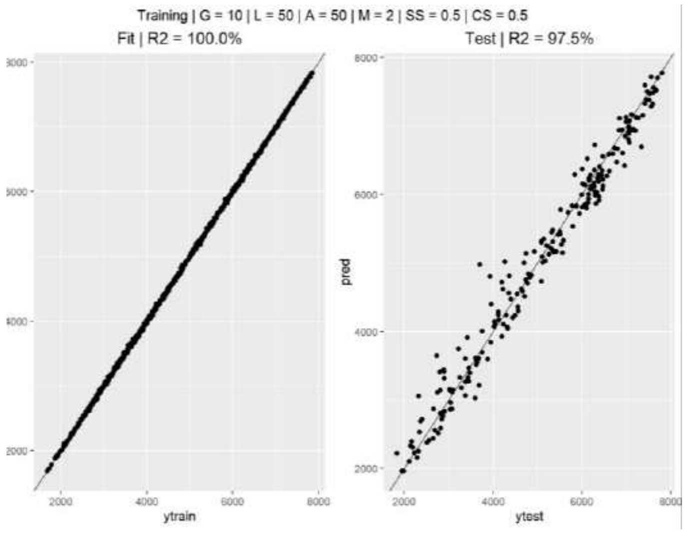

Figure 3: Model performance for training sample and test sample (RoR France).

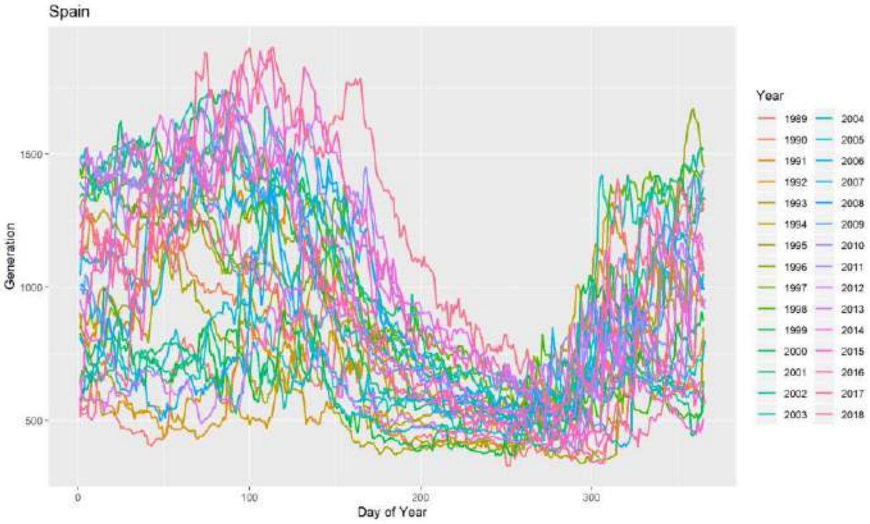

Figure 4: Synthetic production profiles for Spain over 1989-2018

Figure 4 shows an example of the end result after the construction of 30 years of hydro RoR generation profiles, for Spain. The chart illustrates very well the huge variability of hydro power generation, also affected by a strong seasonal pattern.

We can now compare these results with the hydro generation profiles prior to the update brought by study S3. Figure 5 illustrates the differences before and after the update for hydro RoR in Austria and Spain, expressed in terms of load factor (generation divided by installed capacity). The red curves show the initial parametrisation of RoR hydro in METIS. Those production profiles were determined from ENTSO-E's aggregated RoR data, over a limited horizon. To smooth out effects of individual years, the production level was averaged per month, resulting in piecewise flat profiles.

The grey lines on Figure 5 show the updated hydro RoR generation profiles for 30 weather years, resampled at weekly granularity. The green line represents the average production profile, calculated from 30 weather years. To better visualise the specific impact of the stochastic profiles, the series charted in Figure 5 do not incorporate the adjustments of the annual envelope parameters (from Eurostat & SFS), which set the final long term average load factor.

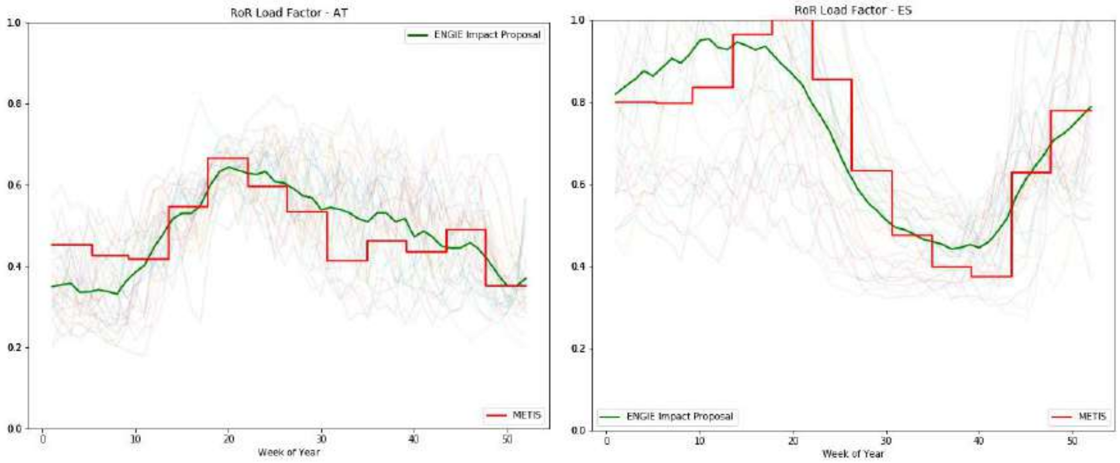

Figure 5: Initial, deterministic RoR inflow profiles (red) versus stochastic profiles (grey) and expected value of the stochastic profiles (green) – aligned with the original envelope parameters, excluding the SFS/Eurostat load factor update

The new RoR generation profiles show the following fundamental improvements over the existing METIS' hydro representation:

- when simulating a single weather year, the new average production profile is smoother and now captures the long-term dynamics of hydro inflows (instead of the limited sample provided by ENTSO-E Transparency);
- the inflow profiles for 30 weather years allow to simulate the uncertainty related to hydro RoR generation in coherence with other risk factors (solar PV and wind).

3.2. CONSTRUCTION OF STOCHASTIC HYDRO INFLOWS FOR HYDRO RESERVOIR

In contrast to hydro RoR generation, it is not possible to directly observe and calibrate a complex relationship between hydro inflows and the related power generation for hydro reservoir assets, because simultaneous measurements of inflows and power generation are non-existent. The river inflows are accumulated reservoirs, only to be turbined weeks or even months later, and therefore it is much more difficult to establish a mathematical relationship between inflows and power generation. National stored reservoir energy levels are published on ENTSO-E's transparency platform[8] and do, in combination with ENTSO-E's data for hydro reservoir generation, theoretically allow for a reconstruction of the inflows. Nevertheless, the limited time resolution of the reservoir levels (published at weekly granularity) and the already mentioned inconsistencies in terms of absolute generation volumes strongly reduce the usability of those data. Therefore, the regression approach used for hydro RoR cannot be applied to reservoir assets, and we need another way to reduce the dimensionality related to the number of hydro inflow stations from E-HYPE. The general methodology is the following:

1. Each country with hydro reservoir assets is segmented geographically in hydrological basins (following the ECRINS database[9], see Figure 6). The 30 years of inflow profiles per hydro inflow station from the SMHI data are reduced to a single 30 year-series per hydrological basin, by means of spatial averaging. It is assumed that this aggregated profile is a good approximation of the inflows received by the hydro reservoirs in the respective basin.

2. A linear relation is assumed between hydro reservoir inflows of a given basin and the related power generation. In that case, a single scaling factor determines the dependence between power generation [GWh] and inflows [hm^3]. This scaling factor is calculated in such a way, that the long-term average generation volume of the basin is reproduced over the 30-year horizon. Finally, the inflows are resampled to weekly granularity.

3. For some countries, detailed data are available (geolocation of assets, annual generation volume per asset/basin, storage capacity per dam/basin, etc.), in which case a calibration per basin can be carried out. When this level of detail is not available, the calibration is performed on a country basis, aggregating over the different basins.

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[8] (ENTSO-E Reservoir Levels, 2020)

[9] (European Environment Agency, 2020)

Figure 6: Hydrological basins according to the ECRINS database – European Environment Agency

Overview of the specificities per country:

Country	Specificities/Remarks
Austria	Covered almost exclusively by one basin: the Danube hydrological basin. Storage capacity from EEX Transparency **(EEX, 2020)**.
France	Hydro reservoirs are mainly located in two distinct catchment areas. Storage capacities based on the UN dams data set **(UNITED NATIONS, 2020)**. Split of annual generation per basin is based on respective share in generation capacity.
Italy	Instead of the hydrological basins, the 6 bidding zones have been used to partition the hydro inflows. Storage capacities extracted from ENTSO-E Transparency **(ENTSO-E TRANSPARENCY, 2020)**.
Norway	Detailed dam characteristics from the Norwegian Water Resources and Energy Directorate **(NVE, 2020)**.
Portugal	The 8 basins show very similar inflow characteristics and are aggregated into a Northern and a Southern basin. Detailed dam data scraped from the Comissão Nacional Portuguesa das Grandes Barragens **(CNPGB, 2020)**.
Spain	Detailed data of the hydro reservoir assets scraped from iAgua **(IAGUA, 2020)**, and generation data at NUTS3 level obtained from ESIOS **(REE, 2020)**, then mapped onto 10 hydrological basins.
Switzerland	Detailed data published by BFE **(BFE, 2020)** on dam locations, annual generation volume and hydro storage capacities allow for a detailed calibration for 9 catchment areas.

4. IMPACT OF CLIMATE CHANGE ON HYDRO INFLOWS

It is generally accepted that besides temperature, precipitation will also be affected by the effects of global warming. Hydro inflows, driven by both temperature and precipitation, are therefore also expected to be impacted by climate change. In order to quantify the impact of climate change on hydro power production, we developed an alternative set of inflows that is subject to climate change. Since an in-depth modelling for a pan-European scope was not possible in the scope of this study, a pragmatic methodology was followed.

The approach consists of exploiting the climate change scenarios published by SMHI, which are based on Representative Concentration Pathways (RCP) from the Intergovernmental Panel on Climate Change[10]. For each RCP scenario, the SMHI has computed the impact on multiple weather variables: precipitation, temperature, maximum wind gust, number of days with heavy precipitation, etc. SMHI provides results for several geographical scopes throughout the world, including a pan-European one[11]. The results are presented on a quarterly basis over 2041-2070, and compared to the reference period 1971-2000 (see Figure 7). We have chosen the medium RCP scenario (RCP 4.5) as a basis for our exercise.

The relative impact of climate change on the precipitation variable is translated directly to the hydro flows, by scaling up and down the flows of the E-HYPE database according to their geographical location. A seasonal effect is included, since the impact is applied on a quarterly basis. An underlying assumption is that the impact on precipitation is also good proxy for river flows being driven by snow-melt.

With this new set of hydro inflows, we apply an identical processing to the normal workflow, in order to translate the impact of climate change to the hydro RoR and reservoir profiles (Figure 8).

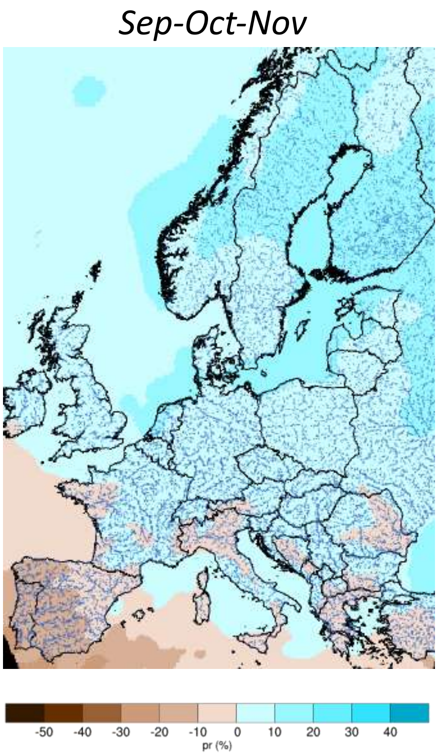

Figure 7: Impact on precipitation according to the RCP 4.5 scenario – Source: (SMHI RCP45, 2020)

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[10] (IPCC, 2014)

[11] (SMHI RCP45, 2020)

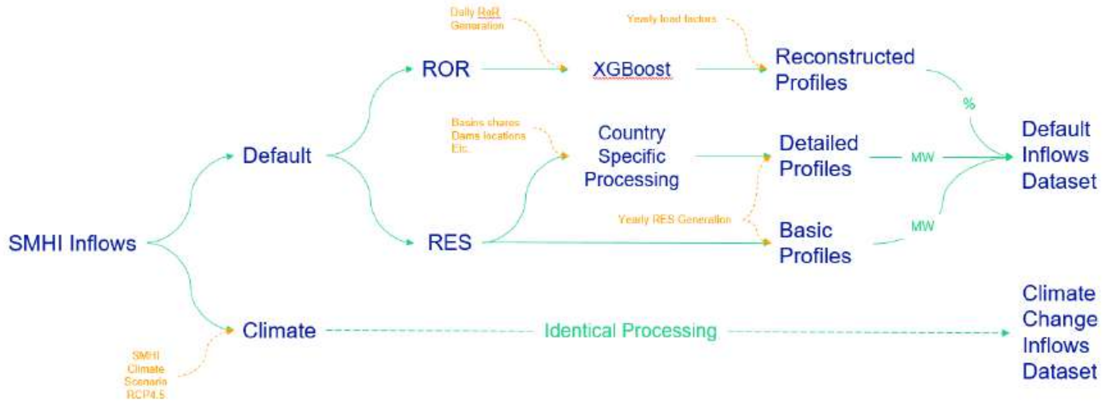

Figure 8: Construction of the profiles: without (top), and including (bottom) the impact of climate change

Figure 9 shows two examples of the resulting hydro inflows (Alpine region & Iberia):

- The RoR profile for Switzerland sees less inflows in springtime, and slightly higher inflows in autumn
- In Portugal, the wet season (December-April) becomes dryer, and the annual envelope of inflows clearly deteriorates.

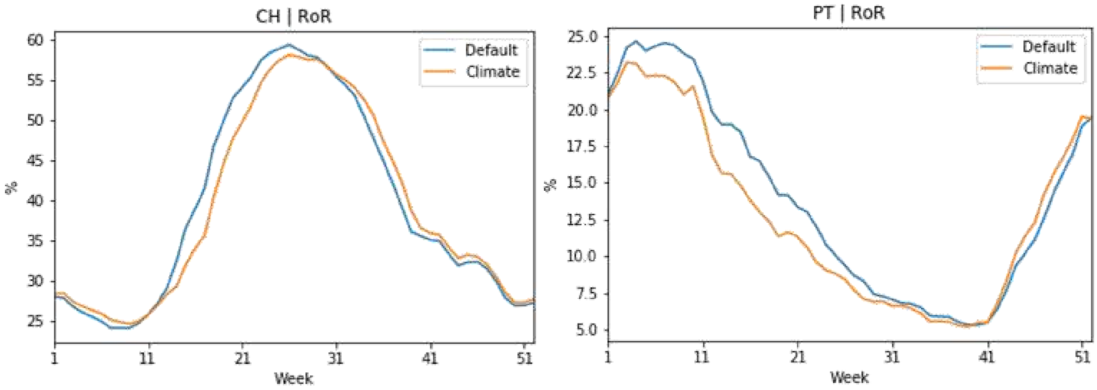

Figure 9: Illustration of the impact of climate change on hydro RoR profiles for Switzerland (left) and Portugal (right)

Despite the generic approach, the impact on the inflows is quite intuitive, especially for Iberia, where hydro inflows are mainly driven by precipitation. For the river flows coming from the Alps, the accuracy of the seasonal shape could be further improved using a detailed run-off model that explicitly factors in temperature and ice melt.

Finally, it is important to emphasise that this presented approach quantifies the impact of the change in average hydro inflow profiles, but does not factor in any change in terms of variability of the flows.

5. HYDRO RESERVOIR DISPATCH USING GUIDANCE CURVES

In METIS, the dispatch of hydro reservoir assets is modelled with the help of so-called *guidance curves*. These curves represent a target state of the hydro reservoir level throughout the year, and are defined at a weekly granularity. For a given week, the power simulation model is given the flexibility to optimise the dispatch of hydro reservoir assets. It starts from the reservoir level reached in the previous week, and is required to reach an end-of-week target level, defined by the guidance curve[12]. Guidance curves are not a "hard" constraint in METIS as slight deviations are possible though the use of penalties.

Guidance curves are a powerful tool to parameterise the dispatch of hydro reservoir assets:

- They constrain the otherwise unlimited flexibility of modelled hydro reservoir assets, and force operation in a realistic range as a function of the time of the year, the expected hydro inflows further in the season, and the characteristics of the residual demand.
- Guidance curves offer a pragmatic, yet elegant way to avoid over-optimisation of the hydro reservoirs dispatch due to perfect foresight in the optimisation model, which does not exist in reality.
- They are simple to implement and light in terms of computational burden, compared to techniques that deal with optimisation under uncertainty, such as SDDP.

The trajectory of guidance curves needs to be defined a priori, before the simulation. A good starting point is historically observed (average) hydro reservoir level trajectories, if available. For simulations on a short-term horizon, this approach makes sense because the historical dispatch will be close enough to the target horizon. On a longer term, using historical guidance curves becomes problematic. The power system is undergoing fundamental changes over the next decades: increasing renewable penetration, increased electrification, power-to-gas… Guidance curves based on historical reservoir levels lose their relevance because they are conditioned on the past dispatch of the power system, and do not accommodate for the dynamics of the future power system. This is why study S3applies SDDP to calibrate new guidance curves for 2050 in a high renewable context. However, the concept of guidance curves in METIS is conserved, because of the computational efficiency and robustness related to their implementation. By computing updated guidance curves separately, the computational burden related to the hydro reservoir optimisation strategy is taken off-line.

5.1. AN INTRODUCTION TO STOCHASTIC DUAL DYNAMIC PROGRAMMING

The SDDP method was first described in the paper of Pereira and Pinto[13]. It attempts to solve the optimisation of a *multistage stochastic hydro-thermal dispatch*, for a system with multiple reservoirs:

- *multistage*: the mathematical optimisation problem consists of sequential stages. Decisions taken in a given stage will impact the state (and decisions made) in later stages.
- *stochastic*: the state of the power system is subject to uncertainty, due to the stochastic nature of some variables (i.e., hydrological inflows)
- *hydro-thermal*: the problem is solved for a system that contains hydro-electric and thermal generation assets. Hydro-electric assets have negligible variable power generation costs, whereas thermal assets incur fuel and emission costs per MWh that they produce.

When a hydro reservoir asset starts to turbine, it lowers the need to dispatch more expensive thermal generation. Therefore, it lowers the immediate operating costs of the power system. Nevertheless, there may be an opportunity cost: it could be more profitable to save the water instead, and use it later on when it is more valuable, because it could decrease the future cost of the power system

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[12] When model runs are performed using a rolling horizon. The simulation horizon (also called 'tactical horizon') may be larger than a week – in such a case, only the reservoir target level at the end of the tactical horizon is accounted for. When model runs are performed over a whole year at once, target levels are defined every week. See (Artelys, 2021) for further details.

[13] (Pereira & Pinto, 1985)

more than today. Therefore, the dispatch decision for a hydro reservoir asset boils down to the following: how much does additional turbining decrease the immediate operating cost of the power system, compared to the expected increase of the future operating cost? (see Figure 10).

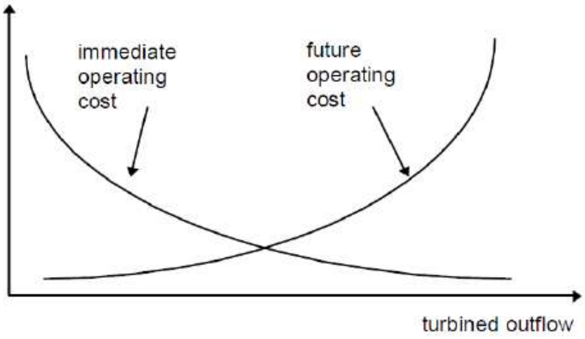

Figure 10: Immediate versus future operating cost as a function of turbined outflow

The SDDP algorithm calculates the future cost function recursively, similarly to the classical Dynamic Programming (DP) method. The novelty about SDDP is its computational efficiency, especially for systems with multiple reservoirs. Traditional DP calculates the Future Cost Function (FCF, or *Bellman* function) exhaustively for every combination of the (discrete) states of the hydro-reservoirs, and suffers from the *curse of dimensionality*, i.e. computational resources that grow exponentially with the number of variables considered [14].

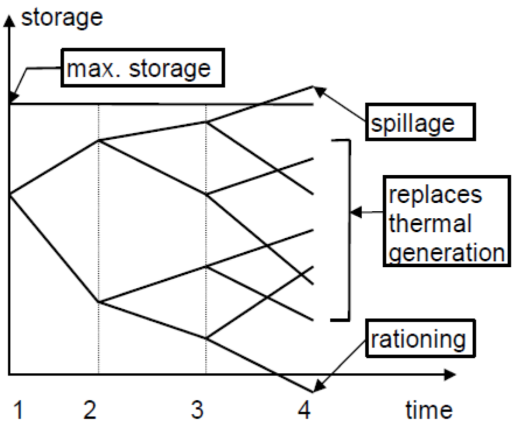

Figure 11: Brute force calculation of the Future Cost Function. Source: (PSR, 2020)

The SDDP algorithm eliminates the need to discretise the space of reservoir levels by constructing a piece-wise linear (lower) approximation of the Bellman function (see Figure 12). SDDP builds up and refines the cuts that determine those piecewise linear functions, by alternating between forward and backward simulations. The SDDP gains efficiency compared to DP because it avoids the characterisation of the full state space, and instead gradually adds precision with additional cuts

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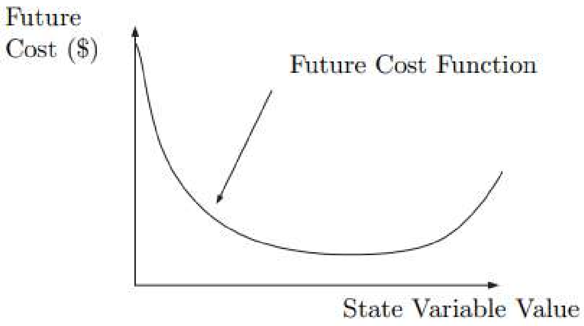
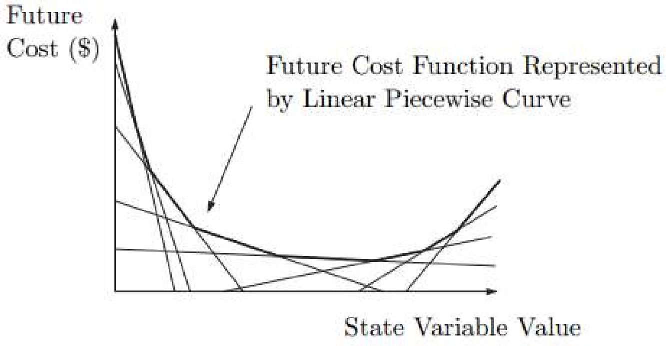
[14] To better understand what is meant by the curse of dimensionality, consider a power system that hosts 10 different hydro reservoirs, each of them being characterised by 10 discrete volume levels. To optimise the hydro dispatch, the future cost function needs to be calculated for each distinct state (10 reservoirs x 10 levels = 100 evaluations) for a given time step. Unfortunately, in the recursive set-up of DP, this future cost function is conditional to the states of the next time step, as depicted in Figure 11. This leads to an exponential growth of the number of objective values that need to be evaluated and makes the DP problem computationally intractable, even for a reasonable number of reservoirs and a limited time horizon. In the simple example of 10 reservoirs with 10 states and a horizon of only 52 steps (one year at weekly frequency), solving the DP problem with brute force would require 100^{52} FCF evaluations.

around the states that are the most probable to be visited. A description of SDDP can be found in (Newham, 2008) (chapter 4 for an introduction).



(a) Convex Future Cost Function



(b) Linear Piecewise Representation

Figure 12: Future Cost function approximated by cuts. Source: (Newham, 2008)

5.2. UPDATE OF THE METIS GUIDANCE CURVES USING SDDP

The SDDP algorithm, described in the previous section, dynamically determines the optimal hydro reservoir dispatch strategy, without relying on a priori constructed guidance curves. We exploited SDDP to determine the optimal hydro reservoir dispatch of the power system in the future according to the following procedure (see Figure 13):

1. Transfer the complete power system model of 2050 from METIS[15] to PSR's SDDP software (PSR, 2020), including the updated hydro model and newly developed stochastic hydro RoR and reservoir profiles.

2. Run the power system optimisation model with SDDP: the model freely optimises the hydro dispatch as a function of the assumptions on the future power generation: thermal plant list, renewable profiles, power demand, dynamics of the hydro inflows, etc.

3. From the Monte Carlo simulations performed with SDDP, extract the expected value of the reservoir levels, and feed them back to METIS as guidance curves.

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[15] METIS S1 scenario was used to compute the guidance curves. It consists in a high-vRES and carbon-neutral European power system scenario for 2050, based on inputs from the European Commission's EUCO30 scenario. In order to improve the capture of high-vRES system dynamics, the hydrogen demand (which was considered fully flexible) was reduced, too. See (Artelys, 2018).

4. Run a long-term capacity expansion and dispatch simulation with METIS[16], based on updated guidance curves.

Figure 13: Global scheme of the guidance curve update

More precisely, the scripted data transfer from METIS to SDDP consists of:

- Detailed thermal plant list, including technical parameters
- Fuel & emission allowance definitions
- Hydro reservoir & run of river plant list
- Installed renewable generation capacities & production profiles
- Batteries
- Power demand & demand profiles
- For the interconnections: net transfer capacities between zones

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[16] The impact of updated guidance curves was assessed on the METIS 2 S6 scenario, which is a European multi-energy scenario (electricity, industrial heat, hydrogen) built on the Long-Term Strategy's 1.5TECH scenario for 2050. See (Artelys, 2021). The capacity expansion was performed on power system technologies (including vRES) along with electrolysers – to limit the model complexity, the heat supply technology mix was fixed as per the reference model run.

5.3. RESULTING CHANGES OF THE GUIDANCE CURVES

Prior to assessing the impact of the guidance curve update on the power system, we compare the shapes of the original and updated guidance curves. The next charts show the guidance curves for countries that have a significant annual volume of hydro reservoir production (> 5 TWh/y) in the European power system and grouped according their larger geographical region.

Figure 14 shows the results for Norway and Sweden. For those two countries there are no fundamental changes in terms of shape. In Norway, the reservoir levels maintain a somewhat higher level from August to April, this is, outside the high inflow (ice melting) season. The curves estimated with SDDP are remarkably close to the original guidance curves, which are based on historical data. This behaviour is due to the fact that also in the future, the power system of those countries will be dominated by hydro production. Also, as solar PV resources are limited in the Nordic regions, it makes sense to observe no seasonal shifts in the guidance curves of those countries. Higher wind production can mitigate the hydro consumption in winter and allow for a slight shift to higher storage levels in this season.

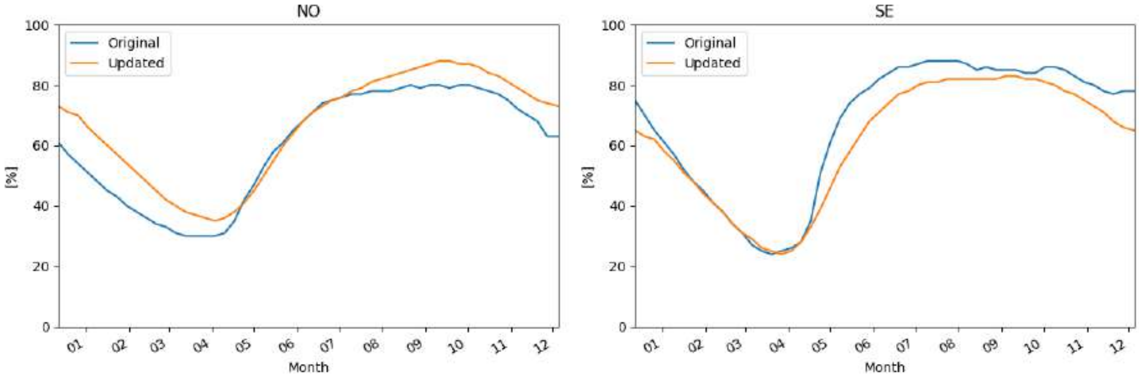
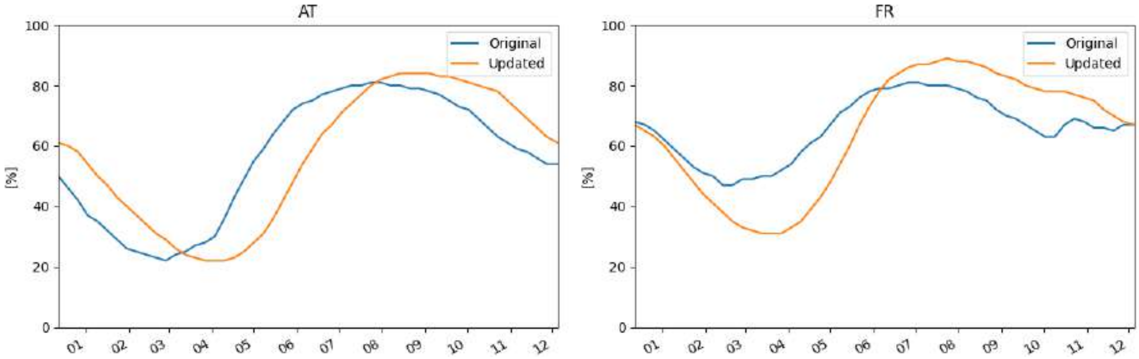


Figure 14: Guidance curve update for the Nordic countries

The guidance curves of Austria, France, Switzerland and Italy are shown in Figure 15. The results among the countries in the Alpine region are quite similar: after the update, the maximum level of the reservoir is reached with a delay of 2 to 3 months compared to the historical curves. Given that the Alpine flows start to decay after the month of June, this indicates that the lesser inflows of July and August are saved for later use. This is possible due to the overall higher penetration of solar PV in the European power system, which introduces the bulk of its energy in the summer months.



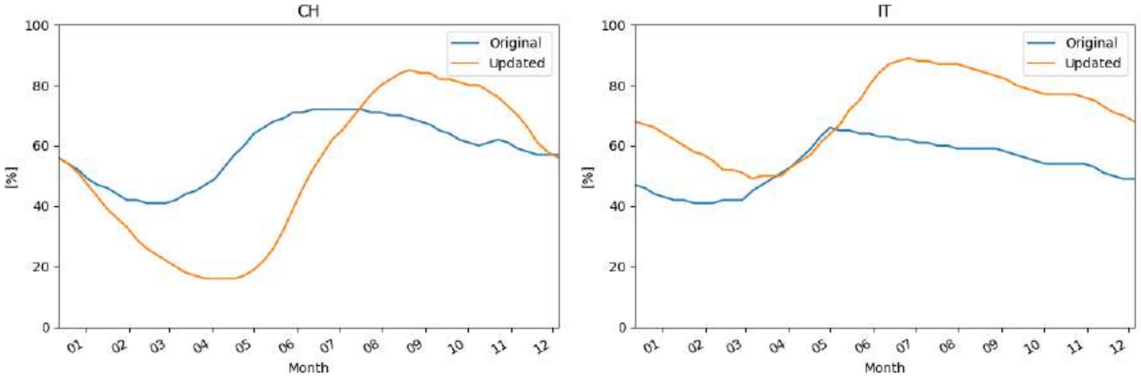


Figure 15: Guidance curve update for the Alpine countries

Figure 16 depicts the changes of the guidance curves for Spain and Portugal. In these countries hydro production is primarily driven by precipitation between November and April. Similar to the Alpine countries, massive solar PV generation as of the springtime season postpones the peak reservoir level by one or two months. This prepares the system to cope with the peak demand which takes place in summer for the Iberian countries. It also seems that the usable range of the hydro reservoirs (maximum value minus minimum value) is better exploited than before.

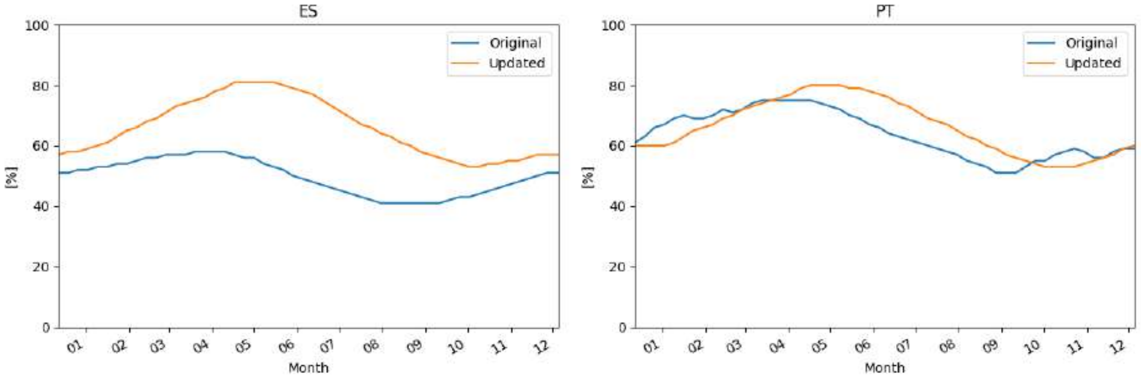


Figure 16: Guidance curve update for Iberia

The two last countries that are relevant in terms of hydro reservoir production in the EU28+ perimeter, are Romania and Greece, shown in Figure 17. The seasonality is quite similar than before, although updated guidance curves are somewhat smoother.

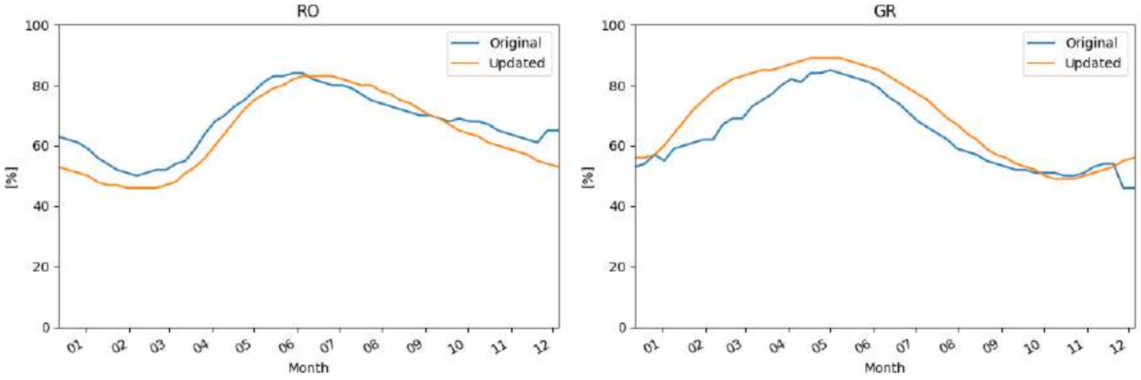


Figure 17: Guidance curve update for Romania and Greece

6. IMPACT ASSESSMENT OF THE GUIDANCE CURVE UPDATE

This section assesses the impact of the guidance curves quantitatively, considering the following indicators:

- the capacity mix computed by the long-term capacity expansion of METIS, followed by the generation mix;
- the system costs: capital expenditures (CAPEX), and variable operational expenditures (OPEX).

The impact of updated guidance curves was assessed on the METIS 2 S6 scenario, which is a European multi-energy scenario (electricity, industrial heat, hydrogen) built on the Long-Term Strategy's 1.5TECH scenario for 2050 (see *(Artelys, 2021)*). The capacity expansion was performed on power system technologies (including vRES) along with electrolysers – to limit the model complexity, the heat supply technology mix was fixed as per the reference model run.

6.1. IMPACT ON THE CAPACITY AND GENERATION MIX

Figure 18 shows the relative impact of the updated guidance curves on the invested capacity mix in the year 2050 the form of a waterfall chart. Changes of less than 100 MW are not shown. The chart shows that after the update of the guidance curves, an additional capacity of 40 GW of solar PV, 4 GW of open cycle gas turbines (OCGTs) and 1.4 GW of batteries make their entrance in the capacity mix. Those technologies appear at the expense of approximately 18 GW of wind (onshore and offshore), and 5 GW of combined cycle gas turbines (CCGT's). These changes in the capacity mix are modest when compared to the overall installed capacity in the given geographical scope (~3300 GW).

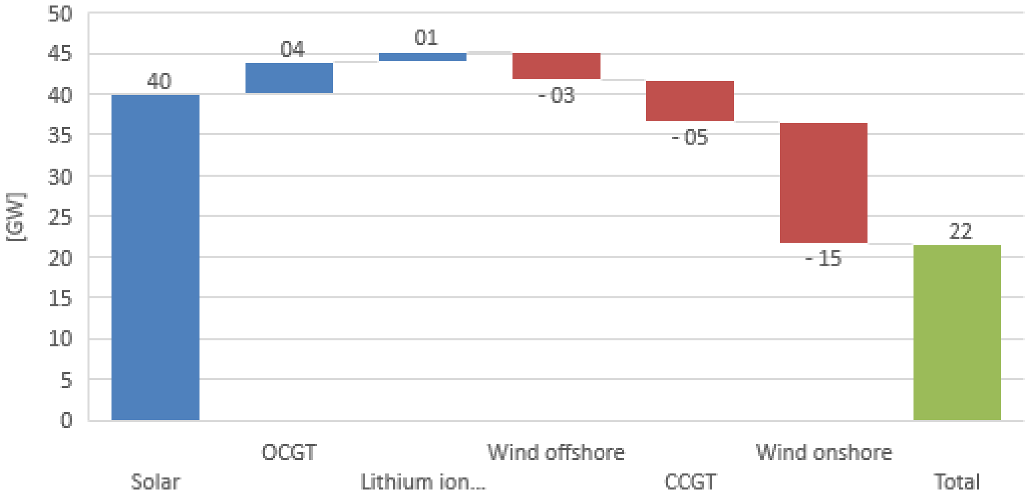


Figure 18: Impact of New Guidance Curves on the Capacity Mix

The variations in the capacity mix translate into the generation mix (see the waterfall chart on Figure 19, which shows technologies with an impact greater than 3 TWh): the production by solar PV increases following the capacity mix, by almost 48 TWh. Wind onshore and wind offshore decrease by 42 TWh. Interestingly, a small additional fraction of hydropower also appears. Given that the hydro inflows between the reference model and the updated model are identical, this indicates that less hydro inflows are lost due to spillage or renewable curtailment. Also, production by biomass facilities and CCGTs is slightly reduced.

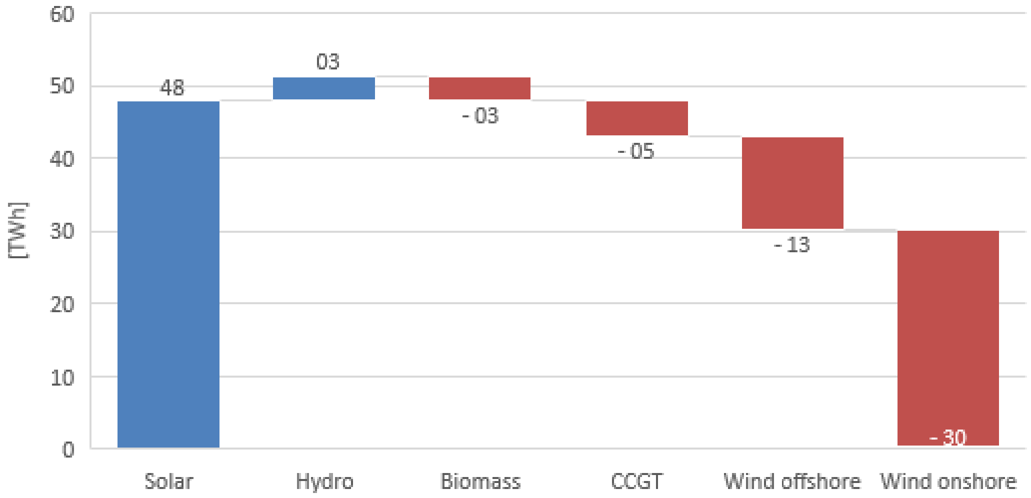


Figure 19: Impact of New Guidance Curves on the Generation Mix

6.2. IMPACT ON THE INVESTMENT AND VARIABLE COSTS

Figure 20 shows the relative impact of the guidance curve update on the capital and operational expenditures simulated by METIS. The CAPEX figures in this chart (blue and red bricks) are expressed as annuities, to account for investments taking place over multiple years. The new guidance curves allow the system to absorb a higher installed capacity of solar PV, a technology that is cheaper on LCOE (Levelised Cost of Electricity) basis than wind. The increased solar PV does require slightly higher investments in OCGT's and batteries, which are complementary to the intermittent profile of solar PV. CCGTs, showing better complementarity with wind onshore and offshore, see their contribution in the mix diminishing together with wind. Overall, the CAPEX annuities decrease by 700 MEUR. The variable costs (OPEX) decrease by another 1.4 BnEUR, which is explained the decreased production by biomass and CCGTs. It corresponds to a 4% decrease in production costs compared to total production costs (34.7 BnEUR). In total, the simulated annual system costs decrease by 2.1 BnEUR[17].

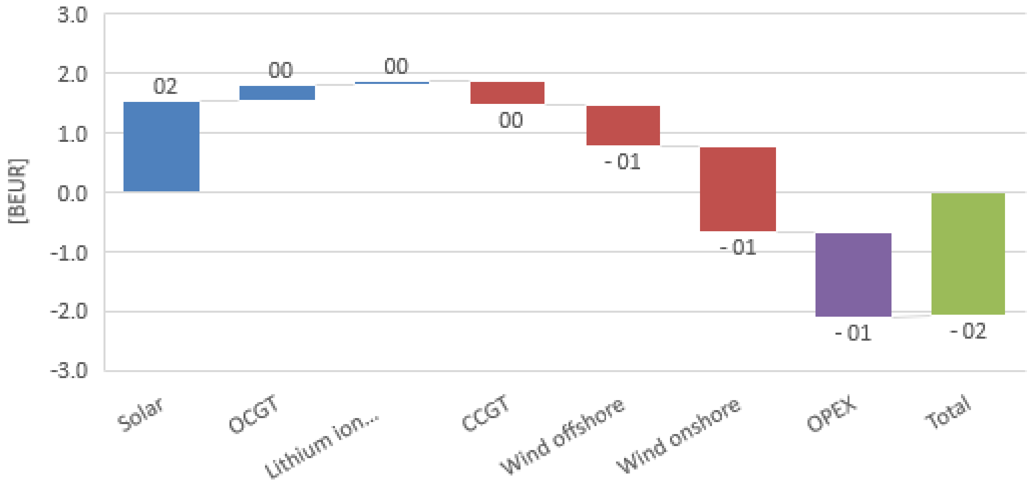


Figure 20: Impact of new guidance curves on the system costs

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[17] This cost decrease is not compared to total system costs as some technologies have exogenous capacities based on EC's LTS 1.5TECH scenario (typically, nuclear, coal and lignite).

6.3. DISPATCH OF HYDRO RESERVOIR ASSETS IN SYSTEM WITH A HIGH PENETRATION OF VRES

The charts of the guidance curves shown in section 5.3 may give the impression that the dispatch of hydro reservoirs simulated in METIS is does not change significantly between different weather years. Figure 21 shows that this is not the case. It displays the hydro reservoir level for Spain throughout the year, simulated over all the weather years. The combined intermittency of solar PV, wind, demand and hydro heavily impacts the reservoir trajectory. The convergence of the reservoir level to a single point at the start and end of the horizon is set as a boundary condition (i.e., initial reservoir level) of the power system simulation. The convergence observed around the month of June, on the other hand, is a systematic effect: the reservoir levels are prepared to anticipate for the demand, which on average peaks in summer in Iberia. The second half of the year shows the highest variability: the reservoir is fully exploited to cope with the intermittency of the abundant RES production in the region.

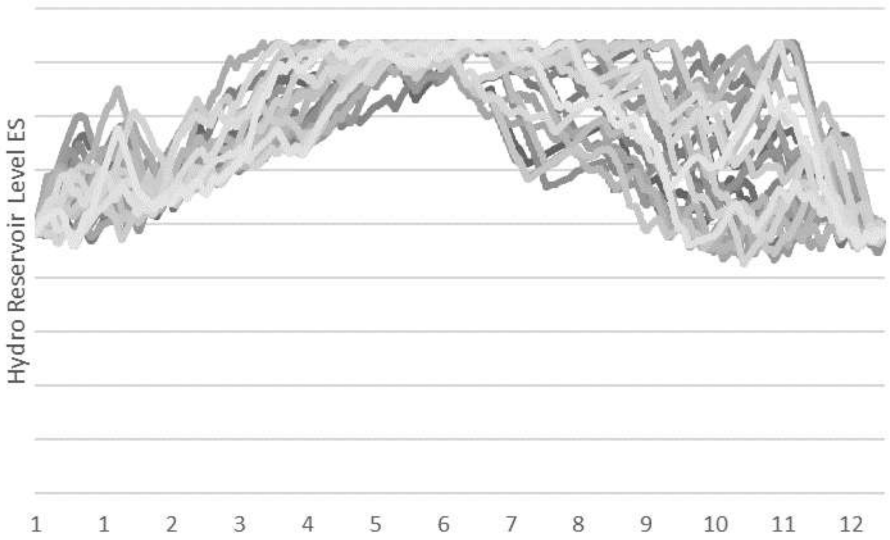

Figure 21: Hourly dispatch profile of hydro reservoir in Spain with the updated guidance curves & stochastic hydro inflows

It is interesting to compare the profiles of the reservoir dispatch of the model with updated guidance curves and stochastic hydro inflows, with the reference METIS model. Figure 22 corresponds to the reference METIS model and when compared to Figure 21, shows that the improvements made in study S3 have brought much more richness and realism in the METIS simulations.

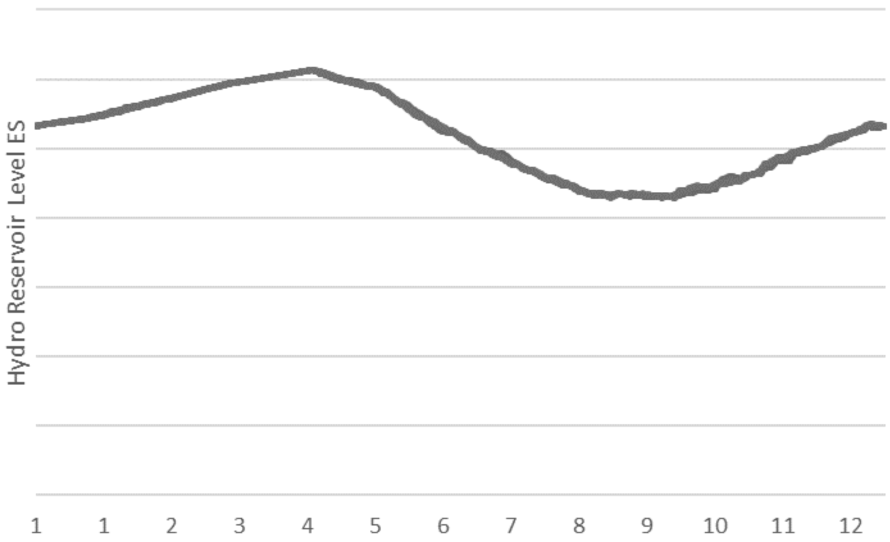

Figure 22: Hourly dispatch profile of hydro reservoir in Spain with the old guidance curves & deterministic hydro inflows (single curve)

7. IMPACT OF CLIMATE CHANGE

An alternative set of hydro inflows, subject to the impact of climate change, was prepared as explained in section 4. We quantify the impact of this change on the power system, with respect to the reference case, which is the power system model that includes the update of the guidance curves.

7.1. IMPACT ON THE CAPACITY AND GENERATION MIX

Figure 23 shows the impact on the optimal capacity mix, when hydro inflows are affected by climate change. Again, changes less than 100MW are not shown on the chart. Globally, the impact of climate change is compensated by more solar PV. Changes with respect to the installed capacity for wind are negligible. When it comes to flexible thermal assets, CCGTs replace batteries and OCGTs.

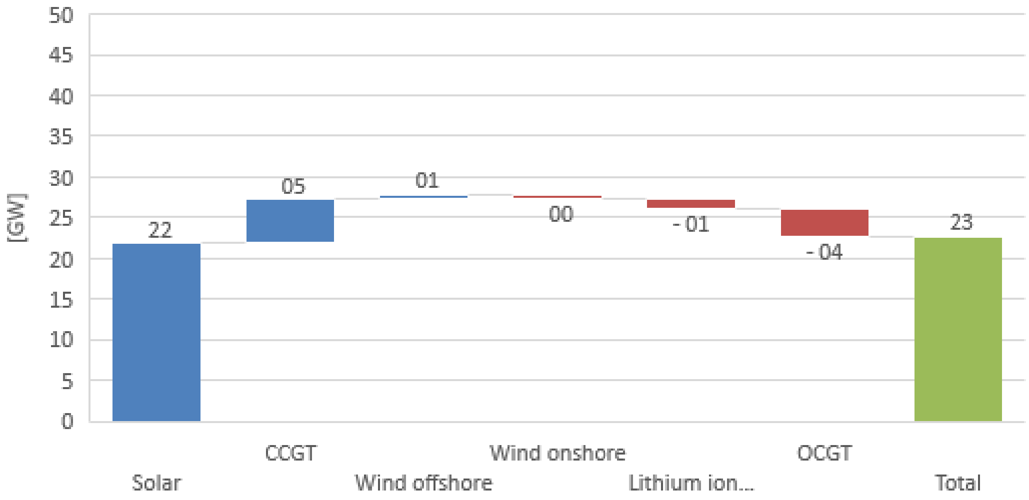

Figure 23: Impact of Climate Change on the Capacity Mix

Figure 24 shows the impact of climate change on the generation mix (omitting changes < 3 TWh). The global hydro generation volume decreases with 31 TWh – which is around 5% of the hydro power production for the EU28+ scope. This is the consequence of reduced inflows that appear in the climate change variant of the hydro inflow profiles. The bulk of this energy is replaced by solar PV.

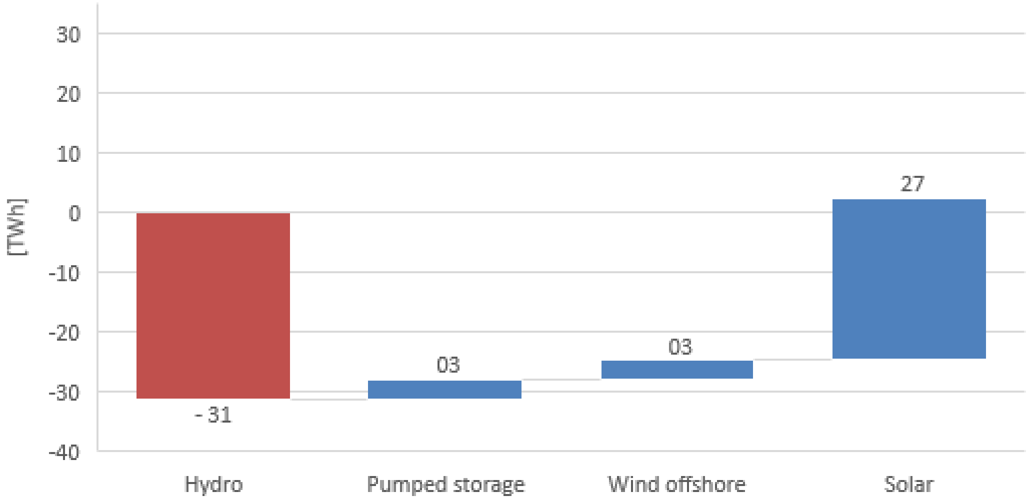

Figure 24: Impact of Climate Change on the Generation Mix

7.2. IMPACT ON THE INVESTMENT AND VARIABLE COSTS

Figure 25 shows the relative impact of hydro inflows affected by climate change on the capital and operational expenditures. In terms of CAPEX (red and blue bricks), the changes reflect the shifts in built capacity: less OCGTs and batteries in favour of more CCGTs. The dominant effect is the increased investment in solar PV. The operational expenditures slightly increase. The 0.4 BnEUR increase in production costs corresponds to 1% of total production costs. The additional annualised system costs due to the effect of climate change on hydro inflows is estimated at 1.4 BnEUR (see footnote 17).

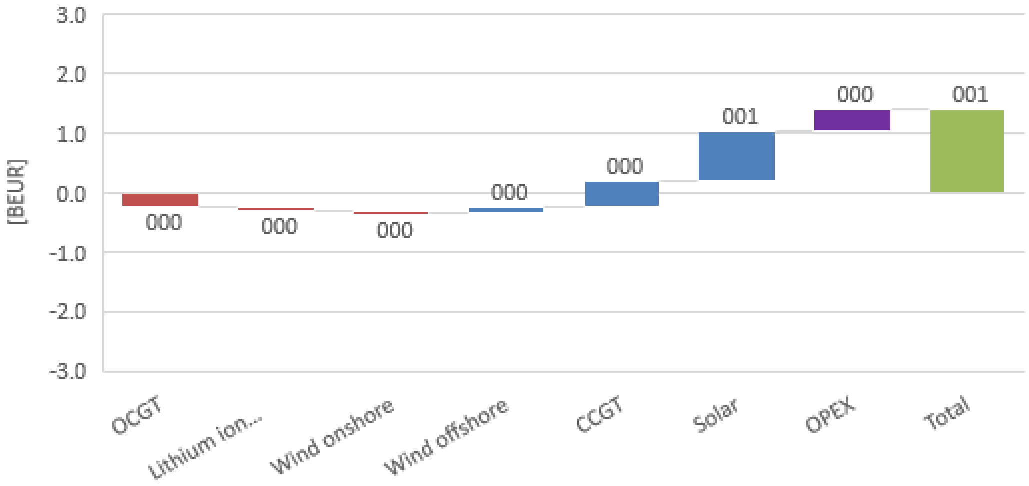

Figure 25: Impact of Climate Change on the system costs

8. CONCLUSIONS

The work performed in the course of the study S3 has resulted in a significant upgrade of the hydro modelling in METIS:

- update of the envelope parameters (installed capacities & annual generation), leading to a more realistic representation of the hydro fleet in the power system;

- integration of stochastic inflow profiles for hydro RoR and hydro reservoir assets, bringing the representation of the hydro fleet's variability to the same level as the other renewable energy sources in METIS;

- update of the guidance curves, reflecting the structural changes of the power system by 2050, and unlocking the full flexibility of the hydro fleet;

- established a climate change variant of the hydro inflows.

The impact of the new guidance curves has been quantified: it shows that correctly representing the hydro flexibility results in a less costly power mix. The updated hydro parametrisation absorbs more solar PV, at the expense of more expensive wind technologies. As a consequence, the annualised system costs decrease by approximately 2 BnEUR, of which one third is attributed to capital expenditures, and two-thirds to decreased operational costs (4% of total operational costs).

The impact of climate change on hydro inflows shows an overall decrease of hydro production of approximately 30 TWh over the complete geographical scope. The reduction of hydro production triggers 22 GW of additional solar PV investment which covers the bulk of the decrement. As a consequence, the overall system costs increase by 1.4 BnEUR (annualised), which can be mostly attributed to the additional CAPEX for solar PV.

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