OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

Cross-border reserve exchange for improved flexibility and efficiency

Internal Deliverable T1.4.2

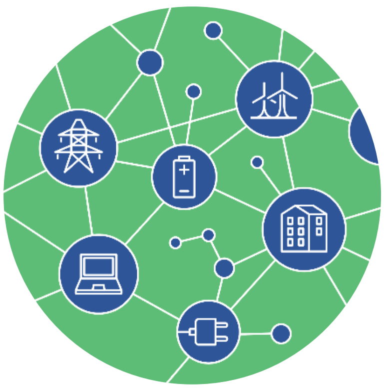

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Table of content

List of figures

List of tables

0 Executive summary

This report presents the internal deliverable *Cross-border reserve exchange for improved flexibility and efficiency*, within the scope of the work performed by REN under T1.4.2. Here, brief descriptions of the main simulation tools used are presented as well as the different analysis and studies performed.

WP1 focus on the Optimal Mix of Flexibilities, starting by proposing long-term scenarios (2030 and 2050), which differ on demand levels, installed capacities, investment options, and on the amount and location of flexibility options. Based on those scenarios, static reserve adequacy analysis was carried-out by RTE using its ANTARES model, aiming to assess and validate the referred scenarios.

Using data from T1.1 and T1.2 as input, REN analyses built scenario credibility for the CSW region (Portugal, Spain and France) as well as medium to long-term adequacy from an operational reserve perspective, using PS-MORA simulation tool. The impacts of considering RES forecast uncertainty are assessed by comparing the reliability indexes resulting from different types of simulations and assumptions.

Simulations studies of the CSW region for different future scenarios allowed to determine the operating reserve requirements and to evaluate cross-border/interconnections benefits arising from a regional coordinated use of flexibility resources. Those studies included:

- *Adequacy Assessment Simulation Studies for CSW Region*, including the evaluation of adequacy of the generation systems and of the available operational reserves using PS-MORA model.
- *Year-by-year Operational Reserve Assessment and the Impact of Interconnection Reserve Capacity During Day-ahead Market*, evaluating the benefits of increasing cross-border/interconnections arising from a regional coordinated use of flexibility resources.
- *Sensitivity Analysis on Flexible Capacity Requirements to be Integrated in the CWS Region*, including the calculation of reliability indexes considering different levels of added flexibility.
- *Benefit Analysis from Increased Interconnection Capacity*, where the impact of considering different levels of interconnection reinforcement within the CSW region is assessed.
- *Sensitivity Analysis on the Increase of RES Generation that PT Region can Accommodate – NECP*, including the impact on thermal-based generation and interconnection energy flows between PT, ES and FR, as well as CO_2 emission reduction

As main conclusions, it stands out that, for the scenario *Current Goals 2030*, the operational reserve assessment shows inexistence of loss of load expectation (LOLE) and expected energy not supplied (EENS), validating the flexibility options available and previously defined by T1.1 and T1.2. Furthermore, for the scenario *Current Goals 2050* some additional flexibility capacity might be necessary, depending on the reliability criteria assumed, and on the level of

RES uncertainty considered. In addition, it was confirmed the positive impact of increasing interconnection capacity in the reliability indexes, namely on the interconnections between Spain and France.

Moreover, hydro-power generation management proved to be of key importance on evaluating the impact of hourly power deviations coming from RES units, such as PV and wind, in reliability indicators, which means that the hydro resource management is strategic to ensure security of supply in the CSW medium and long-term horizons. Portuguese 2030 NECP sensitivity analysis show that scenario *Current Goals 2030* should consider some RES installed capacity redefinition.

Studies presented in this report illustrate the impacts from the operational reserve perspective that uncertainty from RES generation can have on system reliability indexes and interconnection interchanges.

1 List of acronyms and abbreviations

You can find in the table below the list of the acronyms and abbreviations used in this document.

Acronym	Meaning
ANTARES	Sequential Monte-Carlo simulator designed for short to long-term studies of large interconnected power grids. It simulates the economic behavior of the whole transmission-generation system, throughout the year and with a resolution of one hour.
CDF	Cumulative Distribution Function
CSW	Continental South West
CCGT	Combined Cycle Gas Turbine
DSM	Demand Side Management
EENS	Expected Energy Not Supplied
EPNS	Expected Power Not Supplied
ES	Spain
EV	Electric Vehicle
FR	France
GTC	Grid Transfer Capacity
I. **D.**	Internal Deliverable
LOLE	Loss Of Load Expectation
LOLP	Loss Of Load Probability
NECP	National Energy and Climate Plan
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PS-MORA	Power System Model for Operational Reserve Assessment
PT	Portugal
REN	Redes Energéticas Nacionais
RES	Renewable Energy Sources
RTE	Réseau de Transport d'Electricité
SCG	Scenario Current Goals Achieved
UC	Unit Commitment
VALORAGUA	Model for the optimal management of the operation of hydro/thermal systems

2 Introduction

This report presents internal deliverable *Cross-border reserve exchange for improved flexibility and efficiency*, which REN is responsible for within WP1 and its sub-task 1.4.2. Here, dependencies that T1.4.2 has with other tasks within WP1 are presented along with the main assumptions that were established aiming at standardizing concepts and different representations between the study in focus here and the studies that precede it.

Adopted methodology is presented while offering brief introduction to the models used in this study: VALORAGUA and PS-MORA. Main results will focus on:

- average energy production comparison between ANTARES and PS-MORA as means of high-level validation of adopted methodology and homogeneity;
- adequacy assessment for the CSW region, considering operational reserve analysis;
- sensitivity analysis regarding flexible capacity requirements to be integrated in the CSW region and increase of RES generation that CSW region can accommodate;
- benefit analysis regarding increased interconnection capacity and cross-border reserve exchange;
- Portuguese NECP sensitivity analysis.

2.1 Scope of proposed study

Decarbonisation of EU energy system implies a reshaping of today's power system, abandoning most of conventional thermal-based power plants, like coal-fired units, and replacing it with renewable based options, such as wind power (onshore and offshore) and solar.

Conventional mid and long-term studies regarding security of supply would, for different stages in the planning future, evaluate whether defined installed capacities are enough to meet forecasted demand. This is an important process as it allows one to identify investment needs on additional generation units and/or investments on interconnections reinforcement between different countries (also, at a national level, internal grid reinforcements).

The increasing share of renewable-based generation brings new challenges for the operation of power systems, making it more complex than what conventional security-of-supply studies tackle. Renewable-based generation is intrinsically linked with its primary source, wind or sun, which are intermittent and uncertain resources. With that in mind, REN developed[1] a new simulation model called PS-MORA (Power System Model for Operational Reserve Adequacy) where security-of-supply studies can be carried-out evaluating the impact of uncertainty present in RES generation and the impact of short-term load uncertainty. More than evaluating whether installed capacities are enough to meet forecasted demand, PS-MORA is also

[1] In cooperation with INESC TEC

capable of assessing whether the planned power system configuration is capable of dealing with the Operational reserve needs that RES uncertainty will impose.

Accordingly, REN uses its PS-MORA model to study the operation of the CSW power system under the conditions defined by T1.1 and T1.2 and attempts to provide feedback on whether flexibility needs are met within the defined scenarios.

2.2 Position within WP1 and dependencies

T1.4.2 dependencies with other WP1 task are depicted in Figure 1. Initially, T1.1 was responsible for defining mid and long-term scenarios, regarding the evolution of installed capacities and identifying which RES and flexibility options should be EU focus for 2030 and 2050. Additionally, T1.1 identified the locations (clusters) where those investments should occur. Demand levels per cluster and investment on interconnection are also present in T1.1 results.

In a second stage, and using T1.1 outputs as base for its studies, T1.2 performed long-term security-of-supply studies for the European power system, in an attempt of validating T1.1 investment decisions, providing feedback whenever necessary with suggestions for future iterations of T1.1 models.

Results from T1.2, namely load and RES time-series, as well as activation of flexibility options are used as input of T1.4.2, along with scenarios defined by T1.1. Outputs from T1.4.2 will be used by T1.1 to redefine, if necessary, RES and thermal-based installed capacities within the CSW region as well as the flexibility options located in that region.

3 Methodology

T1.4.2 main simulation model for CSW adequacy analysis is PS-MORA, which requires, in a preliminary step, the inputs from REN's VALORAGUA simulation tool. In Figure 1, the main outputs from these models are depicted. VALORAGUA is a model capable of performing the management of mixed hydro-thermal and renewables electric power systems, and in this study, its main outputs are the water management for the CSW region (although very much restricted by T1.2 results) and the weekly market bid prices for all hydro units, which are used by PS-MORA for merit order criteria.

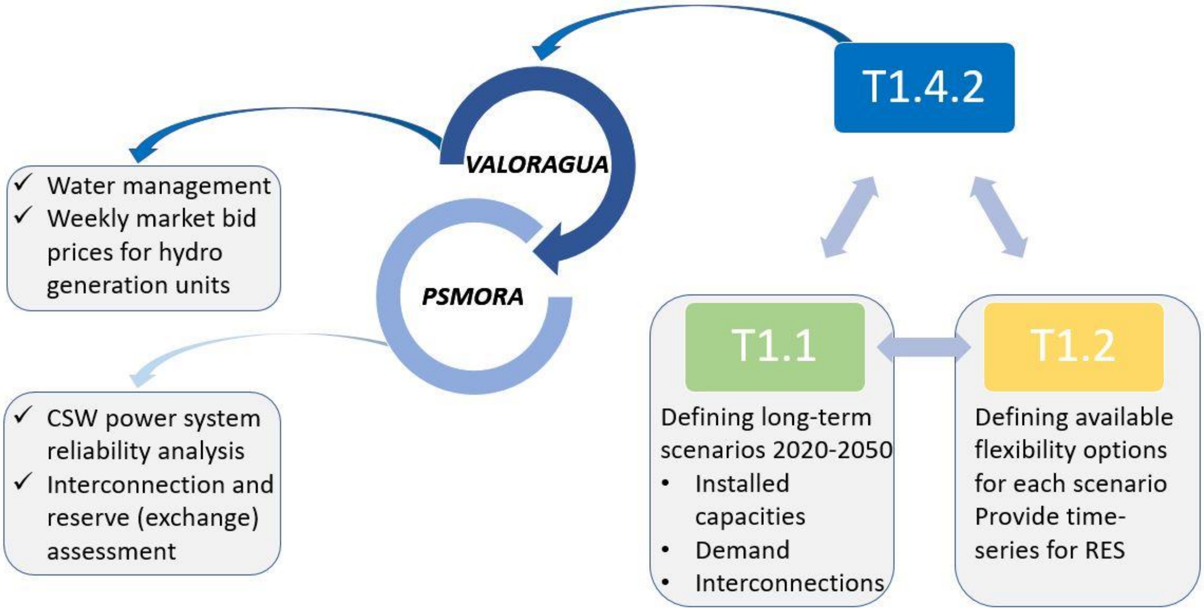


Figure 1: T1.4.2 dependencies with other tasks and used models' main outputs

PS-MORA will perform T1.4.2 main studies to assess the flexibility needs in the CSW region and whether or not the installed capacities defined in T1.1 scenarios and flexible options considered are enough to meet those flexibility requirements.

Next, VALORAGUA and PS-MORA are briefly described, as well as the CSW case study and main assumptions defined for T1.4.2.

3.1 Description of VALORAGUA model

VALORAGUA[2] model is a decision-making support tool to perform the management of a mixed hydrothermal and renewables electric power system, at a national level or considering interconnections with other countries (or areas). Through the concept of "value of water", VALORAGUA is capable of establishing the optimal strategy of operation for a given power system in each power station, for each time interval (i.e. month/week) and for each hydrological condition. Additional water usages other than energy generation can be accounted during the optimization process, which influence the operation of hydro-power plants.

The optimization process performed by VALORAGUA, while accounting for the technical information used as input, allows the model to determine optimal operation conditions while minimizing operational costs and complying with all technical constraints. The model supplies great detailed information about technical, economic and environmental behaviour of the entire system as a whole and of each generation power plant, taking into consideration the randomness of hydrology. It also supplies a detailed calculation of the economic dual variables, the marginal generation costs and the marginal value of water for each hydroelectric plant.

VALORAGUA performs its analysis for a one-year period. The time interval unit considered for the management purposes of the electric power system can be defined as monthly or weekly. Each time interval, month or week, is discretized in time steps for the load characterization. Each one, with its own duration, is called load step. The main objective of the model is to optimize the integrated management of a mixed hydrothermal and renewables electric power system, making the link between the water management and the operation of the electric power system, and taking into account physical, technical, economical and operational characteristics of the system. It also enables an evaluation of emissions from thermal generation units, considering the type of fuel used and the associated emission rates used as input.

The model provides a detailed management of an electric power system. Each component is completely and independently characterized, with its identification and topological connections to the electric and/or the hydraulic network. The detailed management of water makes possible the representation of:

- hydroelectric cascades, taking into account the links between reservoirs and hydroelectric plants;
- reversible hydro plants (with turbine and pumping modes) with the possibility of analysing weekly and seasonal pumped storage plants operation;
- head and power output variations;
- head losses variation, depending on the turbined/pumped water flow;
- utilization of water for other uses than energy production.

From a methodological point of view, the optimal management of the modelled electric power system is formulated as a non-linear optimization problem where the hydro subsystem is

[2] VALORAGUA - A model for the optimal management of a hydro-thermal power system. Available at: https://inis.iaea.org/search/search.aspx?orig_q=RN:19024153

completely disaggregated. The main objective function is the minimization of total variable generation costs while assuring that demand is met and all decisions are feasible. The problem solution involves several mathematical areas, namely stochastic dynamic programming, linear programming and non-linear programming.

Essentially, the solution of the problem is divided in two steps:

Step 1. *Medium Term Problem:* knowing the system configuration, the model optimizes the management of reservoirs, minimizing the expected value of future generation costs, using a stochastic programming algorithm. In this step, a single equivalent storage is defined as energy storage with maximum capacity equal to the sum of energy storage capacity of all reservoirs in the system. The single storage model requires the calculation of the water inflows in terms of energy, representing the aggregation of all water inflows. In this first step, VALORAGUA calculates, for each elementary time period of the year, the so called cost-to-go functions, which give the value of water for each point considered for the energy stored in the system equivalent reservoir.

Step 2. *Short Term Problem:* performs the management of the electric power system with each component completely disaggregated, in order to minimize the sum of generation costs and the expected value of future generation costs. This step is subdivided in two new ones:

- knowing the cost-to-go functions and the state of the different components of the system, the final storage for each reservoir is calculated, using linear programming in order to optimize the water flows allocation in the hydraulic network;
- A non-linear optimization approach (including Lagrangian relaxation and decomposition algorithms), is used to solve the dispatch problem providing the better system generation schedule found by the model. The Lagrangian relaxation algorithm enables the calculation of dual variables associated with the most important constraints of the problem and consequently also enables the economical analysis.

Figure 2 illustrates this methodology.

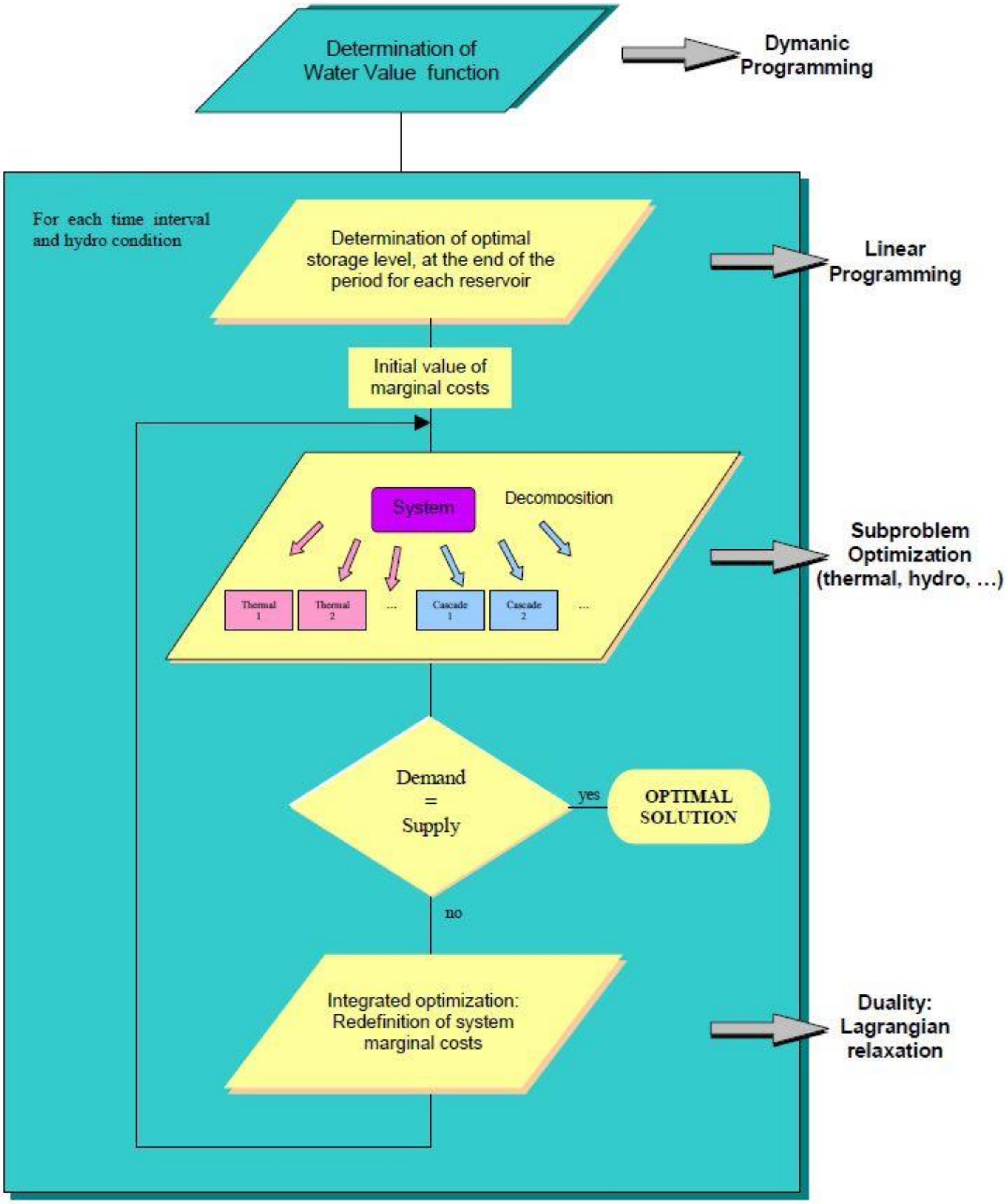


Figure 2: VALORAGUA methodology flowchart

3.2 Description of PS-MORA model

PS-MORA is a planning simulation tool own by REN and its main goal is to perform reliability and flexibility studies at multi-area power systems, and, also, power flow analysis, considering different representations of the system under evaluation and different multi-area interchange models. It also allow its user to consider different models to represent the existing technologies in the electric power system, such as detailed hydro-power plants characterization and modelling.

Reliability assessment studies main purpose is to assist in decisions with uncertainty, related to events such as forced outages, unavailability of resources, among others. In general, the results of these studies are translated into reliability indexes, which can be used as relevant merit figures upon which decisions are made regarding power systems expansion planning. Historically, these studies were conducted considering deterministic approaches and, more recently, namely due to the increasing integration of intermittent renewables, probabilistic approaches, with PS-MORA following the latter.

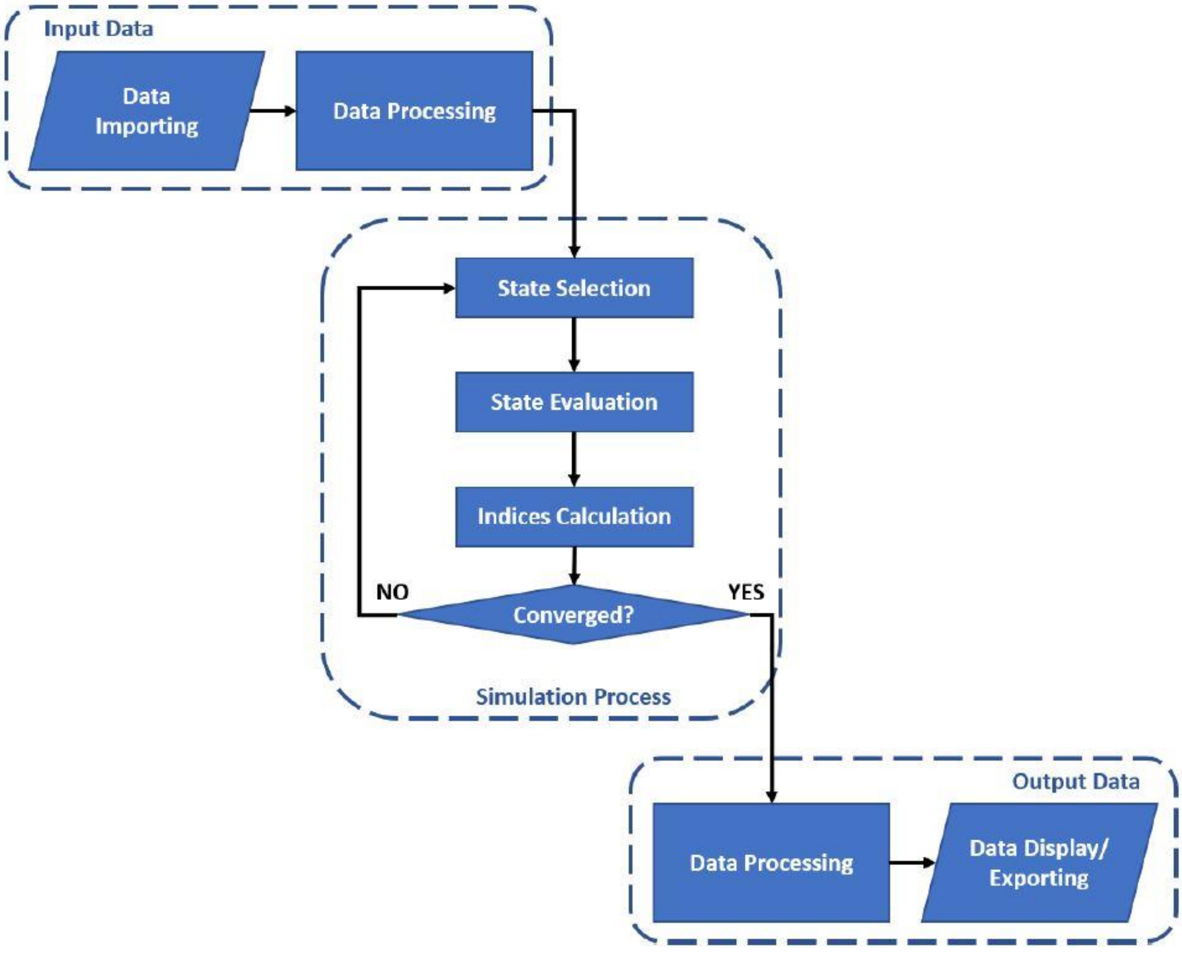


Figure 3: PS-MORA methodology flowchart

Monte Carlo simulation methods are considered the most suitable for assessing the reliability of interconnected systems, especially for complex and large systems. These methods are categorized according to the methodology adopted to represent the states of the system. If a state space representation is adopted, then the Monte Carlo simulation method is called non-chronological. On the other hand, if the states of the system are sampled considering the chronological sequence of events, then the method is called sequential/chronological. PS-MORA performs sequential/chronological Monte Carlo simulations.

The simulation process section depicted in Figure 3 represents the main steps of the Monte Carlo procedure within PS-MORA simulations. Once started, the first task of the simulation process is to generate sequences of system states. In these states, it is represented the up and down cycles (i.e. connection/disconnection) of the generating units and transmission elements (interconnections), the availability of wind, solar, hydro, mini–hydro and other generating units' primary energy resources, as well as the correspondent hour load value. After that, each state is evaluated.

PS-MORA model allows one to consider three different formulations for state evaluation. In the most traditional options, the evaluation of states of the composite system (generation plus transmission) consists of assessing whether there is a load shedding for the state under evaluation by solving a linear optimal power flow problem that considers power flow equations and restrictions of transmission capacity and generation production. Alternatively, there is an option similar to the previous one, but where network line capacities (represented by NTC) are considered, neglecting voltage angles deviations between buses. Finally, it is also possible to perform an evaluation via linear optimal power flow considering an estimate of the losses that occur in the transmission system.

In the reliability indices calculation task, the corresponding estimates are computed. It is also computed the coefficient of variation of those estimates which will be used as one of the criteria to be tested in the convergence analysis task. If the convergence criteria are not met, the Monte Carlo sequential simulation proceeds to the generating states task; otherwise, the Monte Carlo simulation process ends.

During PS-MORA simulation there is a set of different multi-area policies that can be selected, which concern support policies between areas. Multi-area policies define the way exchanges are carried out and in what manners generating units are to be scheduled, considering the availability by areas and/or the total interconnected system. Accordingly, different multi-area policies lead to different levels of reliability.

In the **Assistance based** multi-area policy, each system allocates generating units individually, aiming to meet the generation amounts necessary to cover the expected load of its own system and its primary and secondary reserve requirements previously defined by the operator. This policy follows a philosophy of not sharing the load shedding, that is, each system tries to cover its load with its own generating units and, if necessary, tries to cover the deficit through import actions, if there is export capacity in neighbouring systems. The export capacity of a given area corresponds to the amount of programmed generation not used to service the load. Eventually, if more than one system needs support, a list of support priorities is used to decide which area will have priority in the service.

In the **Market based** multi-area policy, commercial exchanges between electrical areas are acceptable, letting lower cost generating units to be allocated for neighbouring areas. This means that the Unit Commitment process is carried out jointly, so that generating units from any area can be allocated to cover the load and reserve requirements of the other areas. Power exchanges occur according to the spatial distribution of the generating units over the areas, defined after the joint allocation of all available generating units. If there is a need of load shedding due to generation deficit, the priority list of areas support is used.

For simulations carried out for the studies presented in this report, the Market based multi-area policy was preferred, as it is the one that most approximates to the representation of current and future market behaviour for Europe.

3.3 Case study and main assumptions

T1.4.2 case study comprises the CSW region which includes Portugal, Spain and France. T1.2, from whose results T1.4.2 is linked and depends, uses the e-Highways project[3] EU power system, representing the CSW region with 27 clusters. T1.4.2 aggregates those 27 clusters into 7, as depicted in Figure 4.

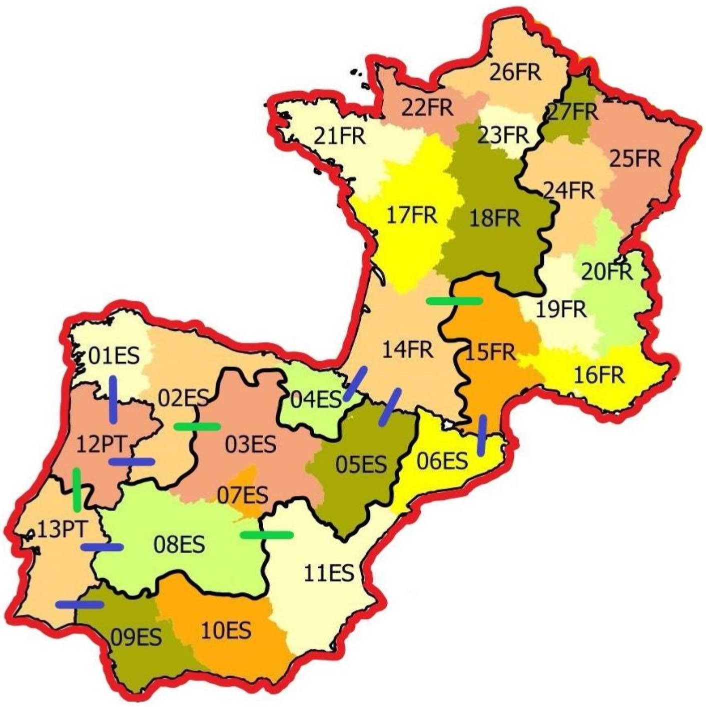


Figure 4: T1.4.2 case study representation of CSW region

The originated 7 clusters result from:

- Cluster 1: 12PT
- Cluster 2: 13PT
- Cluster 3: 01ES + 02ES + 04ES
- Cluster 4: 08ES + 07ES + 03ES + 05ES
- Cluster 5: 09ES + 10ES + 11ES + 06ES
- Cluster 6: 14FR + 17FR + 18FR + 21FR + 22FR + 23FR + 26FR
- Cluster 7: 15FR + 16FR + 19FR + 20FR + 24FR + 25FR + 27FR

There are 7 interconnections that connect clusters from different countries with respective GTC defined and provided by T1.2. Additionally, there are 4 interconnections between clusters from

[3] The e-Highway2050 project was supported by the EU Seventh Framework Programme and aimed at developing a methodology to support the planning of the Pan-European Transmission Network, focusing on 2020 to 2050, to ensure the reliable delivery of renewable electricity and pan-European market integration. The project was concluded in the end of 2015.

the same country which were modelled as infinite GTC and pose no constraints regarding energy flow within the same country.

For each one of the 27 clusters, T1.2 provides hourly data regarding load profiles, DSM activation, RES production (wind and solar), hydro management and reservoir storage levels, as well as the entire power system characterization including installed capacities (which come from D1.1 – European Long-Term Scenarios Description) and some power generation units technical characteristics. 11 meteorological years were provided in order to be used as input during Monte Carlo simulations of PS-MORA, with RES generation, hydro management and load profiles diverging between the different years. Production costs are defined by T1.2 for all generation technologies with the exception of hydro units, which come from VALORAGUA simulation outputs. Table 1 and Table 2 present the installed capacities provided by T1.1 for SCG_2030 and SCG_2050, respectively.

	Hydro ROR	Hydro Pump	Hydro Storage	PV	Wind	Coal
Cluster 1	1538	3416	1308	1422	2557	0
Cluster 2	153	704	270	120	2206	0
Cluster 3	1370	5369	5757	5015	16796	2400
Cluster 4	1856	1478	1586	18236	2585	0
Cluster 5	275	3303	3543	10337	6962	800
Cluster 6	1003	626	1669	15450	17093	0
Cluster 7	6214	4873	12968	11231	19704	0
	Gas CCGT	Gas OCGT	Nuclear	Other	Battery	P2G
Cluster 1	1500	250	0	140	0	0
Cluster 2	2500	500	0	252	0	0
Cluster 3	4500	500	0	665	0	0
Cluster 4	6500	750	3200	950	0	0
Cluster 5	15000	3000	4800	2862	0	0
Cluster 6	5000	12750	22800	0	0	3000
Cluster 7	4500	4500	22400	0	0	0

Table 1: Installed capacities – SCG_2030

	Hydro ROR	Hydro Pump	Hydro Storage	PV	Wind	Coal
Cluster 1	1538	3416	1308	11265	6127	0
Cluster 2	153	704	270	5593	3679	0
Cluster 3	1370	5369	5757	17754	36369	0
Cluster 4	1856	1478	1586	38853	26136	0
Cluster 5	275	3303	3543	36971	35632	0
Cluster 6	1003	626	1669	85086	170246	0
Cluster 7	6214	4873	12968	65583	75794	0
	Gas CCGT	Gas OCGT	Nuclear	Other	Battery	P2G
Cluster 1	500	250	0	0	563	2000
Cluster 2	500	0	0	0	0	2500
Cluster 3	2000	1250	0	520	1286	4500
Cluster 4	1500	3000	0	764	2102.75	4000
Cluster 5	1000	500	0	1907	1890.5	5000
Cluster 6	6500	25750	0	133	3237.3	20000
Cluster 7	4500	11500	0	0	3375	12500

Table 2: Installed capacities – SCG_2050

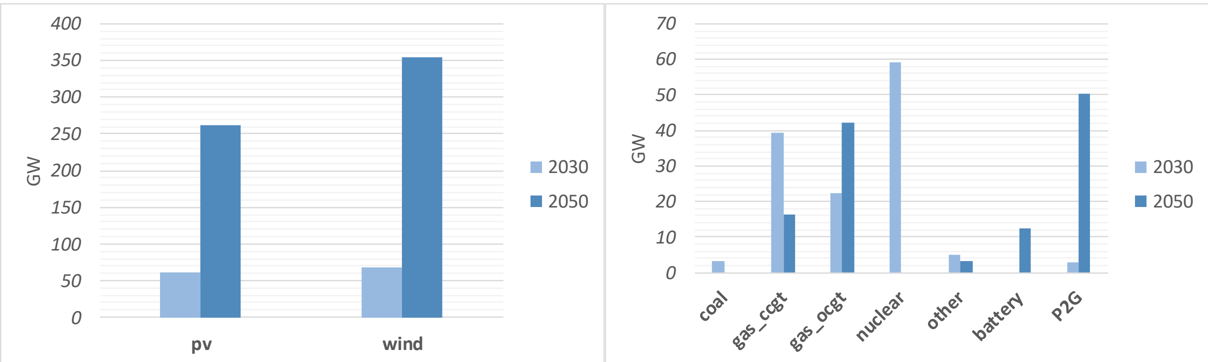


Figure 5: Comparison between installed capacities for SCG_2030 and SCG_2050

Figure 5 illustrates the main differences regarding installed capacities between SCG_2030 and SCG_2050. There is a significant increase of wind, PV and P2G (units that burn natural gas from previously made electrolysis) installed capacities, a complete phase-out of coal and nuclear, a replacement of CCGT units with OCGT capacity and the increase of batteries. DSM is not listed above as it was not modelled with specific installed capacity within PS-MORA simulations. After analysing and discussing T1.2 results with the partners involved in that task, it was understood that as DSM from EV is already optimally managed by T1.2 and as DSM from heat-pump is not activated for the CSW region, the best practice would be to include the effect of EV charging management directly into the load profiles used as input for PS-MORA.

The amount of energy available each week to be produced from hydro, P2G, and batteries is defined based on T1.2 results. Based on merit order criteria, PS-MORA will define hourly unit-commitments.

Components such as DSM, battery charging, pumping and electrolyser are added to the provided load profiles, for each cluster. Additionally, clusters from France will also consider within their load profiles the impact of energy interchange (from T1.2 results) between other EU countries (not considered within CSW region): exporting to EU increases load profile; while importing from EU decreases load profile.

Figure 6 shows load profile changes for cluster 6 and SCG 2050 – *Year 1* – that come from including DSM, battery, pumping and electrolyser managements, creating the "First step Load" profile. Figure 7 illustrates the "Final Load" profile for cluster 6 and SCG 2050 – *Year 1* – after adding the energy exchange between cluster 6 and the interconnected clusters from the rest of Europe.

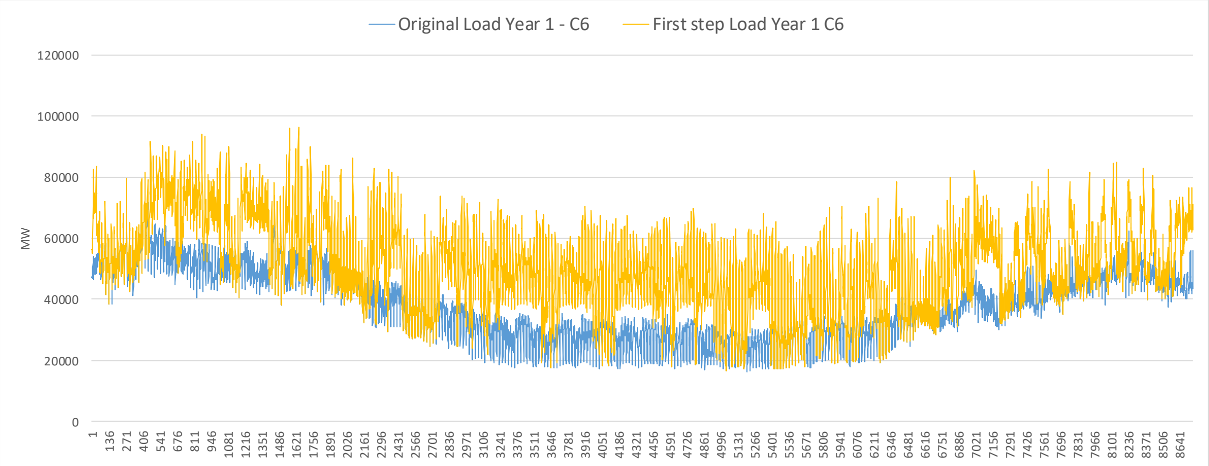


Figure 6: Changes in load profile of Cluster6 SCG_2050 – year 1 – after adding impact from DSM, battery, pumping and electrolyzer

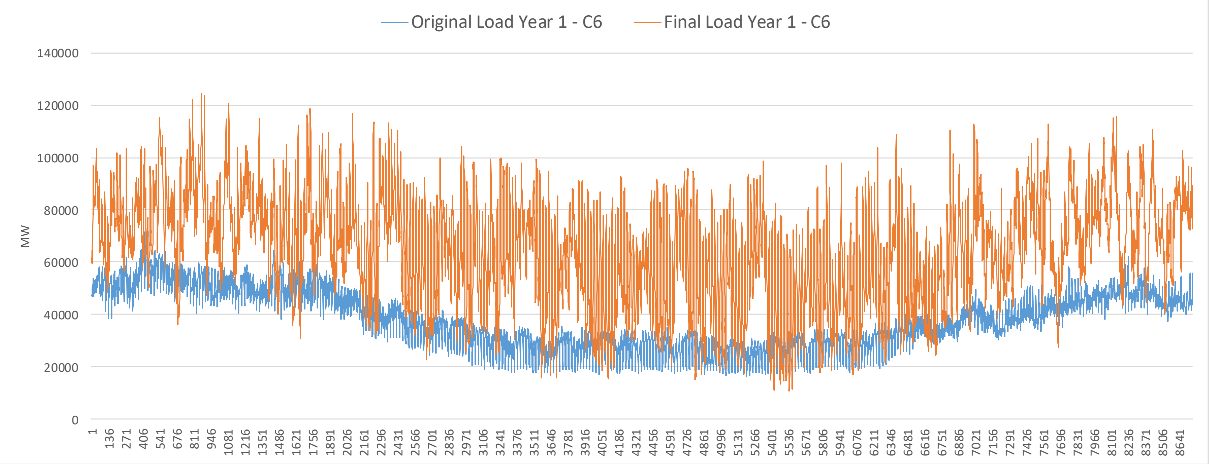


Figure 7: Changes in load profile of Cluster6 SCG_2050 – year 1 – adding energy interchange between other EU countries to the "First Step" load profile (above)

Regarding forecast error modelling, as no alternative was given in time from any other partner/WP, T1.4.2 will use as reference REN internal data regarding its own wind and solar power forecast error CDF (cumulative distributed function), scaling it up and down based on installed capacities of each one of the 7 considered clusters. CDF data used can be consulted in Table 3.

Wind			Solar	
uncert. (p.u.)	cum. prob.		uncert. (p.u.)	cum. prob.
-0.218971	0.000019		-0.205200	0.000000
-0.194641	0.000057		-0.182400	0.000000
-0.170311	0.000152		-0.159600	0.000114
-0.145981	0.000647		-0.136800	0.000343
-0.121650	0.003006		-0.114000	0.001256
-0.097320	0.010047		-0.091200	0.004681
-0.072990	0.030426		-0.068400	0.015413
-0.048660	0.080584		-0.045600	0.046124
-0.024330	0.201697		-0.022800	0.137116
0.000000	0.463866		0.000000	0.375614
0.024330	0.826084		0.022800	0.765156
0.048660	0.953134		0.045600	0.929444
0.072990	0.986871		0.068400	0.981048
0.097320	0.995909		0.091200	0.996118
0.121650	0.998706		0.114000	0.998858
0.145981	0.999410		0.136800	0.999201
0.170311	0.999772		0.159600	0.999429
0.194641	0.999962		0.182400	0.999772
0.218971	0.999981		0.205200	0.999772
0.243301	1.000000		0.228000	1.000000

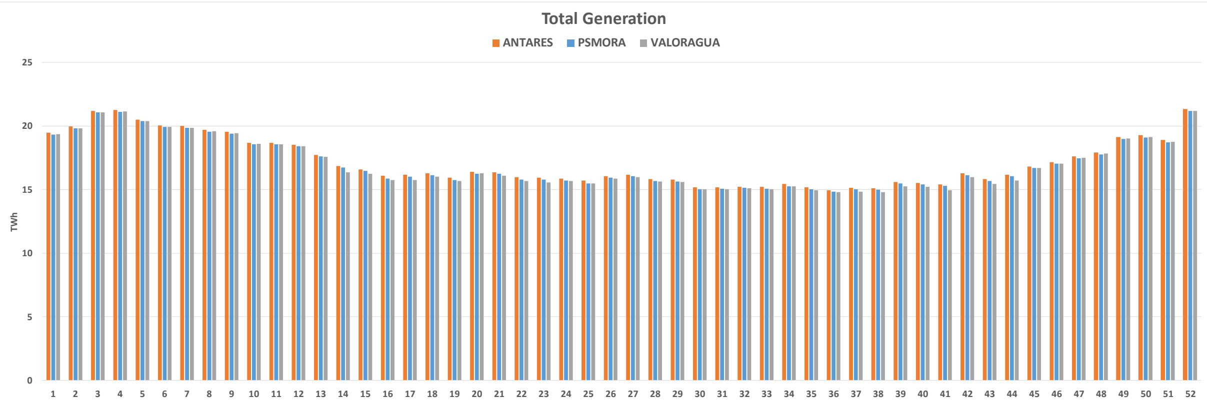
Table 3: Cumulative distribution function of RES forecast errors

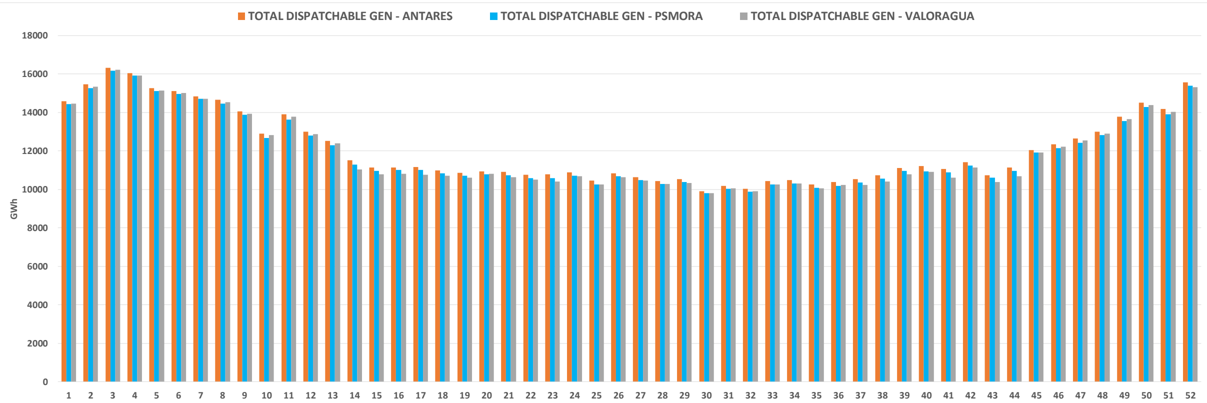
4 Simulation Results

4.1 Average Energy Production Comparison Between ANTARES, VALORAGUA and PS-MORA

As a first step, and in order to validate the modelling assumptions taken while building VALORAGUA and PS-MORA simulation cases, a comparison between high-level results of ANTARES and T1.4.2 simulation tools is presented below. Although the scope of ANTARES and PS-MORA simulations is somewhat different, namely by the inclusion within PS-MORA environment of uncertainty from RES generation and the evaluation of hourly system flexibility to cope with such unforeseen generation deviations, it is important to note that the main simulation conditions and assumptions remain the same along all studies of WP1 (and desirably other WPs working with related data).

Accordingly, simulation results regarding final total generation, total dispatchable generation, total renewable generation, as well as discriminated wind and solar total generations are presented below while comparing ANTARES, PS-MORA and VALORAGUA.





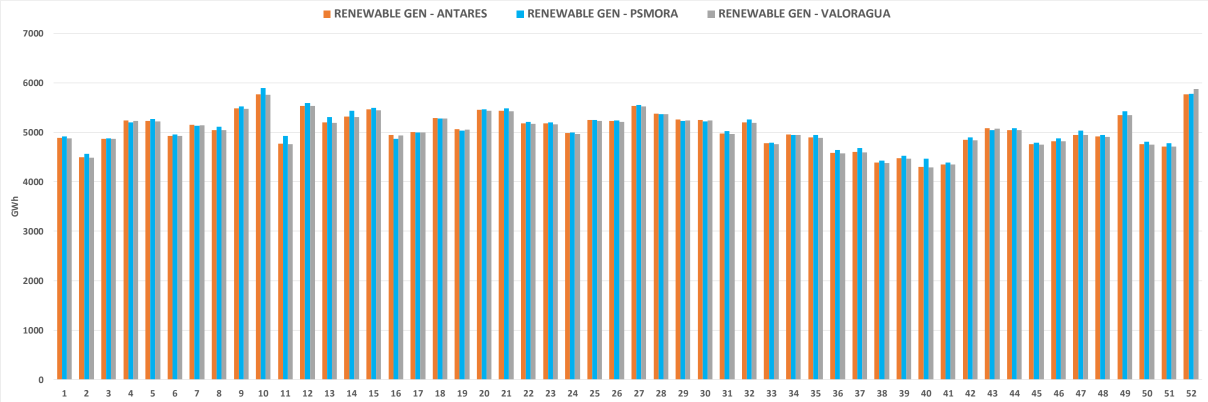


Figure 8: Total weekly Generation, Total Dispatchable Generation, Total Renewable Generation for SCG2030

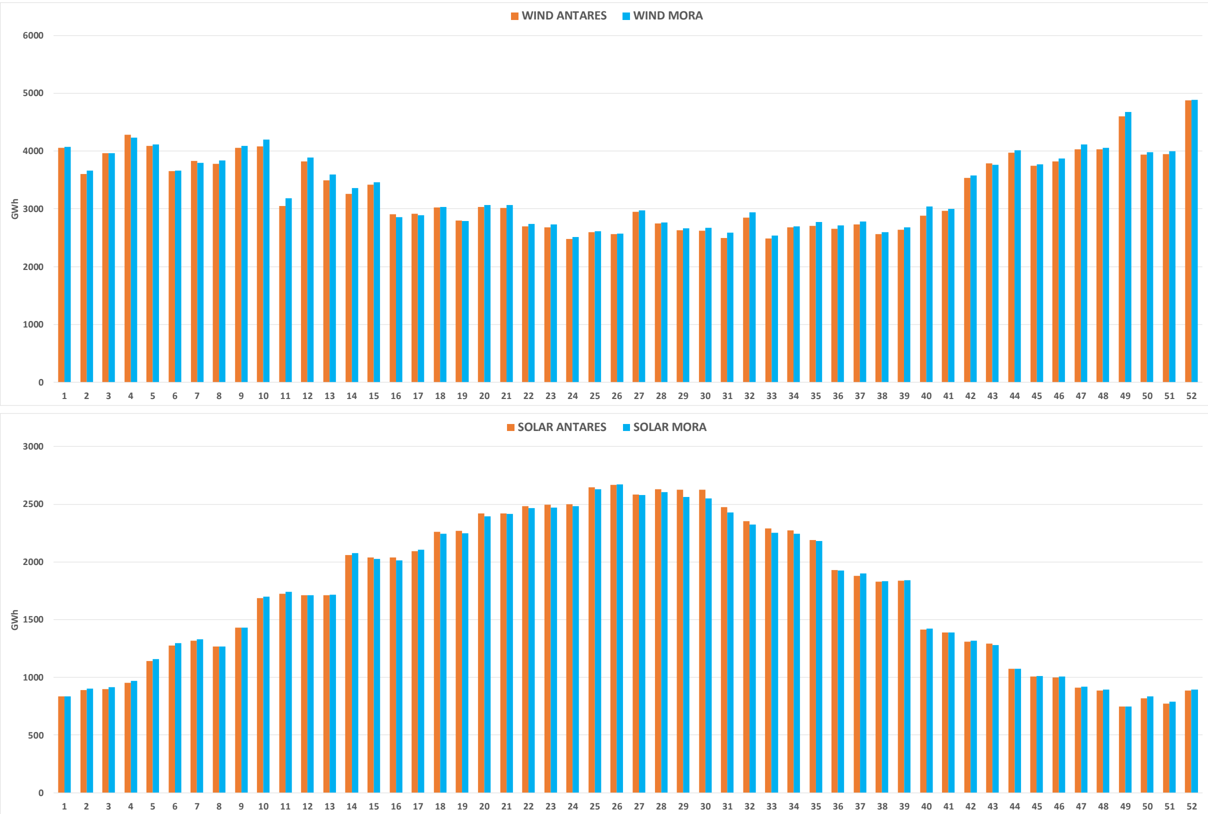


Figure 9: Wind and Solar total weekly generation for SCG2030

Figure 8 and Figure 9 validate the high-level result comparison for SCG_2030. Although T1.4.2 aggregates the original 27 clusters into only 7 clusters, and consequently having to rebuild load and RES generation profiles, ANTARES and PS-MORA production results are in line. It is important to note that uncertainty from RES generation is accounted for PS-MORA simulations, and, also, due to long simulation times, only 100 Monte Carlo years were simulated while there is 11 sample years used as input from T1.2. A greater number of Monte Carlo simulation years would have to be accounted in order to approximate PS-MORA final results even more to the average generation results from ANTARES used here as comparison.

As previously explained, VALORAGUA is responsible of calculating hydro market bid prices which are then used by PS-MORA for simulation of the hourly market process. Table 4 presents the weekly market bid prices calculated for SCG_2030, presenting, as example, data for *Year 1* (out of 11 in total) for Hydro Storage and Hydro Pump. Additionally, Table 5 presents the weekly market bid prices for the Hydro Storage unit from cluster 1, for SCG2030 and for all the 11 years used as input from T1.2 results.

Week	HStor1	HPmp1	HStor2	HPmp2	HStor3	HPmp3	HStor4	HPmp4	HStor5	HPmp5	HStor6	HPmp6	HStor7	HPmp7
1	114.60	118.44	116.72	118.41	115.20	115.27	117.36	158.75	117.61	159.20	116.88	141.66	13.82	18.77
2	112.98	145.59	115.52	145.59	114.62	115.50	117.12	117.81	117.55	145.59	116.72	145.59	13.78	16.80
3	113.32	118.08	115.45	139.94	115.52	116.06	116.66	124.56	117.60	145.05	116.35	144.80	13.66	15.41
4	113.57	145.59	114.70	145.59	145.59	145.59	116.87	145.59	117.62	145.59	116.72	145.59	13.74	15.89
5	115.66	116.83	115.59	145.59	145.59	116.04	117.06	117.81	117.57	117.99	116.73	145.59	13.81	14.76
6	114.12	156.75	115.59	145.59	115.55	115.68	116.74	158.86	117.51	159.26	117.23	117.68	13.81	16.09
7	113.01	116.04	115.37	145.59	114.02	114.17	116.80	117.46	117.43	117.83	117.20	145.59	13.83	17.29
8	114.60	155.72	117.27	145.59	114.52	114.67	117.28	117.47	117.62	117.90	117.33	145.59	13.88	16.21
9	112.86	115.13	115.46	117.81	114.13	114.23	116.29	117.93	117.36	117.67	116.46	135.64	13.75	15.08
10	114.97	156.50	116.47	118.90	115.36	115.42	117.04	119.21	117.54	159.18	116.90	119.60	13.84	15.32
11	117.00	117.13	117.23	145.59	116.92	116.80	117.29	117.46	117.53	117.56	116.84	145.59	13.87	15.31
12	113.34	115.76	116.37	120.01	114.70	114.71	117.13	117.53	117.48	117.67	117.03	118.21	13.85	16.88
13	110.36	114.51	114.11	117.47	112.90	112.98	115.99	117.14	117.37	117.68	117.01	118.98	13.83	13.88
14	103.13	140.33	105.38	111.78	104.01	103.92	106.58	142.87	109.80	110.90	106.74	110.93	13.85	18.74
15	36.20	36.40	36.94	38.64	36.37	36.36	37.17	37.19	38.28	38.41	37.59	38.69	13.85	15.26
16	19.90	20.29	20.27	20.88	20.17	20.25	20.78	20.72	21.53	21.51	21.45	21.43	13.87	18.76
17	29.81	29.90	30.25	32.72	29.86	29.83	146.02	30.48	31.30	31.27	30.70	30.62	13.88	13.85
18	16.38	16.69	16.60	17.37	16.67	16.63	145.59	16.91	17.25	17.25	16.84	16.90	13.86	13.87
19	35.30	35.31	35.88	37.75	35.30	35.26	145.59	35.89	36.55	36.53	35.53	35.52	13.89	13.87
20	13.81	14.21	14.00	15.79	14.17	14.17	145.59	14.44	14.77	14.79	14.63	14.54	13.88	13.87
21	20.79	20.91	21.05	21.36	145.59	20.80	145.59	21.13	21.48	21.46	21.00	20.88	145.59	13.87
22	146.06	50.13	146.00	52.38	50.02	49.99	145.59	50.91	52.06	52.14	146.05	51.44	145.59	13.88
23	13.73	13.99	13.97	17.37	13.95	13.94	145.59	14.20	14.44	14.43	14.19	14.12	145.59	13.85
24	34.86	34.95	35.43	35.72	34.63	34.67	145.59	35.25	35.78	35.77	34.85	46.91	145.59	18.74
25	13.76	14.01	14.03	17.37	13.97	13.97	145.59	14.23	14.42	14.43	14.00	14.00	145.59	13.87
26	37.34	37.33	38.11	38.35	37.28	37.13	145.59	38.01	38.58	38.59	37.50	37.26	145.59	13.86
27	14.16	14.22	14.31	17.37	14.14	14.16	145.59	14.42	14.53	14.60	14.20	14.18	13.90	13.88
28	15.53	15.55	15.73	17.37	15.46	15.48	145.59	15.76	15.90	15.95	15.51	15.52	13.90	13.88
29	14.42	14.44	14.60	17.37	14.36	14.36	145.59	14.57	14.78	14.78	14.54	14.47	13.90	13.87
30	13.93	13.96	14.11	17.37	13.90	13.91	145.59	14.10	14.24	14.26	13.93	13.91	13.89	13.86
31	14.96	14.96	15.13	17.37	14.76	14.79	145.59	15.10	15.21	15.25	14.85	14.83	13.90	13.88
32	145.61	29.96	145.61	30.69	29.50	29.45	145.59	30.15	30.48	30.44	145.60	29.52	145.59	13.88
33	145.59	20.93	145.59	21.76	20.46	20.61	145.59	21.07	21.17	21.28	145.59	20.63	13.90	13.88
34	17.18	17.19	17.43	17.77	17.06	17.13	17.44	17.42	17.51	17.62	17.13	17.17	13.86	13.87
35	19.74	19.75	20.01	20.20	19.54	19.57	19.93	19.93	20.06	20.19	19.55	19.59	13.87	13.87
36	17.68	17.77	17.91	18.08	16.92	17.04	17.46	17.48	17.63	17.72	17.01	17.05	13.86	13.87
37	43.46	43.49	43.97	43.87	30.91	32.65	31.91	32.04	32.26	32.50	31.18	31.20	13.88	13.87
38	146.59	41.10	146.60	41.46	29.27	29.45	30.12	30.17	30.47	30.55	29.46	29.46	13.87	13.85
39	145.59	92.36	145.59	93.21	66.10	66.65	67.99	68.17	68.68	69.14	66.83	67.14	13.87	13.87
40	80.63	81.43	81.80	83.50	79.17	79.63	80.81	82.54	81.58	83.12	79.51	79.91	13.86	13.87
41	53.47	53.66	54.36	54.99	53.24	53.24	54.13	54.18	54.70	54.74	53.39	72.14	13.89	18.77
42	65.57	65.85	66.95	68.67	65.76	65.73	67.23	67.26	69.06	70.02	67.98	68.17	13.88	13.88
43	147.47	31.10	147.44	31.83	30.62	30.61	31.29	31.33	31.70	31.73	30.67	30.70	13.89	13.88
44	85.35	115.50	86.53	88.70	83.93	84.00	86.55	87.11	88.46	88.99	86.92	87.49	13.89	13.88
45	114.37	116.03	116.54	119.56	115.15	115.13	117.18	117.25	117.47	117.74	116.97	119.02	13.88	17.36
46	115.88	116.33	117.16	118.11	115.78	115.75	117.30	133.74	117.49	118.66	117.17	158.68	13.87	17.47
47	115.43	116.38	117.10	119.36	115.10	115.12	117.11	117.64	117.50	120.75	116.88	117.53	13.87	16.35
48	115.27	116.33	116.88	117.90	115.05	115.02	117.03	118.91	117.55	121.68	116.94	121.27	13.84	16.99
49	113.36	145.59	115.73	145.59	114.31	114.34	117.10	117.55	117.69	145.59	117.19	145.59	13.87	15.64
50	116.27	117.34	117.28	145.59	145.59	116.93	117.40	117.83	117.64	145.59	117.16	145.59	13.86	16.53
51	114.66	116.57	115.91	135.57	116.19	116.14	116.94	117.70	117.54	142.93	117.05	141.14	13.82	16.19
52	116.18	116.64	117.37	145.59	145.59	115.69	117.47	117.51	117.91	159.10	117.29	158.97	13.87	16.46

Table 4: Hydro market bid prices calculated with VALORAGUA – SCG2030 – Year 1

Week	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
1	114.60	113.53	113.82	112.74	115.03	112.49	116.90	111.80	114.77	114.60	112.40
2	112.98	116.22	116.29	115.33	115.36	116.10	115.43	114.56	115.68	116.48	116.36
3	113.32	114.10	113.21	113.65	113.13	114.09	112.71	112.80	113.14	113.13	113.79
4	113.57	112.88	115.56	116.19	113.72	113.97	112.71	117.04	113.76	113.79	113.64
5	115.66	114.16	112.43	113.56	112.41	112.92	114.61	113.92	112.75	112.03	111.83
6	114.12	111.79	111.74	110.72	114.89	113.99	112.43	114.98	112.49	113.89	116.27
7	113.01	112.24	111.35	114.95	110.76	116.36	112.17	115.55	112.70	115.23	115.94
8	114.60	115.51	115.98	112.50	112.00	113.18	113.24	111.19	145.59	115.28	107.77
9	112.86	111.32	111.07	112.37	114.05	113.79	111.47	111.50	112.78	112.26	112.06
10	114.97	115.92	115.60	116.03	116.16	115.85	116.17	115.33	115.75	116.23	115.66
11	117.00	113.84	112.53	113.11	113.73	114.11	115.18	113.44	113.64	114.54	113.29
12	113.34	114.23	114.89	115.30	115.62	114.15	114.83	114.19	114.91	114.17	114.85
13	110.36	112.12	114.61	113.91	114.23	113.27	113.70	113.46	113.03	113.41	111.78
14	103.13	66.25	61.12	53.02	65.94	115.52	82.41	61.12	57.10	56.53	63.60
15	36.20	54.72	38.69	20.78	50.22	24.51	38.39	30.74	22.10	23.69	23.17
16	19.90	19.91	33.73	39.54	32.11	23.34	29.25	21.67	75.77	37.11	31.87
17	29.81	49.71	37.44	42.63	33.77	29.68	48.37	39.67	37.83	28.92	27.48
18	16.38	15.76	13.81	23.56	15.05	25.34	21.60	17.30	16.88	22.94	33.50
19	35.30	31.67	23.51	25.95	30.27	16.83	30.67	25.89	23.97	33.03	32.58
20	13.81	16.41	21.40	18.06	14.16	19.03	13.65	15.95	13.84	17.38	23.35
21	20.79	19.18	22.50	20.95	23.18	20.17	26.04	16.02	20.06	28.07	21.21
22	146.06	24.38	31.76	146.05	22.31	24.26	146.35	19.26	18.64	19.18	21.70
23	13.73	146.27	13.63	14.04	17.48	146.25	14.54	18.33	20.52	145.92	146.12
24	34.86	15.53	30.52	145.59	145.83	31.36	145.65	26.91	146.01	16.15	145.59
25	13.76	145.77	14.06	13.82	13.75	13.63	13.65	13.85	15.88	145.71	13.70
26	37.34	16.24	145.59	145.59	145.59	46.84	48.46	41.75	34.22	16.71	145.59
27	14.16	18.03	13.92	15.58	15.58	13.92	13.95	13.81	13.74	17.05	13.88
28	15.53	17.85	16.36	16.79	18.38	14.20	14.19	16.81	14.30	15.66	16.28
29	14.42	17.96	19.04	19.84	145.90	145.59	18.35	14.20	29.94	22.80	19.08
30	13.93	13.93	13.91	14.04	13.86	13.87	13.95	14.01	13.94	13.99	13.88
31	14.96	17.36	16.78	145.59	16.58	16.91	14.54	14.13	15.85	14.17	16.08
32	145.61	15.55	14.43	14.22	15.40	30.37	14.25	34.44	20.82	145.59	14.46
33	145.59	18.20	23.65	20.62	38.11	24.40	17.70	14.00	14.89	14.30	18.63
34	17.18	17.82	13.94	15.92	14.82	17.47	19.56	145.59	15.40	14.44	16.76
35	19.74	19.86	145.59	15.52	19.23	22.28	145.95	14.12	20.42	23.31	145.75
36	17.68	20.22	18.28	29.67	145.89	35.12	14.32	28.28	14.36	14.41	15.42
37	43.46	58.26	35.88	46.79	26.06	146.53	54.03	37.13	44.99	145.59	145.64
38	146.59	146.94	146.40	146.67	145.95	145.59	146.82	146.61	146.57	145.59	145.59
39	145.59	145.59	145.59	145.59	145.59	145.59	145.59	145.59	145.59	145.59	145.59
40	80.63	145.59	80.13	75.98	59.87	35.39	79.12	145.59	145.59	145.59	81.53
41	53.47	49.63	44.25	91.31	59.66	83.70	84.49	88.30	77.67	61.67	66.67
42	65.57	92.93	96.11	106.79	115.85	97.87	109.74	114.60	115.75	115.22	100.17
43	147.47	146.97	147.06	30.41	41.35	147.14	36.30	35.93	41.84	145.72	147.14
44	85.35	48.17	64.94	74.15	79.68	50.43	59.27	60.47	60.56	77.53	85.73
45	114.37	115.21	115.84	115.00	114.40	114.75	114.10	115.70	115.25	115.69	115.13
46	115.88	115.22	115.90	115.22	115.22	115.18	114.91	115.22	115.70	115.98	115.13
47	115.43	114.52	112.94	115.87	115.84	115.76	115.80	115.15	115.08	114.58	114.65
48	115.27	115.47	114.12	115.01	115.40	114.90	115.21	114.93	114.30	114.31	115.10
49	113.36	114.68	111.70	113.98	114.78	113.49	114.76	113.80	114.31	113.30	114.29
50	116.27	115.40	113.02	116.49	115.18	112.82	116.04	115.18	116.52	115.46	116.54
51	114.66	116.12	145.59	112.70	116.54	115.97	116.25	116.25	115.50	115.50	115.59
52	116.18	115.56	116.22	115.56	114.63	115.57	114.97	115.46	114.28	115.95	115.45

Table 5: Hydro market bid prices for Hydro Storage1 calculated with VALORAGUA – SCG2030 – all years

The use of these hydro market bids within PS-MORA simulations is one of the major differences regarding ANTARES simulations, where hydro generation is scheduled to minimise the total system costs without any explicit water value or production cost but considering the limited energy available (similar to using production cost = 0 during PS-MORA simulations). VALORAGUA was designed with a two-fold set of objectives: define the optimal water management for an entire year of operation; and calculate the respective weekly market bids ("value of water") for each hydro generation power plant. Nevertheless, for this WP1 study, water management is being defined during T1.2 using ANTARES, which deeply constrains VALORAGUA simulations and consequently the quality of its results. Furthermore, if the set of simulations years provided by T1.2 accounted for several hydrological conditions (instead of just considering an average hydrological condition) the market bid price differences regarding hydro units in each year would be larger, as water availability would also be significantly different.

In Annex 6.1 one can find total production per technology and per cluster while comparing results from ANTARES and PS-MORA. Hydro generation, for the reasons explained above, are sometimes quite dissimilar, which in fact, as demand levels are the same for both simulation, need to be compensated by other technologies such as Gas. Also worth noting is the fact that PS-MORA case study only represents 7 clusters (from the original ANTARES 27), and so, when comparing total generations one should try to make comparisons regarding total country productions. Finally, as all thermal-based generation units have the same production cost per technology, for clusters within the same country, if interconnection flow is not reaching any constraint, from the objective function perspective (minimization of production costs) it is indifferent which Gas unit (for example) is scheduled to produce: one located in cluster 6 or other in cluster 7. On the contrary, for clusters from different countries this effect is tackled by PS-MORA with the introduction of the so-called hurdle costs, which impose a small penalty on the use of inter-country interconnections just enough to make sure that demand from a country "A" is not being supplied by a generation unit technology from country "B" (which has the same costs as one available to produce in country "A"). This is a practical procedure used to introduce the impact of losses when studying interconnected systems represented by the NTC/GTC capacities that connect them, and is especially useful when production costs are equal among the same technologies across the entire system modelled.

For the sake of clarity, and in order to demonstrate the aptitude and technical capabilities of PS-MORA to adapt to different modelling assumptions the user might define, Annex 6.2 represents what would be the hydro production per cluster, again comparing to ANTARES results, if VALORAGUA hydro market bids were ignored and hydro production costs were zeroed.

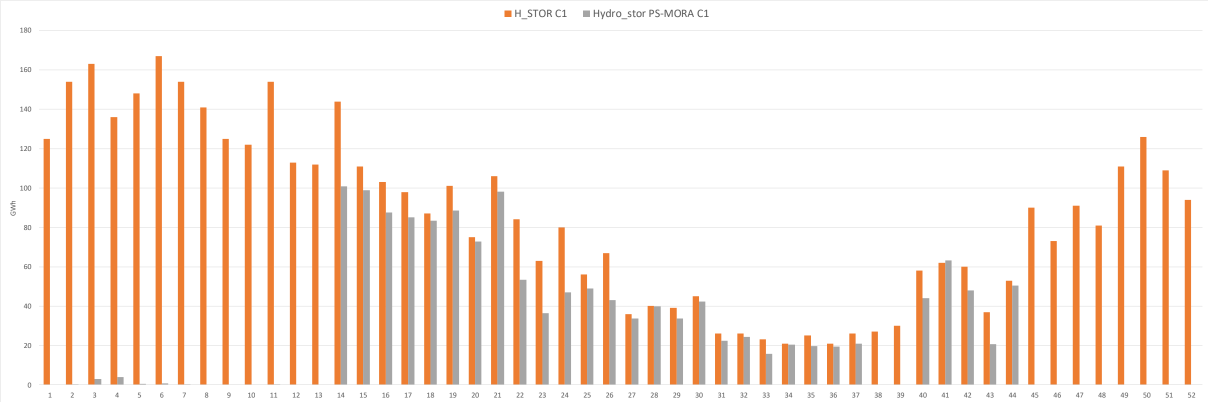


Figure 10: Hydro Storage #1 production comparison between ANTARES and PS-MORA using VALORAGUA computed hydro market bid prices

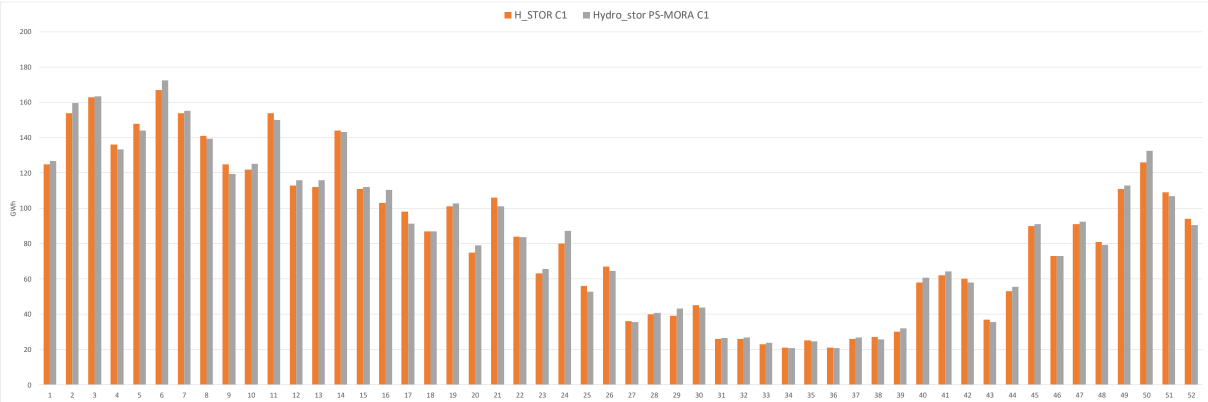


Figure 11: Hydro Storage #1 production comparison between ANTARES and PS-MORA using hydro market bid prices = 0 €/MWh

As one can see in Annex 6.2 and also comparing Figure 10 and Figure 11, PS-MORA hydro generation for all cluster would be very much aligned with what ANTARES presented in T1.2, in contrast with what happens when using VALORAGUA computed hydro market bid prices. Nevertheless, as the studies scope is different, namely by PS-MORA trying to evaluate the system hourly flexibility to cope with RES forecast uncertainty, REN considers that using more realistic market bid prices for hydro units allows those units to be more available to respond to flexibility requests when upward reserves are needed.

For countries such as Portugal (and Spain), with a significant share of hydro capacity, namely with large reservoirs that enable weekly and even seasonal storage and others with pump capabilities, the simplification of scheduling all hydro generation as base production (equivalent of production costs = 0 €/MWh during PS-MORA simulations) as ANTARES assumes, must be avoided (when performing studies with the same scope of PS-MORA). For that reason, VALORAGUA weekly market bid prices for hydro units are used regarding the simulation results presented in the following sections.

4.2 Adequacy Assessment Simulation Studies for CSW Region Using PS-MORA Model

In this section, results from reliability studies performed using PS-MORA are presented for SCG_2030 and for SCG_2050. Here, main security of supply indices are computed, namely the Loss of Load Probability, Loss of Load Expectation, Expected Power Not Supplied and Expected Energy Not Supplied.

As already explained in this report, case studies for SCG_2030 and SCG_2050 are deeply dependent and constrained by outputs from T1.2 ANTARES simulations. The major difference and benefit that PS-MORA offers is the capability of performing operational reserve assessments while introducing hourly uncertainty coming from RES.

Put in simple terms, after the Unit Commitment is settled based on the hourly forecast of RES, load, and planned maintenance of thermal-based units, a power deviation is forced into RES output based on the forecast error CDF presented in Table 3. At this point, the hourly flexibility of the system is assessed taking into account the response from primary and secondary reserve requirements taken into account during UC definition, and, also, from additional power variations from scheduled and/or fast-response units (e.g. hydro or gas turbines units) as well as last resort activation of DSM, and battery (tertiary reserve/replacement reserve).

PS-MORA is also able to perform static reserve analysis which do not account for RES forecast error uncertainty. Static reserve assessment from PS-MORA show that, for SCG_2030 and SCG_2050, no stressful event is expected.

Table 6 presents the Operational reserve assessment results, providing the probabilistic security of supply indices while considering uncertainty from RES generation and from thermal-based units forced outages. Although PS-MORA allows for the modelling of short-term demand uncertainty, for the scope of this study it was not considered.

	CSW System	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
LOLP (prob.)	0	0	0	0	0	0	0	0
LOLE (h/year)	0	0	0	0	0	0	0	0
EPNS (MW)	0	0	0	0	0	0	0	0
EENS (MWh/year)	0	0	0	0	0	0	0	0

Table 6: Operational reserve assessment for SCG_2030 considering RES uncertainty and forced outages

Table 6 shows that for the SCG_2030 simulation the flexibility modelled within the CSW region is enough to cope with both the uncertainty coming from the forecast error of RES generation as well as from forced outage rates considered for the thermal-based units.

The adequacy evaluation for the SCG_2050 presents different results, which can be consulted in Table 7 for *Year 1* based on a simulation that does not account for any type of uncertainty.

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	6.85E-04	0	6.85E-04	0
LOLE (h/year)	6	0	6	0
EPNS (MW)	1.222157	0	1.222157	0
EENS (MWh/year)	10 706.10	0	10 706.10	0
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	0	0	0	0
LOLE (h/year)	0	0	0	0
EPNS (MW)	0	0	0	0
EENS (MWh/year)	0	0	0	0

Table 7: Operational reserve assessment for SCG_2050 not considering any type of uncertainty

After carefully analysing each one of the six hours identified as LOLE, it is noted that those events come from the lack of hydro resources to tackle the individual clusters demand at those specific hours. The explanation for this fact is two-fold:

- The hydro market bid prices resulting from VALORAGUA simulations could have greater meaning if the true year-base hydro management was made by VALORAGUA; instead of receiving weekly turbined and pumped energy from ANTARES results.
- VALORAGUA simulation performs extremely well for power systems where hydro generation units are modelled explicitly and with great detail, instead of aggregated models used within the OSMOSE scope.

To tackle these limitations, hydro bid market prices were manually updated, making hydro pump units the peak units of the system – new merit order makes this type of units to be scheduled after OCGT. This has the effect of, to some extent, increase the amount of available weekly hydro energy not used, but on the other hand, during scarcity hours there is still some hydro energy available to be scheduled.

In fact, after the aforementioned hydro market bid price change, there is no adequacy problem identified during the PS-MORA simulations for the entire CSW region and considering all the 11 simulation climatic years available.

From these new premises, it is now possible to assess the impact of considering RES forecast uncertainty for the SCG_2050 scenario. The respective Operational reserve assessment results can be consulted in Table 8.

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	6.03E-04	1.14E-05	7.08E-05	2.28E-06
LOLE (h/year)	5.28	0.10	0.62	0.02
EPNS (MW)	1.963788	0.000778	0.050807	0.002329
EENS (MWh/year)	17 202.78	6.81	445.07	20.4
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	9.13E-06	5.48E-05	5.14E-04	4.57E-06
LOLE (h/year)	0.08	0.48	4.50	0.04
EPNS (MW)	0.005006	0.216325	1.682635	0.005909
EENS (MWh/year)	43.85	1 895.00	14 739.89	51.76

Table 8: Operational reserve assessment for SCG_2050 considering RES uncertainty

When considering RES forecast error, the operational reserve assessment analysis made by PS-MORA leads to LOLE of 5.28 h/year and EENS of 17202.78 MWh/year for the entire CSW region. The most affected location is cluster 6 (west France) accounting for LOLE of 4.5 h/year and EENS of 14739.89 MWh/year.

Prioritizing the security of supply, even at the expend of possible hydro generation waste, production costs for pumping hydro units and for storage hydro units are elevated in such manner that become higher than peak gas units. Table 9 presents the results from the Operation Reserve assessment made based on these updated premises.

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	8.45E-05	2.28E-06	1.83E-05	0.00E+00
LOLE (h/year)	0.74	0.02	0.16	0
EPNS (MW)	0.217218	0.000101	0.012587	0
EENS (MWh/year)	1 902.83	0.88	110.26	0
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	0.00E+00	1.14E-05	6.62E-05	0.00E+00
LOLE (h/year)	0	0.10	0.58	0
EPNS (MW)	0	0.017865	0.186664	0
EENS (MWh/year)	0	156.5	1 635.18	0

Table 9: Operational reserve assessment for SCG_2050 considering RES uncertainty and with all scheduling hydro units with increased production costs

As one can see in Table 9, with the hydro market bid price increase LOLE is reduced to below 1 h/year (0.74) and EENS reduced to around 1900 MWh/year. PS-MORA detailed results also show that this 0.74 h/year are due, mainly, to lack of transmission capacity (interconnection). It is important to stress that forced outage rates were neglected for this simulation, and if they had been included reliability indexes would possibly be aggravated. Nevertheless, this modelling configuration and assumptions, as well as security of supply results, will be used as premises and benchmark in the following analyses that will be presented in 4.3, 4.4 and 4.5 sub-chapters. There, alternative strategies will be tested, whether by investigating the impact of reserving interconnection capacity for reserve exchange, by increasing flexibility resources available in the system or by increasing and/or altering interconnection capacities.

The final analysis within this section refers to the impact that increased uncertainty levels could have on the reliability indexes presented in Table 9. To do so, the original CDF regarding RES forecast errors presented in Table 3 and used so far in the aforementioned studies need to be altered accordingly. The new CDF data can be consulted in Table 10. Figure 12 and Figure 13 illustrate the comparisons regarding the original wind and solar power forecast error CDFs graph and the ones resulting from the increased uncertainty presented in Table 10.

Wind			Solar	
uncert. (p.u.)	*cum. prob.*		*uncert. (p.u.)*	*cum. prob.*
-0.33	0.000019		-0.3	0.000000
-0.293333333	0.000057		-0.266666667	0.000000
-0.256666667	0.000152		-0.233333333	0.000114
-0.22	0.000647		-0.2	0.000343
-0.183333333	0.003006		-0.166666667	0.001256
-0.146666667	0.010047		-0.133333333	0.004681
-0.11	0.030426		-0.1	0.015413
-0.073333333	0.080584		-0.066666667	0.046124
-0.036666667	0.201697		-0.033333333	0.137116
0	0.463866		0	0.375614
0.036666667	0.826084		0.033333333	0.765156
0.073333333	0.953134		0.066666667	0.929444
0.11	0.986871		0.1	0.981048
0.146666667	0.995909		0.133333333	0.996118
0.183333333	0.998706		0.166666667	0.998858
0.22	0.999410		0.2	0.999201
0.256666667	0.999772		0.233333333	0.999429
0.293333333	0.999962		0.266666667	0.999772
0.33	0.999981		0.3	0.999772
0.366666667	1.000000		0.333333333	1.000000

Table 10: Aggravated cumulative distribution function of RES forecast errors

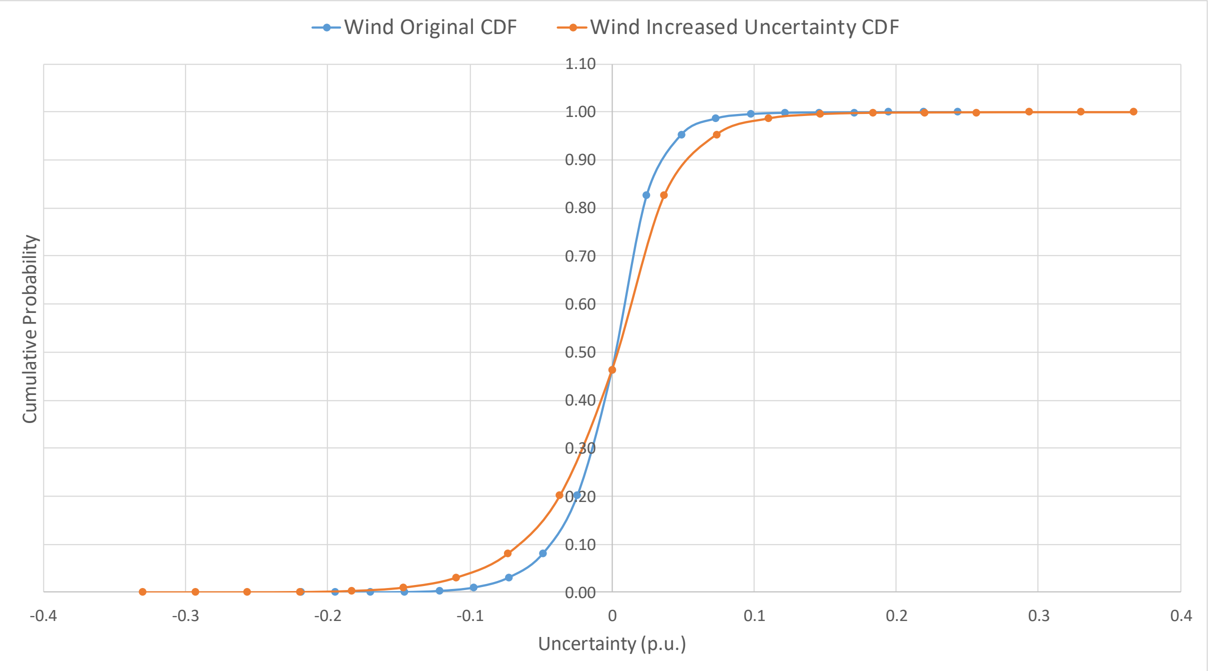


Figure 12: CDF for forecast error comparison – wind power

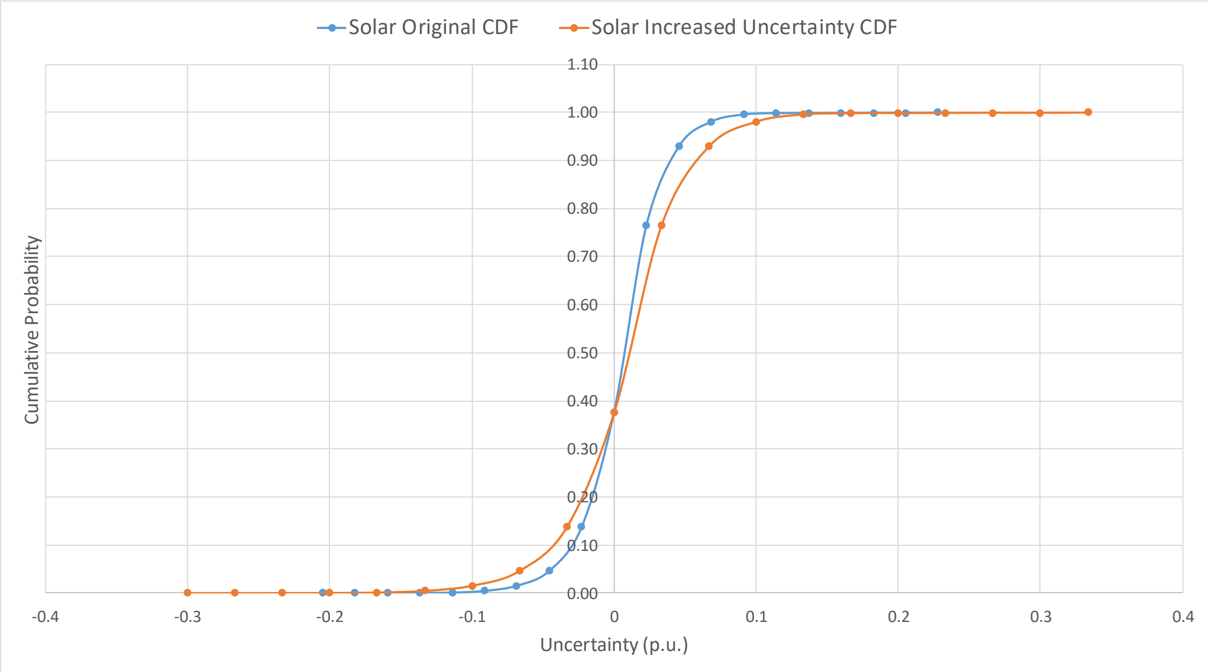


Figure 13: CDF for forecast error comparison – solar power

As one can see in Table 11, the operational reserve assessment for SCG_2050 under this increased RES uncertainty leads to aggravated reliability indexes. LOLE is up to 3.5 h/year from 0.74 h/year, and EENS is up to 14650.89 MWh/year from 1902.83 MWh/year when comparing to results previously presented in Table 9. The 3.5 h/year of LOLE result from 0.3 h/year related to Generation type of failure[4], 2.7 h/year related to Transmission[5], and 0.5 h/year result from events that combine Generation and Transmission deficits. The most affected cluster is cluster 6 with LOLE of 2.92 h/year and EENS of 13224.57 MWh/year.

[4] Generation type of failure is detected when there is no additional generation capacity to meet the demand, either by some power plant outage or when, for instance, due to deficit of RES generation comparing to the forecast, the available flexibility is not sufficient to compensate it

[5] Transmission type of failure is detected when there is generation capacity response in a determined system to support another in need, but the interconnections capacity is not sufficient to allow the assistance

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	4.00E-04	3.42E-05	6.39E-05	0.00E+00
LOLE (h/year)	3.5	0.3	0.56	0
EPNS (MW)	1.672476	0.010664	0.054117	0
EENS (MWh/year)	14 650.89	93.42	474.06	0
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	6.85E-06	2.51E-05	3.33E-04	6.85E-06
LOLE (h/year)	0.06	0.22	2.92	0.06
EPNS (MW)	0.004605	0.082806	1.509654	0.010631
EENS (MWh/year)	40.34	725.38	13 224.57	93.12

Table 11: Operational reserve assessment for SCG_2050 with increased uncertainty

4.3 Year-by-year Operational Reserve Assessment and the impact of interconnection reserve capacity during day-ahead market

In this section, results are presented for reliability studies performed for each one of the 11 representative climate years provided as input for T1.4.2. As the operational reserve assessment for Scenario Current Goals 2030 led to no problems identified from the security of supply perspective, the analyses presented in this section will focus on Scenario Current Goals 2050.

	Year 1	Year 2	Year 3	Year 4
LOLP (prob.)	1.32E-04	7.31E-05	1.23E-04	1.37E-05
LOLE (h/year)	1.16	0.64	1.08	0.12
EPNS (MW)	0.310012	0.289309	0.301644	0.043546
EENS (MWh/year)	2 715.71	2 534.35	2 642.40	381.46
	Year 5	Year 6	Year 7	Year 8
LOLP (prob.)	1.69E-04	1.14E-04	4.11E-05	2.74E-05
LOLE (h/year)	1.48	1	0.36	0.24
EPNS (MW)	0.461064	0.141057	0.087602	0.040676
EENS (MWh/year)	4 038.92	1 235.66	767.4	356.33
	Year 9	Year 10	Year 11	
LOLP (prob.)	3.65E-05	1.05E-04	5.02E-05	
LOLE (h/year)	0.32	0.92	0.44	
EPNS (MW)	0.114599	0.160383	0.145992	
EENS (MWh/year)	1 003.89	1 404.95	1 278.89	

Table 12: Operational reserve assessment for SCG_2050 on a year-by-year basis

Recalling the results previously presented in Table 9, LOLE accounted for 0.74 h/year and EENS for around 1 902 MWh/year, which were calculated during PS-MORA simulation that considered the entire set of 11 years available to be randomly picked during the Chronological Monte Carlo process.

Here, Table 12 present the reliability results on a year-by-year analysis. For each representative climate year, a PS-MORA simulation was run for 25 Monte Carlo years – load, hydro available energies and RES generation profiles are fixed, while the CDFs for RES forecast error ensure different operation conditions in each simulated year. Analysing the results in Table 12 one can verify that the particular conditions regarding load and RES generation that each year represents have a significant impact on the reliability results of the operational reserve assessment. On one hand, *Year 4* represents a LOLE of 0.14 h/year and EENS of 381.46 MWh/year, while on the other hand, *Year 5* represents a LOLE of 1.48 h/year (more than ten times, that of *Year 4*) and EENS of 4038.92 MWh/year.

As previously mentioned, PS-MORA simulation results offer the possibility of identifying what type of event led to the loss of load / energy not supplied. It categorizes the events using three types: *Generation*, where a lack of power is the reason for the event; *Transmission*, where the grid congestion/unavailability causes the event; and *Generation & Transmission*, where the simultaneous occurring of a lack of power and grid unavailability is the reason for the event.

Figure 14 illustrates the CSW region LOLE for each representative year and by type of event. It becomes clear that the key reason for LOLE is related with grid unavailability, which, in the context of this report, represents interconnection congestion, as no forced outage of transmission lines is considered.

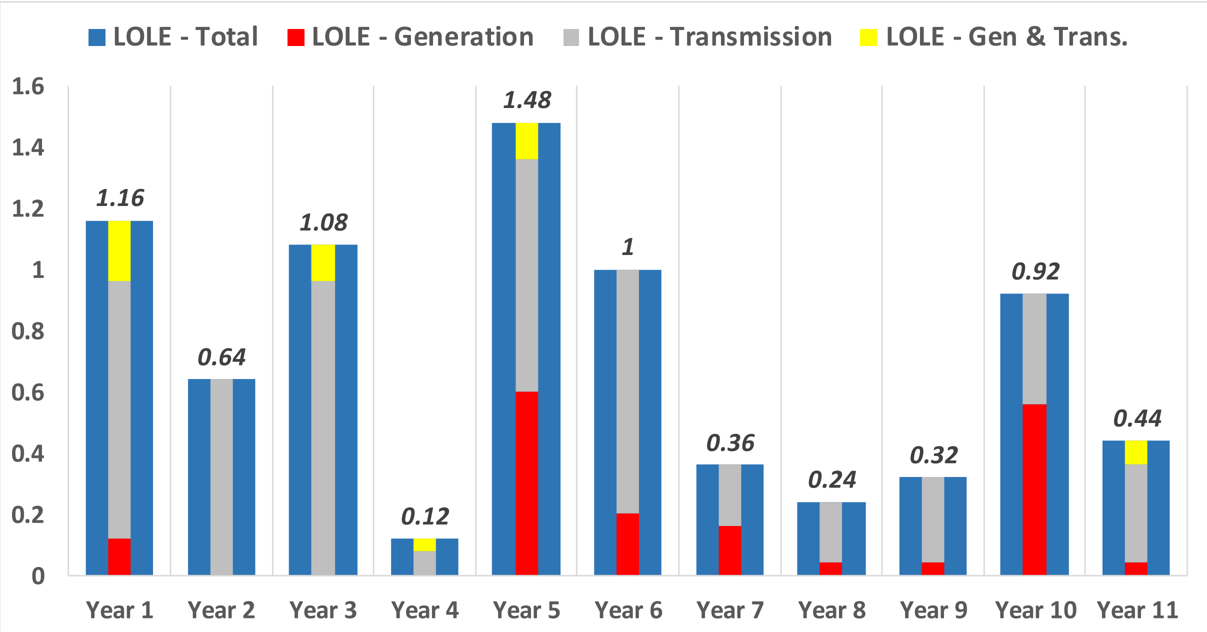


Figure 14: CSW region LOLE for each year and by type of event

Similarly, Figure 15 illustrates the representation of LOLE in cluster 6 for each year and by type of event. In this case, it is even more evident that the congestion of the interconnection lines within the CSW region is the main cause for the LOLE and EENS.

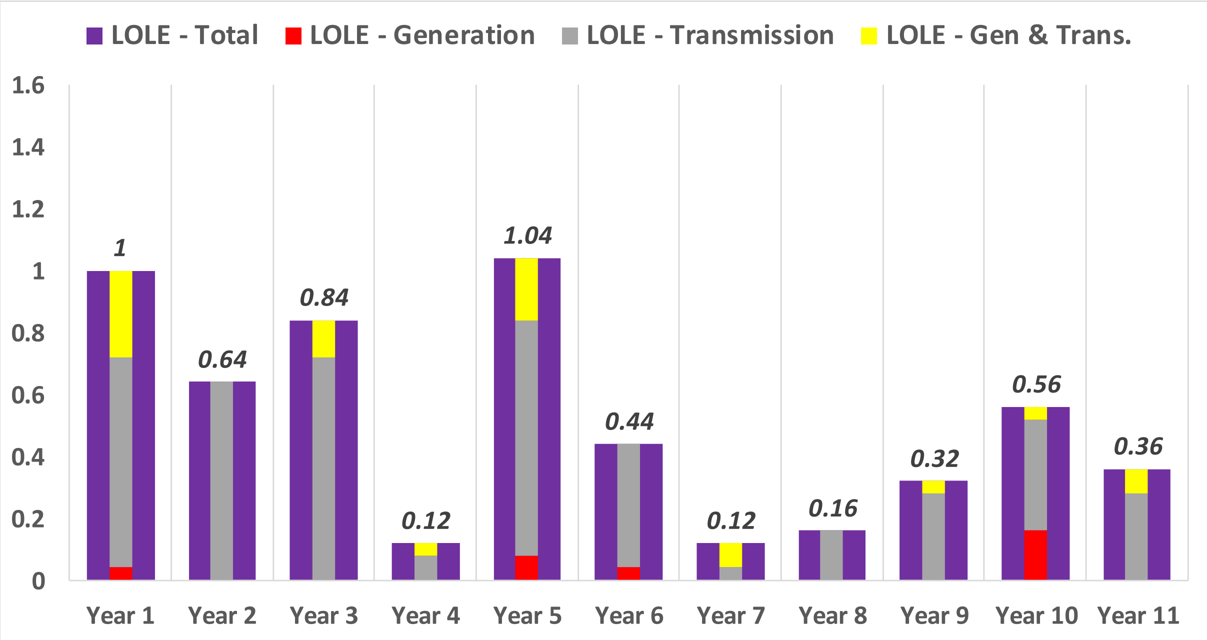


Figure 15: Cluster 6 region LOLE for each year and by type of event

It is also clear from the analysis of Figure 15 that there is a significant discrepancy regarding the reliability indexes from one climate year to the other. In order to understand what could be the factors behind those differences, operating conditions from *Year 4* and *Year 5* are compared, namely by analysing the monthly net demand and the correlation with the EENS calculated by PS-MORA. The monthly net demand is defined by subtracting combined (cluster 6 and cluster 7) RES generation (wind and solar) from the combined demand, and represents the amount of energy that needs to be supplied by the remaining dispatchable units.

Figure 16 illustrates the correlation between the monthly net demand and the EENS, for *Year 4* and *Year 5*, regarding Cluster 6 and 7 combined. As the French clusters are interconnected by infinite NTC capacity, this evaluation must considered the combined net demand and EENS.

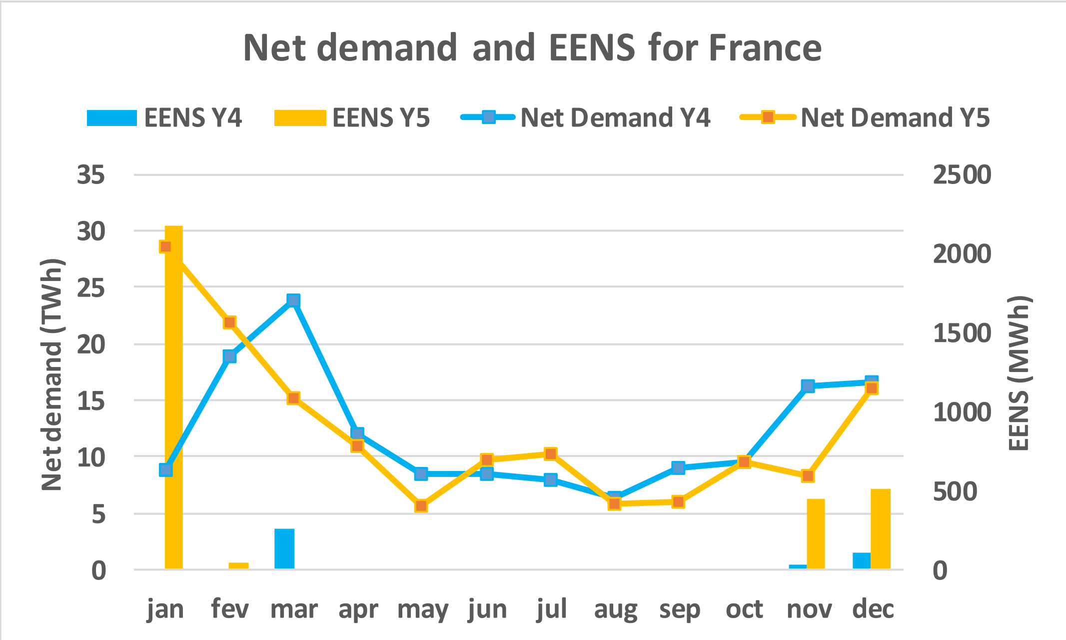


Figure 16: LOLE for each year and by type of event - Cluster 6+7 region

By analysing Figure 16 it becomes clear the connection between high levels of net demand and the EENS. For both *Year 4* and *Year 5*, EENS occurs in months that represent higher levels of net demand for clusters 6 and 7 combined, which, in turn, makes these clusters more prone to import from Iberia (or use the modelled flexible capacity available from the interconnection between France and rest of EU).

Figure 17 illustrates the monthly-accumulated energy flows of interconnection C5-C7, for each direction (i.e. ES->FR and FR->ES) and compares results from simulation of *Year 4* and *Year 5* operation conditions. Again, the influence of the net demand is evident. Taking as example the month of January where the French net demand for *Year 5* is significantly higher than for *Year 4*, it is possible to observe that Iberia is mostly exporting to France to cope with increased demand necessities from clusters 6 and 7.

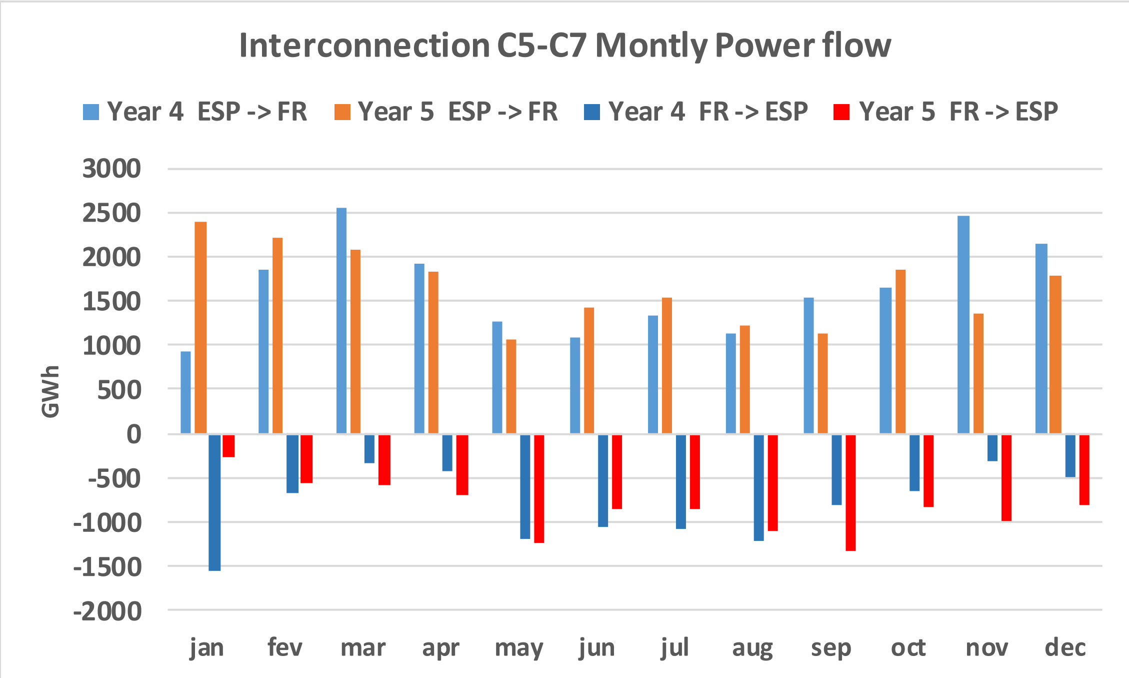


Figure 17: Power flow comparison in Interconnection C5-C7 between Year 4 and Year 5, for both flow directions

By analysing the hourly results for the month of January, it is possible to verify that:

1. There are 101 hours where interconnection C5-C7 is being used above 99% of its capacity for *Year 4*, against the 157 hours for *Year 5*
2. There are 118 hours where interconnection C5-C7 is being used above 98% of its capacity for *Year 4*, against the 185 hours for *Year 5*
3. There are 184 hours where interconnection C5-C7 is being used above 95% of its capacity for *Year 4*, against the 235 hours for *Year 5*

Accordingly, there is, in fact, a close relation between the net demand of each cluster (especially for high values) and the congestion of transmission lines connecting those clusters to the rest of the CSW region.

PS-MORA offers its users the opportunity to perform studies regarding the security of supply of interconnected systems with the possibility of reserving a pre-defined percentage of each interconnection exclusive for operational reserve exchange. This feature allows the user to alter what would be the UC solution based on a common and perfect market environment, by presenting limited NTC during the scheduling procedures. This leads to situations where there is a reducing of the export capacity of a certain system, defined here as *System A*, to another interconnected system, defined here as *System B*. *System B* could be importing from *System A*, as economically more advantageous generation units are located there. Reserving interconnection capacity exclusive for operational reserve exchange, in the case just described, will lead to increased costs imposed by this altered day-ahead market solution. On the other hand, during close-to-real time operation, where PS-MORA evaluates the systems' flexibility to cope with RES uncertainty, the once congested interconnection between *System*

A and *System B*, has now a pre-defined NTC margin available to allow reserve exchange between these systems, possibly reducing operational reserve activation costs or even loss of load events.

In order to assess whether, or not, the stressful events identified in the results presented above could be avoided by implementing this type of market procedure, some additional simulations were carried-out. Interconnections between Iberia and France were the focus of this sensitive analysis, as most of the stressful events already reported indicate that interconnection congestion is the main reason for higher values of LOLE and EENS in cluster 6. Analysing interconnection power flows, the most congested interconnection is the one connecting cluster 5 to cluster 7, which led to some specific focus on that in the following studies. Accordingly, using the operating conditions of *Year 1*, a set of NTC configurations were defined, as follows:

Configuration i. Limited NTC for interconnection between cluster 5 and cluster 7, in the direction C5 -> C7 (300 MW reserved)

Configuration ii. Limited NTC for interconnection between cluster 5 and cluster 7, in the direction C5 -> C7 (300 MW reserved) AND 10% of total interconnection between France and Iberia reserved in the direction FR -> ES (930 MW reserved)

Configuration iii. 10% of total interconnection between France and Iberia reserved in the direction FR -> ES (930 MW reserved)

Configuration iv. 10% of total interconnection between France and Iberia reserved in both directions (930 MW reserved)

	SCG_2050 Year 1	Config. i	Config. ii	Config. iii	Config. iv
LOLE (h/year)	1.16	1.16	1.16	1.16	1.24
EENS (MWh/year)	2715	2715	2715	2715	2454

Table 13: Results comparison for sensitivity analysis regarding NTC reserved capacity

Results from Table 13 clearly demonstrate that the stressful events leading to LOLE and EENS for *SCG_2050 – Year 1* cannot be solved by the limitation of interconnection capacity for prior operational reserve response. These results show that during day-ahead procedures, and for the hours identified as stressful in *SCG_2050 – Year 1*, the operation condition must be such, that in order to meet demand in all clusters, the entire interconnection capacity must be used. Accordingly, the interconnection margin available to cope with RES uncertainty during operational reserve assessment is in fact the same in all the proposed configurations, leading to the same reliability indexes or even aggravated. Aggravated indexes can occur in this type of operation conditions because as one limits the available NTC during UC, in some hours, finite resources like hydro or P2G might be used, which would not be in the case of unreduced

NTC. Accordingly, in prior operation moments, available generation resources can also be reduced, leading to the referred aggravated reliability indexes.

The impact on the reliability indexes for SCG_2050 of increasing the amount of flexibility assets within the CSW region or increasing the NTC characterizing each interconnection is assessed in the following sub-chapters 4.4 and 4.5.

4.4 Sensitivity Analysis on Flexible Capacity Requirements to be Integrated in the CWS Region

In this section, a sensitivity analysis will be carried out to investigate the impact of considering additional flexible capacity in the CSW region on the security of supply results presented in 4.2. As a first step, additional flexible capacity modelled as peak price DSM was considered for clusters 2, 5, and 6, namely an increase of 250MW for both clusters 2 and 5 as well as 1000MW for cluster 6. DSM capacity is modelled as a last-resort asset. Operational reserve assessment results can be consulted in Table 14, which should be compared with the ones presented in Table 9.

	CSW System		Cluster 1		Cluster 2		Cluster 3	
	updated	Tab. 9	updated	Tab. 9	updated	Tab. 9	updated	Tab. 9
LOLP (prob.)	7.53E-05	8.45E-05	2.28E-06	2.28E-06	9.13E-06	1.83E-05	0	0
LOLE (h/year)	0.66	0.74	0.02	0.02	0.08	0.16	0	0
EPNS (MW)	0.18968	0.217218	0.000101	0.000101	0.008023	0.01259	0	0
EENS (MWh / year)	1661.60	1902.83	0.88	0.88	70.28	110.26	0	0
	Cluster4		Cluster5		Cluster6		Cluster7	
	updated	Tab 9	updated	Tab .9	updated	Tab. 9	updated	Tab. 9
LOLP (prob.)	0	0	6.85E-06	1.14E-05	6.39E-05	6.62E-05	0	0
LOLE (h/year)	0	0	0.06	0.10	0.56	0.58	0	0
EPNS (MW)	0	0	0.01272	0.017865	0.168837	0.18666	0	0
EENS (MWh / year)	0	0	111.43	156.50	1479.01	1635.18	0	0

Table 14: Operational reserve assessment for SCG_2050 with increased flexible capacity - comparing results from Table 9

A parallel approach was carried-out, by increasing the flexibility that was being considered as available from the interconnection between FR and the rest of Europe. The base case study, as the interconnections between FR and Europe are not explicitly modelled, considers that 5% of the total interconnection installed capacity between FR and Europe should be taken as last-resort flexibility within PS-MORA, 1202.5 MW for each French cluster (6 and 7), with a total of 2405 MW. Thus, the impact of increasing by 50% this default value was assed and the respective results are presented in Table 15.

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	7.08E-05	2.28E-06	1.37E-05	0.00E+00
LOLE (h/year)	0.62	0.02	0.12	0
EPNS (MW)	0.172896	0.000101	0.006019	0
EENS (MWh/year)	1 514.57	0.88	52.72	0
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	0.00E+00	4.57E-06	5.71E-05	0.00E+00
LOLE (h/year)	0	0.04	0.50	0
EPNS (MW)	0	0.01168	0.155097	0
EENS (MWh/year)	0	102.32	1 358.65	0

Table 15: Operational reserve assessment for SCG_2050 with increased flexible capacity from the interconnection between FR and the rest of Europe

This increase of the flexibility from the interconnection between FR and the rest of Europe, in practice, is the same as adding additional peak generators (last-resort) in clusters 6 and 7.

As one can see in Table 15, CSW system reliability results are somewhat similar to the ones presented in Table 14, while LOLE and EENS reduction in cluster 6 is greater when introducing the increased flexible capacity from the interconnection between FR and the rest of Europe. Accordingly, and considering that the most affected system is cluster 6, as a further step in order to reduce even further those reliability indexes, this sensitivity analysis will carry on by increasing the flexibility from the interconnections with the rest of Europe. This second run considered 10% of the interconnections installed capacity between France and the rest of Europe as flexibility, double of what is considered for the base case-study, corresponding to 2405 MW in both cluster 6 and 7 (total of 4810 MW).

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	5.71E-05	2.28E-06	1.14E-05	0.00E+00
LOLE (h/year)	0.50	0.02	0.10	0
EPNS (MW)	0.147645	0.000101	0.005579	0
EENS (MWh/year)	1 293.37	0.88	48.88	0
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	0.00E+00	4.57E-06	4.57E-05	0.00E+00
LOLE (h/year)	0	0.04	0.40	0
EPNS (MW)	0	0.008935	0.13303	0
EENS (MWh/year)	0	78.27	1165.34	0

Table 16: Operational reserve assessment for SCG_2050 with increased flexible capacity from the interconnection between FR and the rest of Europe – second run

There is another slight improvement in the reliability indexes coming from this second increase of flexibility capacity, in both LOLE and EENS. Cluster 6 remains the most affected system, with 0.4 h/year of LOLE and 1165.34 MWh/year of EENS.

Two additional configurations were assessed, allowing to understand the effects that increasing flexibility between France and rest of EU has on reliability indexes considering the assumptions established for this study. Results from the last PS-MORA run are presented in Table 17, where the flexibility was increased to 30% of the interconnection installed capacity, corresponding to 7215 MW in both cluster 6 and 7 (total of 14430 MW). In Table 18 are summarized the changes made throughout the set of four PS-MORA simulations and the respective impacts in terms of LOLE and EENS.

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	1.60E-05	2.28E-06	6.85E-06	0.00E+00
LOLE (h/year)	0.14	0.02	0.06	0
EPNS (MW)	0.042431	0.000101	0.005261	0
EENS (MWh/year)	371.70	0.88	46.09	0
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	0.00E+00	2.28E-06	1.14E-05	0.00E+00
LOLE (h/year)	0	0.02	0.10	0
EPNS (MW)	0	0.001236	0.035833	0
EENS (MWh/year)	0	10.83	313.90	0

Table 17: Operational reserve assessment for SCG_2050 with increased flexible capacity from the interconnection between FR and the rest of Europe – forth run

	SCG_2030	Run 1	Run 2	Run 3	Run 4
NTC % available for flexibility	5%	7.5%	10%	20%	30%
MW available cluster 6 + cluster 7	2405	3607.5	4810	9620	14430
LOLE (h/year)	0.74	0.62	0.50	0.30	0.14
EENS (MWh/year)	1902.83	1514.57	1293.37	690.52	371.7

Table 18: Flexibility available from interconnections between France and rest of EU and CSW System reliability indexes comparison between SCG_2030 and all defined PS-MORA simulations

With this last increase regarding flexibility capacity on clusters 6 and 7, there was a decrease in LOLE to 0.14 h/year and a decrease in EENS to 371.7 MWh/year.

Finally, with this last flexibility increase, reliability indexes are assessed for the scenario where RES uncertainty is aggravated, comparing to the results found in Table 11.

	CSW System		Cluster 1		Cluster 2		Cluster 3	
	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11
LOLP (prob.)	1.44E-04	4.00E-04	3.42E-05	3.42E-05	4.79E-05	6.39E-05	0	0
LOLE (h / year)	1.26	3.50	0.30	0.30	0.42	0.56	0	0
EPNS (MW)	0.504869	1.672476	0.010664	0.01066	0.042648	0.05412	0	0
EENS (MWh / year)	4422.65	14650.90	93.42	93.42	373.60	474.06	0	0
	Cluster4		Cluster5		Cluster6		Cluster7	
	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11
LOLP (prob.)	2.28E-06	6.85E-06	9.13E-06	2.51E-05	8.45E-05	3.33E-04	0	6.85E-06
LOLE (h / year)	0.02	0.06	0.08	0.22	0.74	2.92	0	0.06
EPNS (MW)	0.000289	0.004605	0.020113	0.08281	0.431155	1.5097	0	0.01063
EENS (MWh / year)	2.53	40.34	176.19	725.38	3776.92	13225	0	93.12

Table 19: Operational reserve assessment for SCG_2050 with increased uncertainty and considering increased flexible capacity from the interconnection between FR and the rest of Europe – (conditions of forth run) - comparing results from Table 11

There are clear improvements from the security of supply perspective when comparing the reliability indexes from Table 11, where SCG_2050 was assessed considering increased uncertainty from RES, with the reliability indexes presented in Table 19, where the same increased uncertainty is used but the additional flexibility (total of 14430 MW) is also considered. CSW system LOLE is decreased from 3.5 h/year to 1.26 h/year, while EENS decreased from 14650 MWh/year to 4422 MWh/year.

4.5 Benefit Analysis from Increased Interconnection Capacity

In this section, a sensitivity analysis was carried out to investigate the impact of considering additional interconnection capacity within the CSW region. As results from Table 9 show, the cluster where most of LOLE and EENS is located is cluster 6. Accordingly, increased interconnection capacity was focussed at interconnections between ES and FR, namely by increasing 200MW on interconnections between cluster 3 and 6, and between cluster 4 and 6. Results from this new configuration can be consulted in Table 20. The operational reserve assessment results presented are only slightly improved when compared to what has been assessed in Table 9.

	CSW System		Cluster 1		Cluster 2		Cluster 3	
	updated	Tab. 9	updated	Tab. 9	updated	Tab. 9	updated	Tab. 9
LOLP (prob.)	7.31E-05	8.45E-05	2.28E-06	2.28E-06	1.60E-05	1.83E-05	0	0
LOLE (h/year)	0.64	0.74	0.02	0.02	0.14	0.16	0	0
EPNS (MW)	0.191779	0.217218	0.000101	0.000101	0.011588	0.01259	0	0
EENS (MWh / year)	1679.99	1902.83	0.88	0.88	101.51	110.26	0	0
	Cluster4		Cluster5		Cluster6		Cluster7	
	updated	Tab. 9	updated	Tab. 9	updated	Tab. 9	updated	Tab. 9
LOLP (prob.)	0	0	1.14E-05	1.14E-05	5.71E-05	6.62E-05	0	0
LOLE (h/year)	0	0	0.10	0.10	0.50	0.58	0	0
EPNS (MW)	0	0	0.017865	0.017865	0.162225	0.18666	0	0
EENS (MWh / year)	0	0	156.50	156.50	1421.09	1635.18	0	0

Table 20: Operational reserve assessment for SCG_2050 with increased interconnection capacity

Aiming at decreasing even further the reliability indexes, a new interconnection configuration is proposed which represents an increase of 600 MW for interconnection between C3 and C6, 400 MW between C4 and C6, and 200 MW between C5 and C7, when comparing to the NTC installed capacities defined by SCG_2050.

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	5.25E-05	2.28E-06	1.14E-05	2.28E-06
LOLE (h/year)	0.46	0.02	0.10	0.02
EPNS (MW)	0.147834	0.000972	0.004044	0.000972
EENS (MWh/year)	1 295.03	8.51	35.43	8.51
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	2.28E-06	9.13E-06	4.34E-05	2.28E-06
LOLE (h/year)	0.02	0.08	0.38	0.02
EPNS (MW)	0.000972	0.015966	0.123936	0.000972
EENS (MWh/year)	8.51	139.86	1 085.68	8.51

Table 21: Operational reserve assessment for SCG_2050 with increased interconnection capacity – second run

Another reduction of the reliability indexes was achieved with the increased NTC capacity proposed, namely when comparing the global indexes. On the other hand, one can see that for clusters 1, 3, 4 and 7, where there were no problems identified on Table 20, there is now the identification of some failure events. As the indexes values are exactly the same for all the referred clusters it is possible to conclude that those come from the same events, where the EENS is divided between all clusters, as no priority order was defined. The additional NTC capacity is capable of reducing the global indexes as clusters from PT and ES have more room to assist FR (cluster 6). Accordingly, some finite resources, such as hydro and P2G, are used to solve part of those previously identified stressful events (in cluster 6) and then are not available further in time to meet demand and/or uncertainty from RES.

Similarly to the process made before, this sensitivity analysis carried on by proposing two additional assessments. The last NTC configuration being proposed considered an increase in all the 6 interconnections of the CSW system, as follows: more 1700 MW between C3 and C6, 1100 MW between C4 and C6, 1400 MW between C5 and C7, 790 MW between C1 and C3, 400 MW between C2 and C4, and 604 MW between C2 and C5, when comparing to the NTC installed capacities defined by SCG_2030. The results for this final proposed interconnection configuration, which led to reliability indexes closer to 0, can be consulted in Table 22.

	CSW System	Cluster1	Cluster2	Cluster3
LOLP (prob.)	2.97E-05	9.13E-06	1.14E-05	9.13E-06
LOLE (h/year)	0.26	0.08	0.10	0.08
EPNS (MW)	0.082256	0.002471	0.002718	0.002471
EENS (MWh/year)	720.56	21.64	23.81	21.64
	Cluster4	Cluster5	Cluster6	Cluster7
LOLP (prob.)	9.13E-06	1.37E-05	2.51E-05	9.13E-06
LOLE (h/year)	0.08	0.12	0.22	0.08
EPNS (MW)	0.002471	0.009906	0.05975	0.002471
EENS (MWh/year)	21.64	86.77	523.41	21.64

Table 22: Operational reserve assessment for SCG_2050 with increased interconnection capacity – forth run

With this last increased NTC configuration for all the interconnections within the CSW region, there was a reduction in LOLE to 0.26 h/year, and a decrease in EENS to 720.56 MWh/year. From the 0.26 h/year LOLE, 0.10 reflects transmission network (interconnections) constraints, while 0.16 comes from generation deficit and 0 from events where generation deficits and transmission constraints occur simultaneously. Table 23 summarizes the NTC installed capacities considered in each sensitivity *Run* and the impact regarding LOLE and EENS.

	SCG_2030	Run 1	Run 2	Run 3	Run 4
C3 – C6	3800	4000	4400	4800	5500
C4 – C6	1900	2100	2300	2800	3000
C5 – C7	3600	3600	3800	4600	5000
C1 – C3	2210	2210	2210	2600	3000
C2 – C4	1900	1900	1900	2100	2300
C2 – C5	1596	1596	1596	1900	2200
LOLE (h/year)	0.74	0.64	0.46	0.34	0.26
EENS (MWh/year)	1902.83	1679.99	1295.03	857.35	720.56

Table 23: NTC installed capacity and reliability indexes comparison between SCG_2030 and all defined PS-MORA simulations

Finally, with this last interconnection expansion option from *Run 4*, reliability indexes are assessed considering the increased uncertainty represented by the CDFs of Table 10. Results from Table 11 are used for comparison purposes.

	CSW System		Cluster 1		Cluster 2		Cluster 3	
	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11
LOLP (prob.)	1.76E-04	4.00E-04	4.57E-06	3.42E-05	3.88E-05	6.39E-05	4.57E-06	0
LOLE (h / year)	1.54	3.50	0.04	0.30	0.34	0.56	0.04	0
EPNS (MW)	0.799501	1.672476	0.001629	0.01066	0.036532	0.05412	0.001629	0
EENS (MWh / year)	7003.63	14650.9	14.27	93.42	320.02	474.06	14.27	0
	Cluster4		Cluster5		Cluster6		Cluster7	
	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11	updated	Tab. 11
LOLP (prob.)	1.14E-05	6.85E-06	4.34E-05	2.51E-05	1.44E-04	3.33E-04	4.57E-06	6.85E-06
LOLE (h / year)	0.10	0.06	0.38	0.22	1.26	2.92	0.04	0.06
EPNS (MW)	0.008194	0.004605	0.114848	0.08281	0.635042	1.5097	0.001629	0.01063
EENS (MWh / year)	71.78	40.34	1006.07	725.38	5562.97	13225	14.27	93.12

Table 24: Operational reserve assessment for SCG_2050 with increased uncertainty and considering increased interconnection capacity – (conditions of forth run)

In line with the results presented in 4.3 (Table 19), also here clear improvements from the security of supply perspective were found when comparing the reliability indexes from Table 11, where SCG_2050 was assessed considering increased uncertainty from RES, with the reliability indexes presented above in Table 24. Although increased uncertainty is modelled, the interconnection configuration proposed for *Run 4* of Table 23 allows LOLE to decrease from 3.5 h/year to 1.54 h/year, while EENS decreases from 14650 MW/year to 7003 MW/year.

4.6 Sensitivity Analysis on increase of RES generation that PT region can accommodate - NECP

The interactions and cooperation between WP1 partners (also between other WPs) is expected to occur and, with that, achieve more reliable assumptions and useful results. Accordingly, REN revisited the installed capacities envisioned by T1.1, with special emphasis on 2030. REN expects that, by providing to T1.1 its updated plans for installed capacity investments for 2030, T1.1 2050 envisioned investment plans could also benefit from REN's feedback by correcting generation investment trends.

The NECP from Portugal defines the country's main energy and climate ambitions and targets, covering, among other things, what should be the RES installed capacities for 2030. Based on those expectations, and based on current installed capacities and ongoing projects, REN presents here the main discrepancies identified regarding T1.1 scenario results.

Figure 18 presents a comparison of installed capacities for Portugal between 3 scenarios: *PT_Installed_2020* containing present installed capacities, *NECP_2030* where NECP installed capacities for 2030 are accounted; and *SCG_2030* considering the installed capacities for the scenario Current Goals 2030.

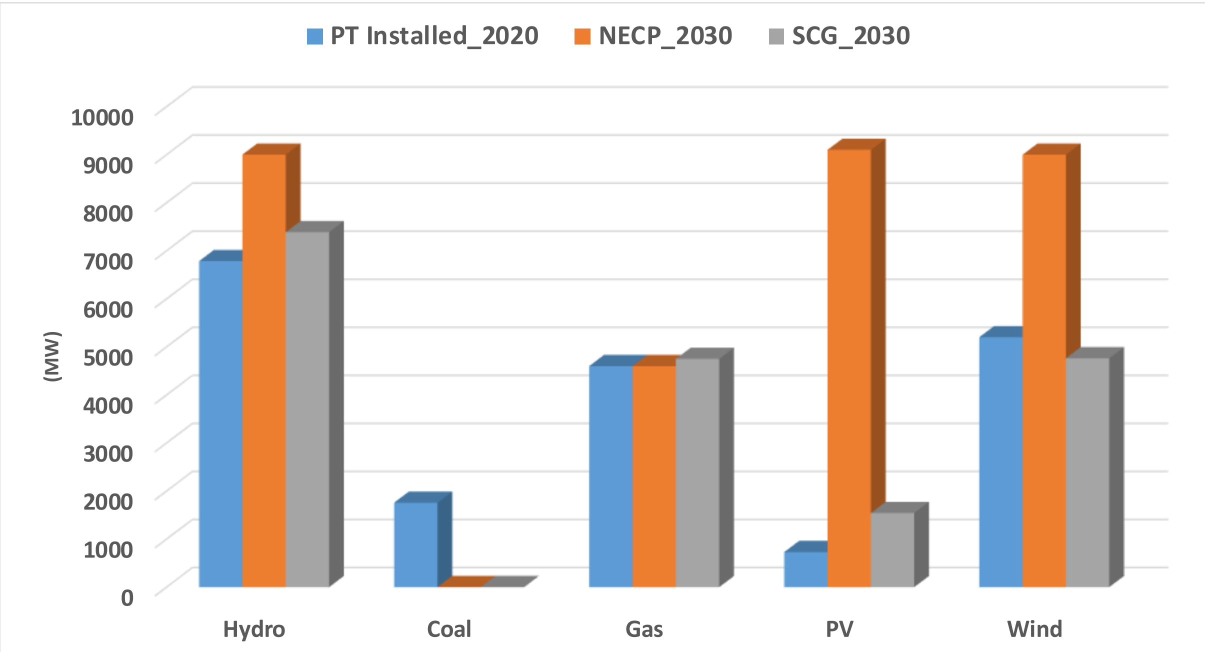


Figure 18: Installed capacity comparison between REN 2020, NECP 2030 and SCG2030

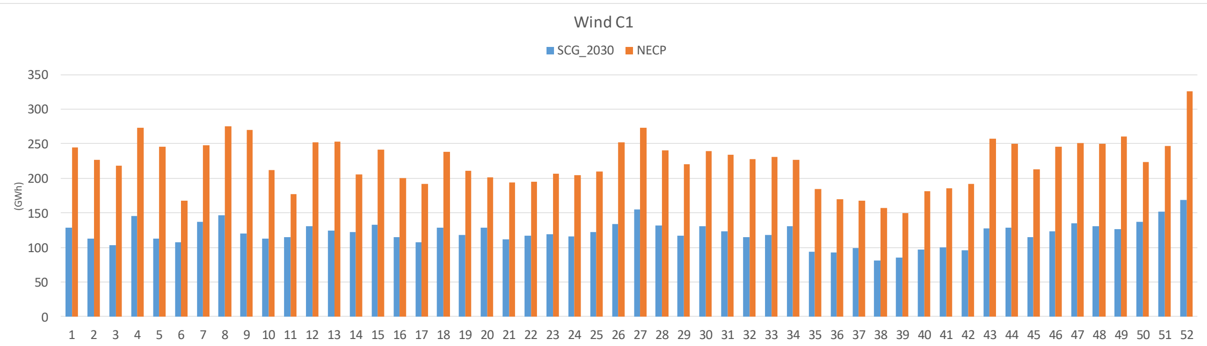
The most conflicting data regards wind and solar installed capacities. If one analyses Figure 18 it will stand out the differences between the PT's NEPC 2030 scenario and Current Goals 2030 from T1.1. PV installed capacities are significantly underestimated in SCG_2030 when comparing to NECP_2030. Also, wind installed capacities for 2030 from SCG are even lower than 2020 registered values (*PT_Installed_2020*) and significantly lower than the ones considered in NECP_2030.

The task T1.1 has in hand, which, among other aspects, consists on the envision of medium/long term energy systems for the entire EU is a very complex one, and so, several iterations are expected to occur, each one of them fed by inputs from other OSMOSE partners. As part of this commitment, REN used its power system simulation tool, PS-MORA, to evaluate the feasibility of NECP_2030 scenario. Accordingly, for cluster 1 and cluster 2 (Portugal) additional 4.2 GW of wind power and additional 7.6 GW of PV were considered to match with the ones envisioned by NECP_2030, while all other technologies and other countries' installed capacities remain the same (from SCG_2030).

The study REN proposes here intends to compare RES energy production from both scenarios (SCG_2030 and NECP_2030) while taking into account the increasing factor that NECP_2030 RES installed capacities represent. Therefore, possible spilled energy coming from increased RES installed capacity could be identified. Table 25 presents the result comparison from PS-MORA simulations considering the referred scenarios.

C1	C2	C3	C4
Ratio NECP_2030/SCG_2030 capacity			
188%	186%	/	/
Total production SCG_2030			
6.18	6.28	53.21	4.40
Total production NECP_2030			
11.62	11.60	53.21	4.40
Variation total production NECP_2030 vs SCG2030			
188%	185%	100%	100%

Table 25: Wind installed capacity increase and energy production comparison between SCG_2030 and NECP_2030



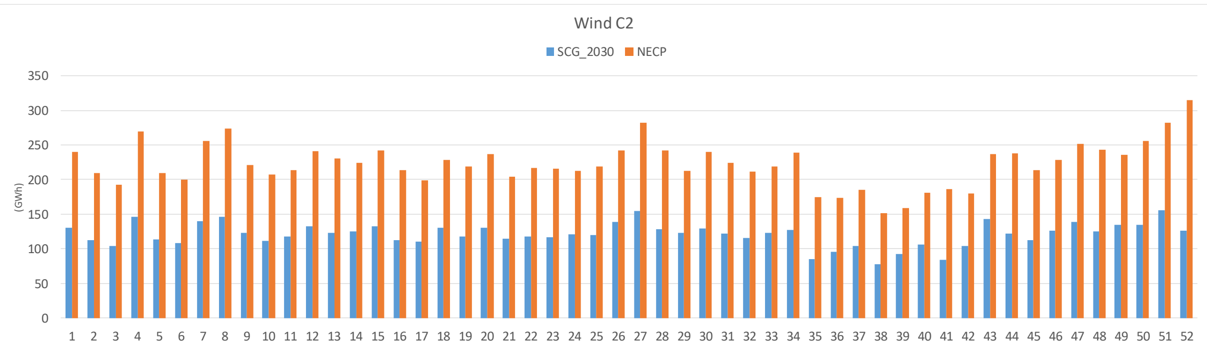
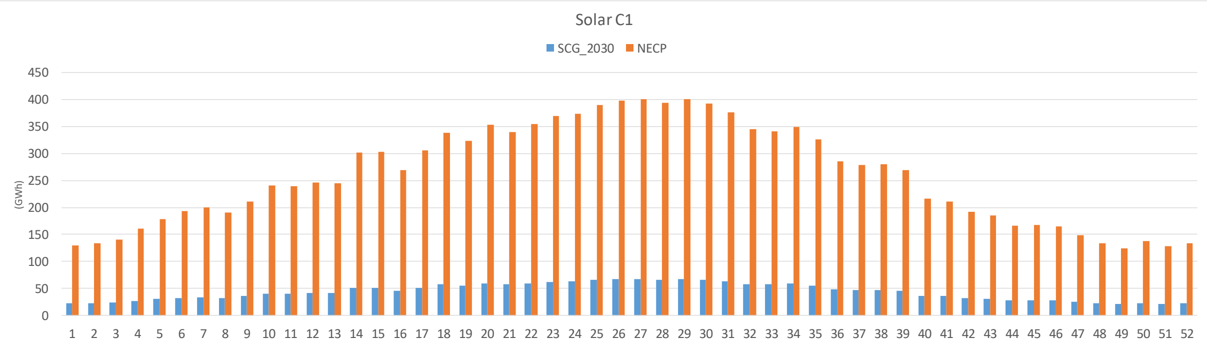
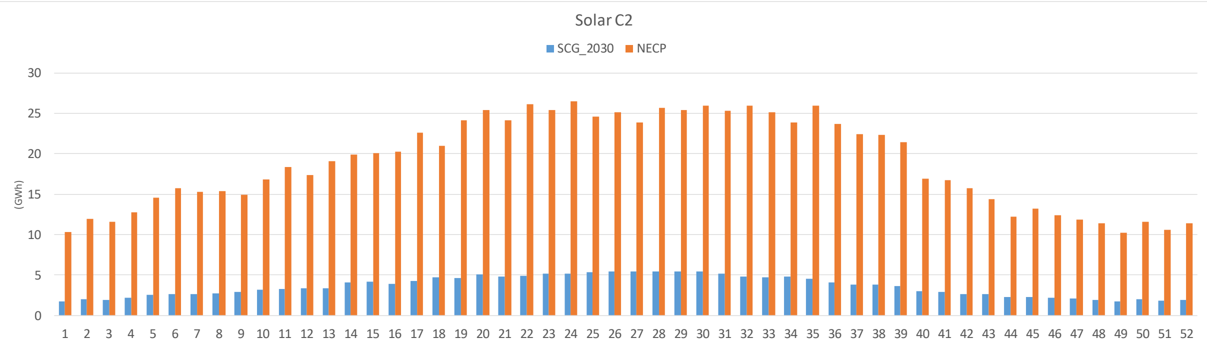


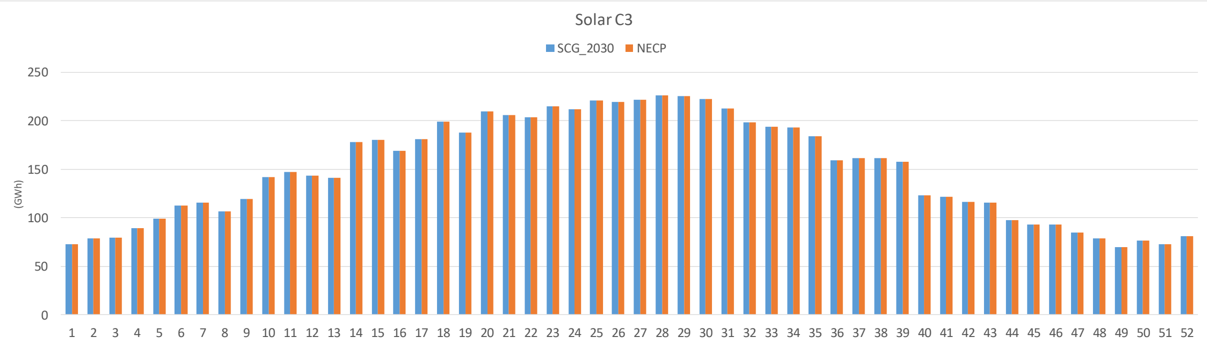
Figure 19: Weekly wind energy production comparison between SCG_2030 and NECP_2030

C1	C2	C3	C4
Increased Solar Capacity			
593%	600%	/	/
Total production SCG_2030			
2.27	0.19	7.77	30.39
Total production NECP_2030			
13.48	0.98	7.77	30.39
Variation total production NECP_2030 vs SCG2030			
593%	530%	100%	100%

Table 26: Solar installed capacity increase and energy production comparison between SCG_2030 and NECP_2030







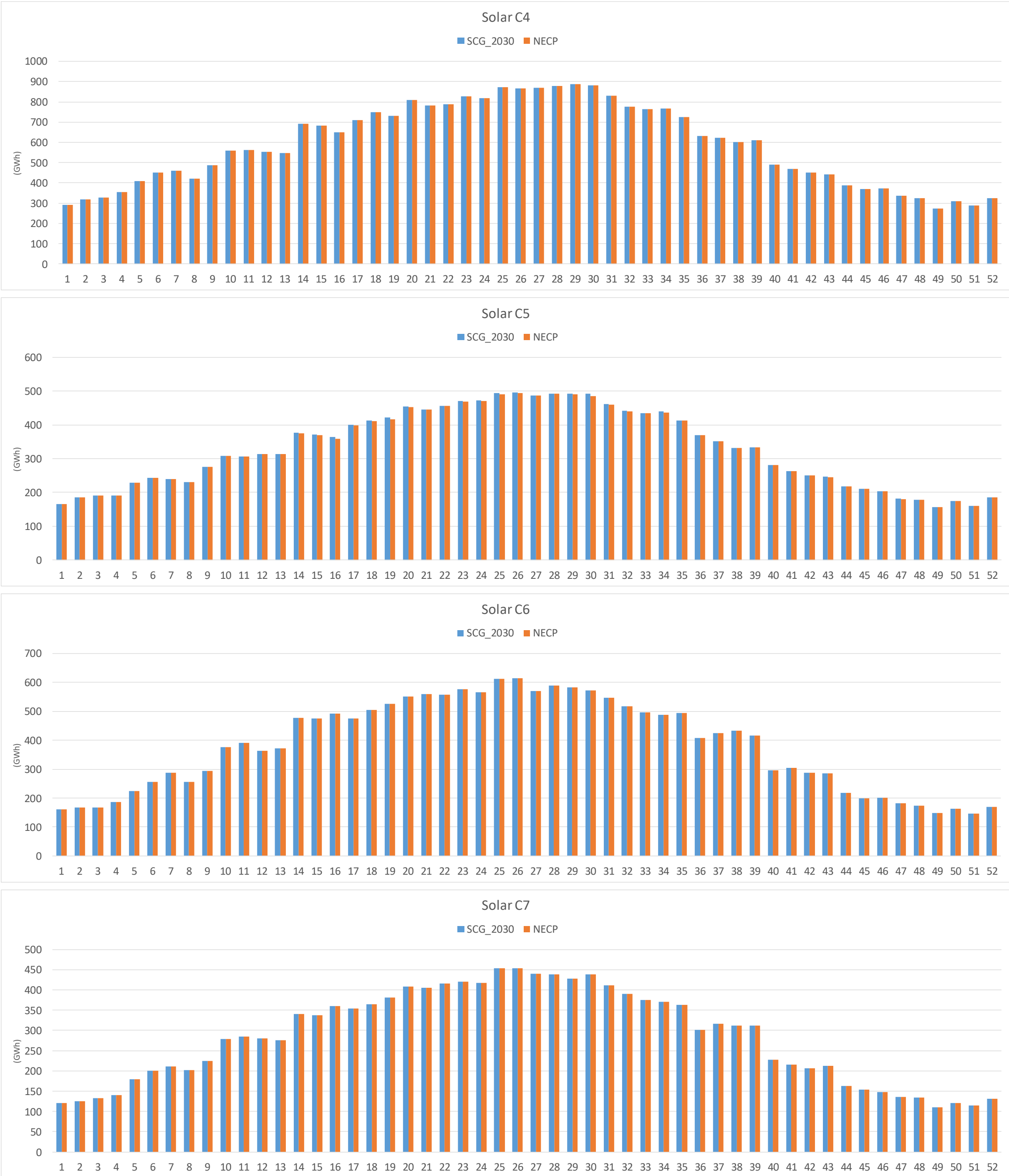


Figure 20: Weekly solar energy production comparison between SCG_2030 and NECP_2030

Figure 19 and Table 25 show that all the wind increased energy potential is fulfilled for cluster 1 while on cluster 2 from the 186% increased installed capacity an increase of 185% is verified. Meanwhile, wind power generation in adjacent clusters remains the same.

On the other hand, Figure 20 and Table 26 show that in cluster 1 from the increased solar installed capacity representing 593% of SCG_2030 levels an increase of 593% of generation was achieved, while for cluster 2 the 600% increased installed capacity translated into 530%

increased generation. The installed capacity increase from cluster 2 of 600% converts into an increase generation potential from 0.19 annual TWh to 1.14 TWh, from which 0.98 TWh (530% referred above) total annual generation is achieved. As for the wind power analysis, solar power generation in adjacent clusters remains the same.

Impacts on interconnection power flow were assessed for the CSW region. Figure 21 illustrates the total yearly energy flow in each interconnection individualized by flow orientation considering both scenarios: SCG_2030 and NECP_2030.

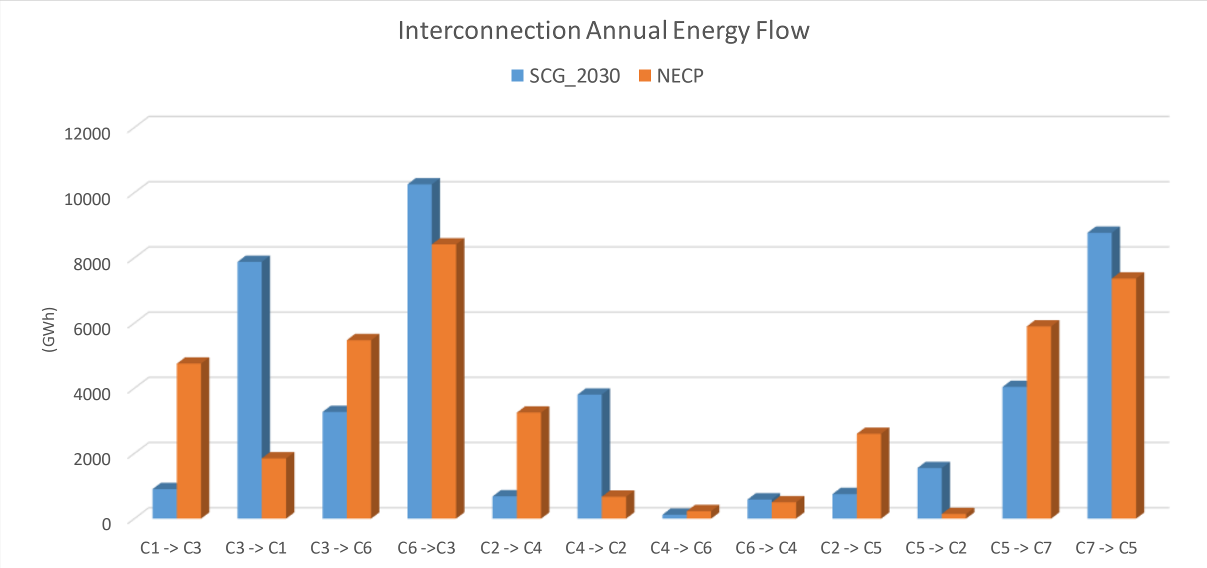


Figure 21: Comparison of total yearly energy flow in each interconnection

By analysing Figure 21 it is clear that the increased RES installed capacity in Portugal increases the total energy being exported to Spain while on the other hand decreases the energy being imported from Spain. Additionally, although with smaller changes, Iberian exporting to France increases while importing decreases.

Other than reshaping interconnection energy flows within the CSW region, the increase of RES installed capacity following the Portuguese NECP_2030 scenario also allowed for a decrease of thermal-based generation from Coal, Gas and Nuclear. Figure 22 illustrates the weekly power generation decreases within the CSW region, per cluster and per technology, when considering the increased RES installed capacity in Portugal.

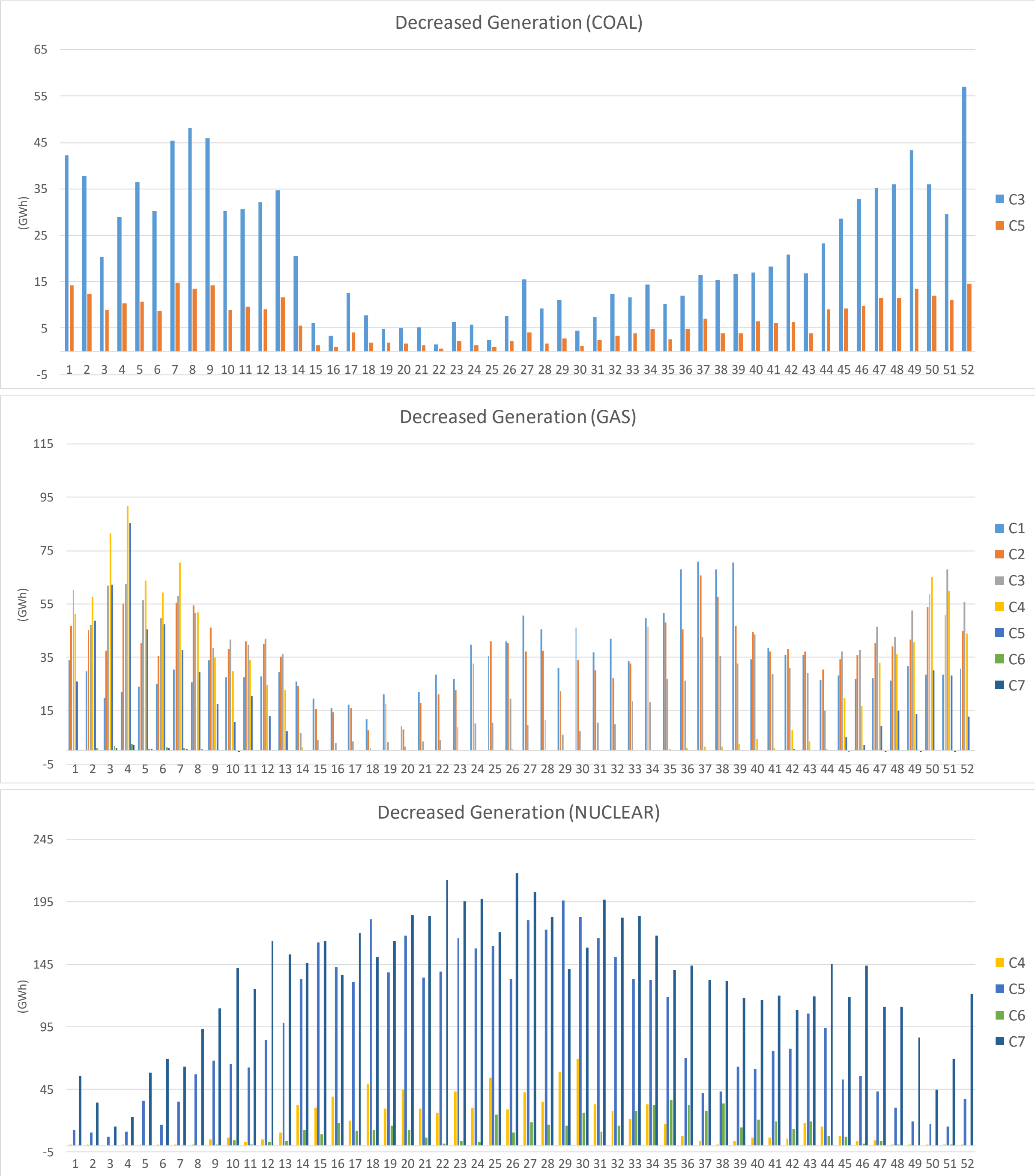


Figure 22: Energy production decrease from thermal-based technologies – CSW Region

With this study, REN investigated the feasibility and energy mix impacts that modelling the Portuguese NECP scenario for 2030 would have, while preserving all other premises from SCG_2030. Table 25 and Table 26 show that most of the increased energy production potential is accomplished (with the exception of solar generation coming slightly short in cluster 2). Nevertheless, when T1.1 revisits its scenario building process in order to accommodate the inputs gave from this report, the increased installed capacity due for Portugal might implicate some reduction in other country in the vicinity, which could offset the amount of energy being spilled for NECP_2030.

Interconnection energy flow assessment was also carried-out which showed that the NECP_2030 scenario leads to a decrease energy importing from Spain to Portugal, while also increasing the almost inexistent energy exporting from Portugal to Spain in the SCG_2030. Finally, results show that increasing wind and solar levels to match Portugal NECP scenario for 2030 would further reduce the thermal-based power generation within the CSW, and consequently help reducing the total CO2 emissions in around 2.76 MtonCO_2[6].

Taking into account the assumptions and conclusions presented above, REN considers that T1.1 should incorporate the solar and wind installed capacity levels defined by the Portuguese NECP when redefining scenario Current Goals 2030, and with this new starting point revisit what should be the implications to the scenario Current Goals 2050.

[6] Considering emission factor per technology (kCO_2/kWh): coal = 0.75; CCGT = 0.327; OCGT = 0.488

5 Conclusions and Key Takeaways

In this chapter, the main conclusions and the key takeaways from all the studies and sensitivity analyses carried-out during T1.4.2 work are gathered and highlighted.

For the study developed by REN under T1.4.2 two main simulation tools were used: VALORAGUA and PS-MORA. VALORAGUA is an electricity market model simulation that considers in detail all the technical characteristics of the hydro generation units, including the cascade relations between them. Its main output are the monthly/weekly hydro management for a 1-year operation and the monthly/weekly water value for each hydro-power plant (similar to the variable generation cost of thermal power plants for market merit order). On the other hand, PS-MORA is a simulation tool that performs Chronologic Monte Carlo Simulations aiming to perform adequacy and operational reserve assessments. PS-MORA is capable of assessing the total capacity in technologies that are flexible to face operational reserve requirements for interconnected power systems to cope with the hourly RES generation uncertainty, while still accounting for other sources of uncertainty such as generation and interconnections forced outages as well as short-term demand uncertainty.

The first step of T1.4.2 was the data treatment of all the information provided by T1.1 and T1.2. On one hand, there was a need to aggregate the original 27 clusters data format for the CSW region that T1.1 and T1.2 used into the 7 clusters that T1.4.2 adopted.

In parallel, the modelling assumptions taken during T1.2 while running ANTARES were, far as possible, merged into VALORAGUA and PS-MORA simulations. Aspects such as the daily character of battery use adopted by T1.1, the DSM activations defined by T1.2 and its impacts on load profiles, and the energy flows between France and the rest of Europe (not modelled with T1.4.2 scope) were incorporated into VALORAGUA and PS-MORA environments. The communication between T1.4.2 team and the partners involved in T1.1 and especially T1.2 was essential to reach this first objective.

The integration of T1.1 and T1.2 results and assumptions into REN’s simulation tools, the first main objective of T1.4.2, was achieved, which was fundamental to allow the comparison between T1.4.2 and T1.2 results (despite of the different scopes of the two analyses). In this context, synergies between ANTARES and PS-MORA (and partially with VALORAGUA) were successfully established and allowed a more comprehensive analysis using PS-MORA, regarding operational reserve assessment, using as background previously defined operational scenarios by ANTARES.

T1.4.2 reserve assessment results coming from PS-MORA simulations, which included uncertainty from the forecast error of RES generation (wind and solar) in order to calculate balancing needs, allows one to infer the following conclusions regarding the operation of the CSW power system:

- For both scenarios, Current Goals 2030 and Current Goals 2050, static reserve assessment[7] does not lead to any type of security of supply constraint.

- For the scenario Current Goals 2030 the operational reserve assessment shows that no loss of load and energy not supplied are expected, validating the flexibility options available and previously defined by T1.1 and T1.2.

- Operation conditions for the scenario Current Goals 2050 showed to be more demanding, presenting reliability indexes such as LOLE and EENS greater than zero. REN investigated on possible strategies to reduce the identified security of supply indexes, either by increasing dispatchable generation (like hydro, peak Gas units, or DSM) and/or additional investments in interconnections within the CSW region.

- Hydro management and hydro hourly schedule (due to the high flexibility operation features it delivers) proved to be of key importance when evaluating the impact of considering hourly power deviations coming from RES units, such as PV and wind. In power systems whose generation-mix are significantly centred on RES installed capacities, hourly (and even shorter intervals, e.g., 15 min, 5 min) power deviations gain significant weight on the operation of such systems. Optimally managing finite resources such as hydro (and renewable gases such as H2) becomes strategic to ensure security of supply in the medium and long-term horizons.

- The impact that RES uncertainty (modelled using CDF of forecast error) has on the operation of the CSW region was demonstrated, with increased levels of uncertainty leading to aggravated operational reserve reliability indexes. Studies show that the consideration of uncertainty effects in order to calculate balancing needs on an operational perspective are progressively more critical when evaluating medium to long-term scenarios, as far as increasingly levels of intermittent and uncertain RES installed capacities are considered. PS-MORA simulation tool estimates the effects of these operational reserve necessities into the planning scope, as demonstrated in and by T1.4.2.

- By changing hydro generation merit order for hydro storage and hydro pump units, so that this type of units become used only as last resort, reliability indexes for scenario Current Goals 2050 accounted for LOLE of around 0.74 h/year and EENS of around 1900 MWh/year (down from 5.28 h/year and 17202 MWh/year), with most of this impact located on cluster 6 (part of France). It is important to note that for balancing needs calculations these results only include the effect of considering RES uncertainty and do not contemplate the uncertainty from forced outage rates of thermal-based units or grid elements (interconnections) neither from short-term demand deviations.

  Different sensitivity analysis were carried out considering investments on either additional flexibility capacity or additional NTC, aiming at reducing the reliability indexes referred above. With additional 5994 MW of NTC within the CSW region (with special

[7] Reliability analysis similar to what ANTARES performs. Does not account for uncertainty coming from RES hourly generation error forecast

focus on interconnection between Iberia and France), operational reserve reliability indexes can be reduced to 0.26 h/year and 720.56 MWh/year. Analogously, by adding a total of 12025 MW of flexible assets to be used as last resort in clusters 6 and 7 (France), the equivalent reliability indexes can be reduced to around 0.14 h/year and 371.7 MWh/year.

- ❖ Finally, after analysing RES installed capacities for scenario Current Goals 2030, significant discrepancies when comparing to the Portuguese investment expectation until 2030 (included in the Portuguese National Energy and Climate Plan (NECP)) were identified. A sensitivity analysis regarding those investment expectations was carried out.

Additional 4.2 GW of wind power (close to 190% increase) and additional 7.6 GW of PV (close to 600% increase) were considered for Portugal when comparing to scenario Current Goals 2030. Results show that virtually all the additional energy potential generation is fulfilled with insignificant renewable energy spilling, while maintaining the operational reserve reliability indexes unaltered. Moreover, by analysing interconnection power flow one can see that Portugal becomes less energy dependent from Spain (overall energy interchange profile alters from importer to exporter), while Iberia is capable of increasing energy export to France.

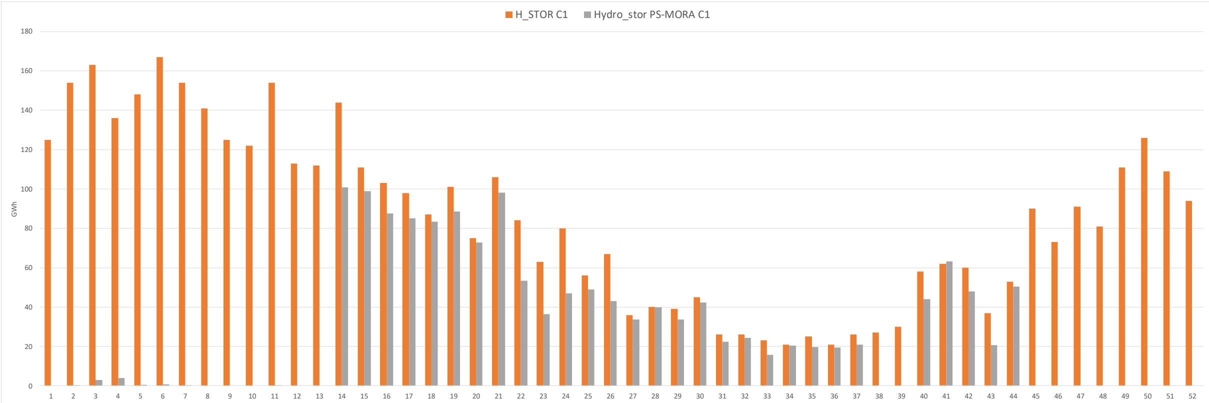
Last, but not least, the increased RES generation in Portugal leads to overall diminished thermal-based energy production in the CSW region, which decreases the total CO_2 emissions in around 2.76 MtonCO_2[8].

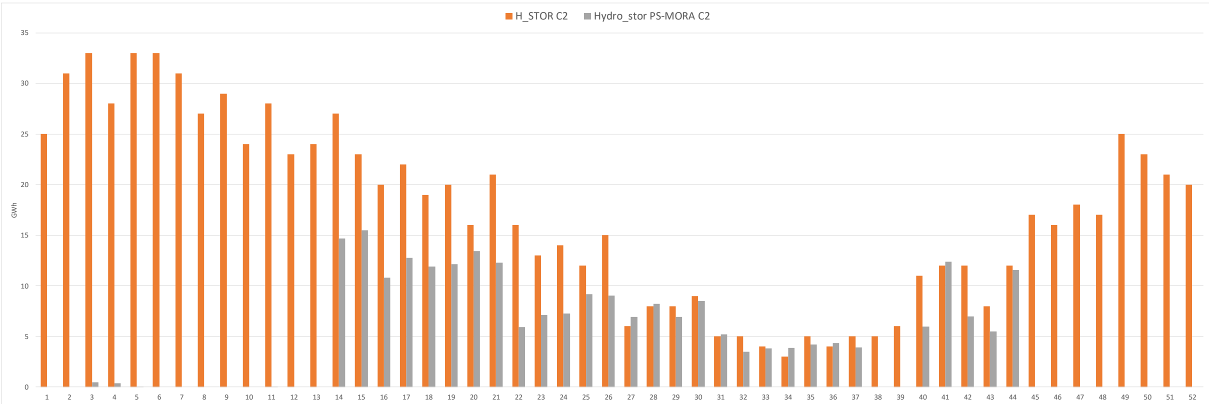
[8] Considering emission factor per technology (kCO_2/kWh): coal = 0.75; CCGT = 0.327; OCGT = 0.488

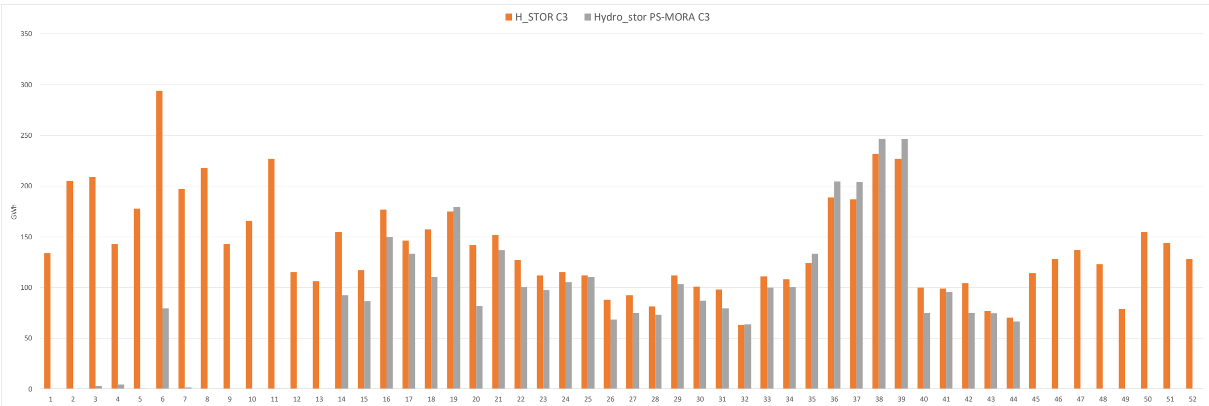
6 Annexes

6.1 Weekly production comparison per cluster and technology between ANTARES and PS-MORA

6.1.1 Hydro Storage







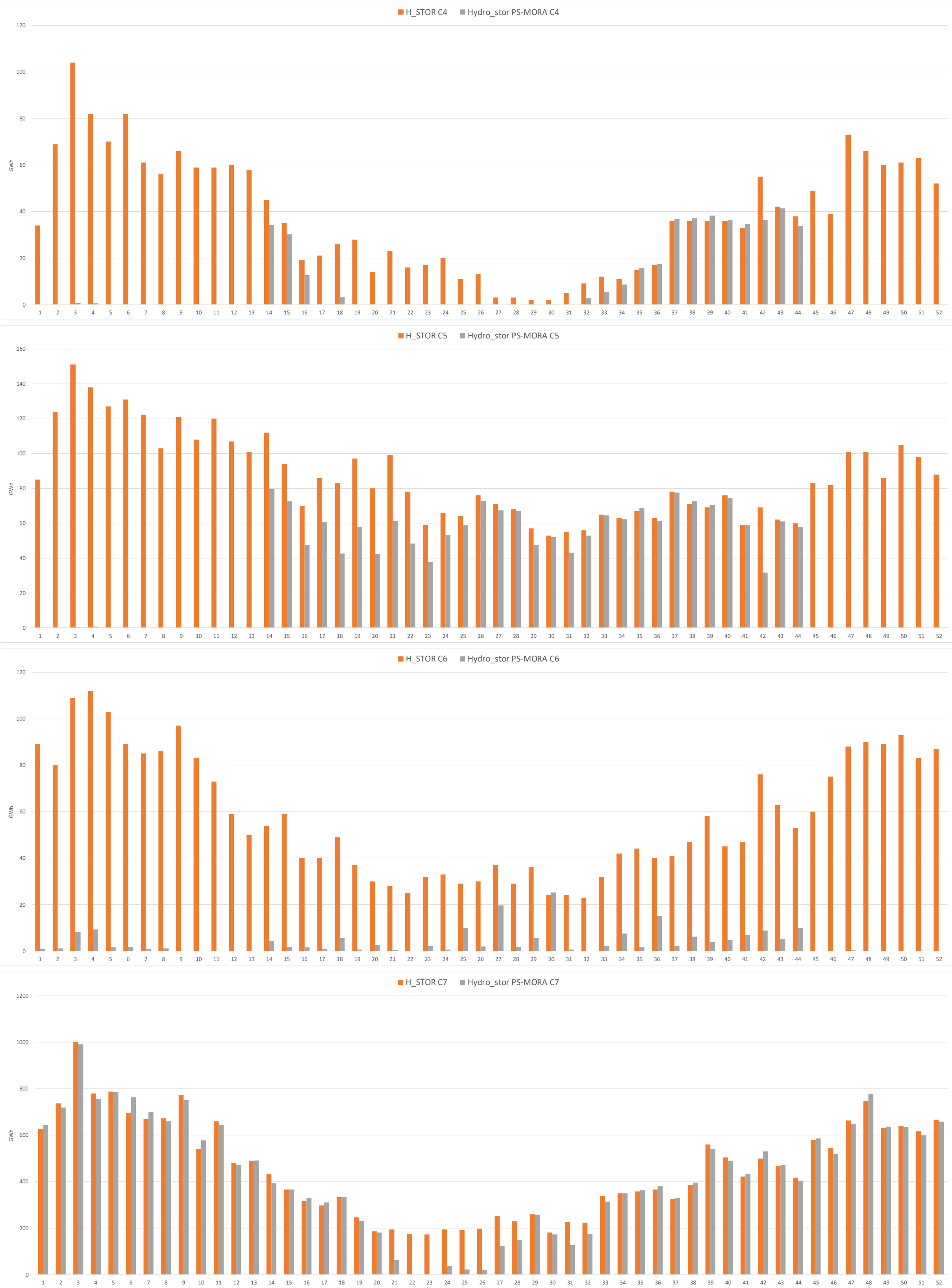
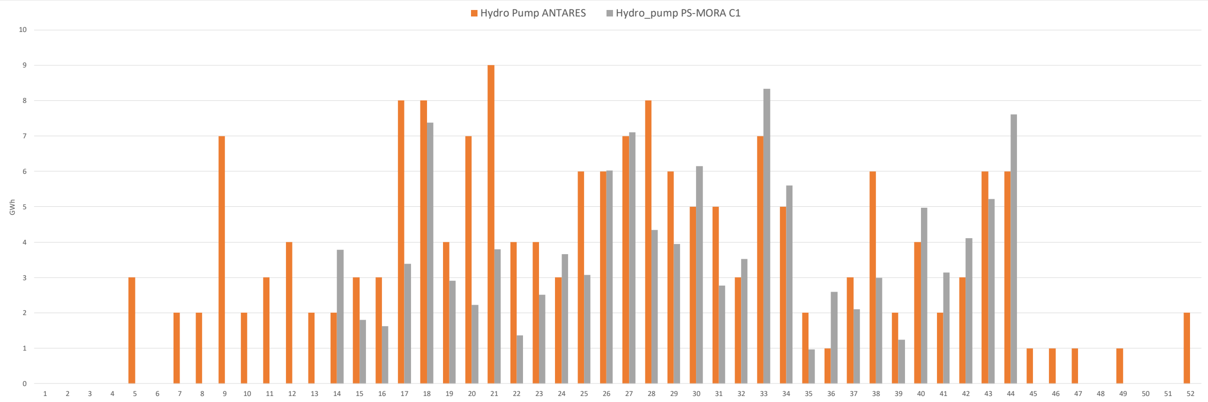
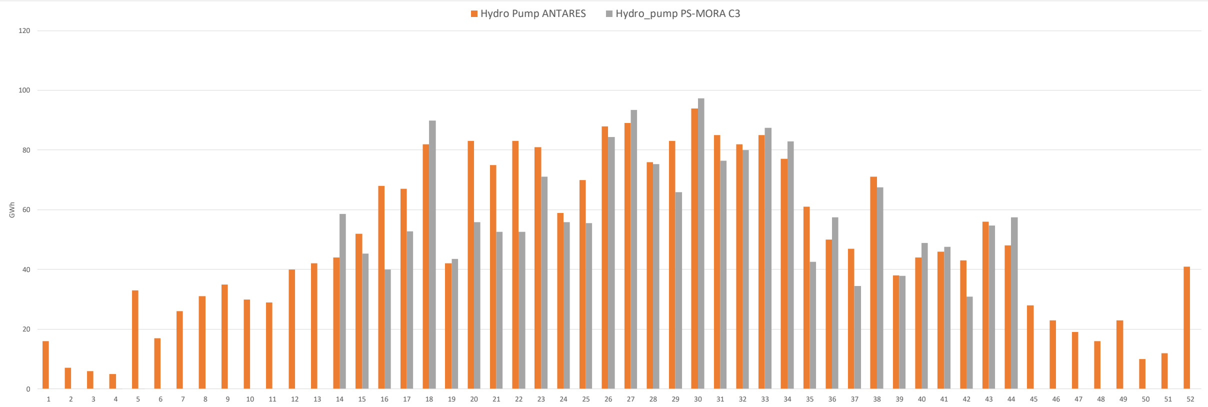
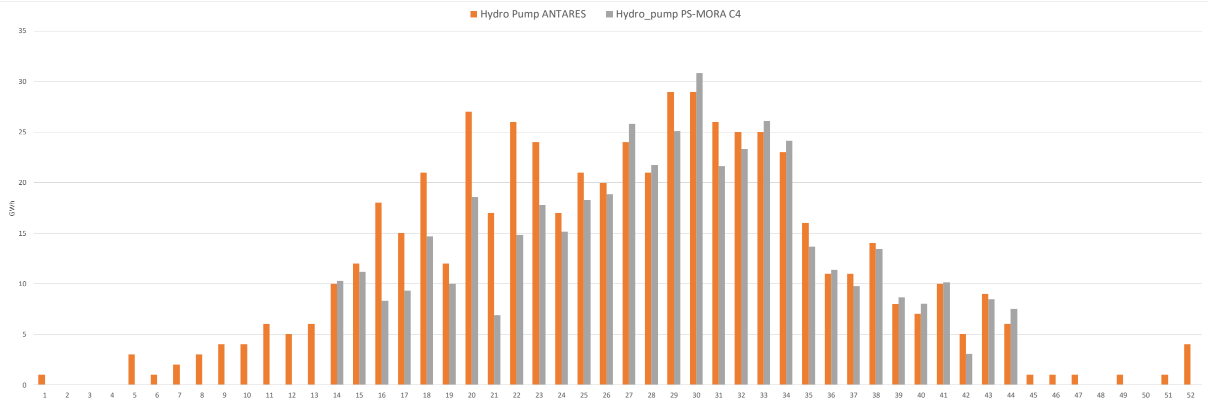


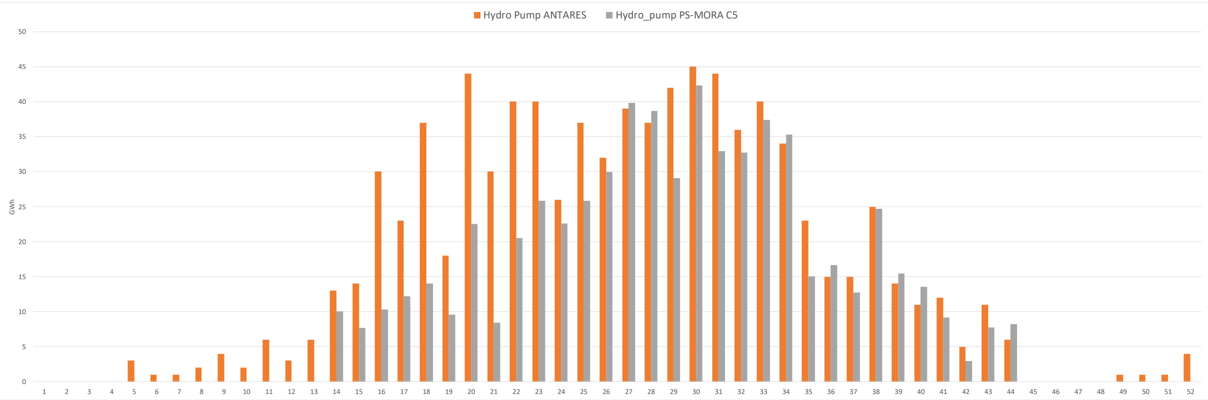
Figure 23 – Hydro Storage Production Comparison between ANTARES and PS-MORA

6.1.2 Hydro Pump









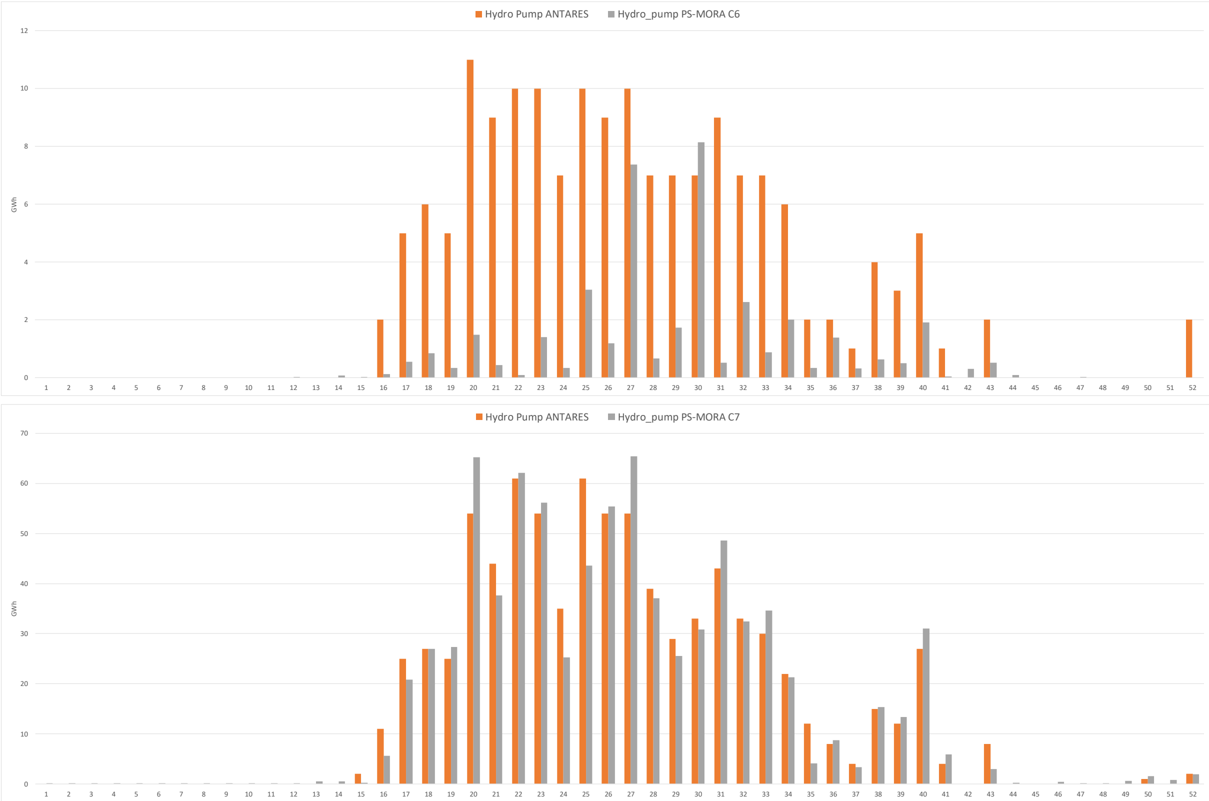
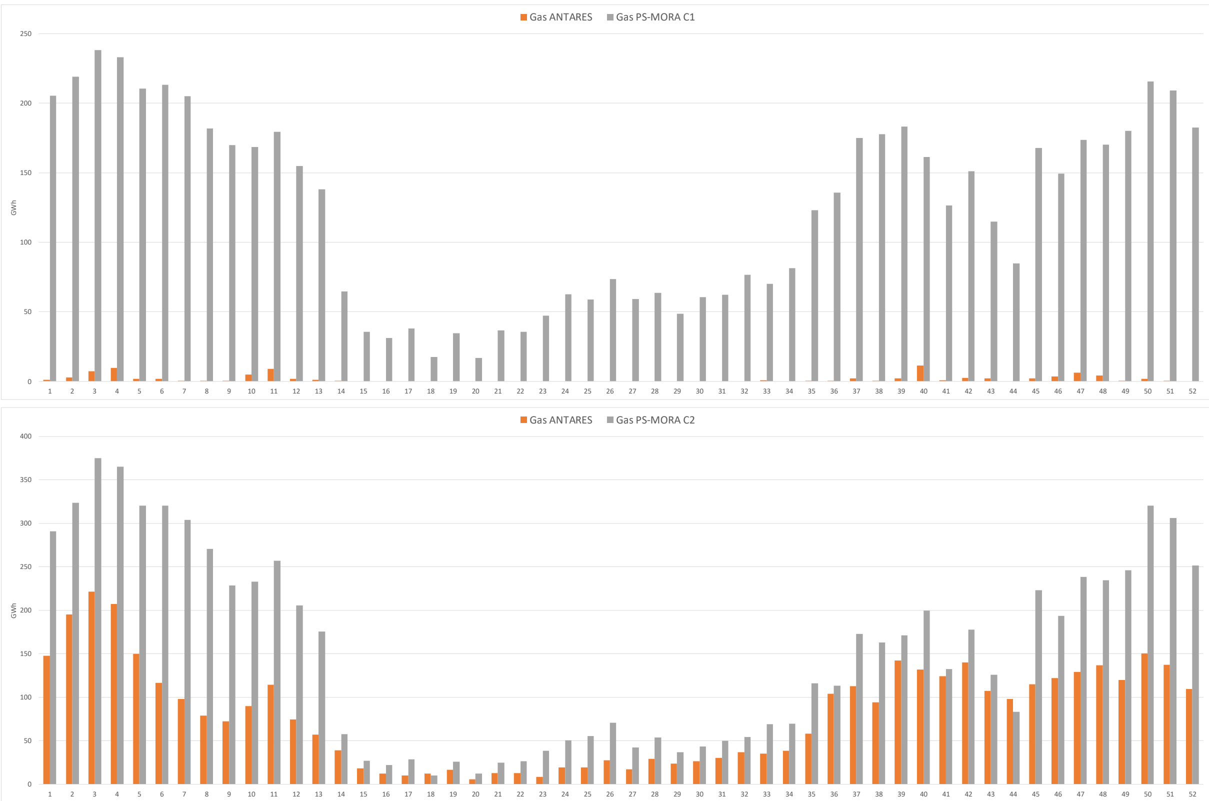
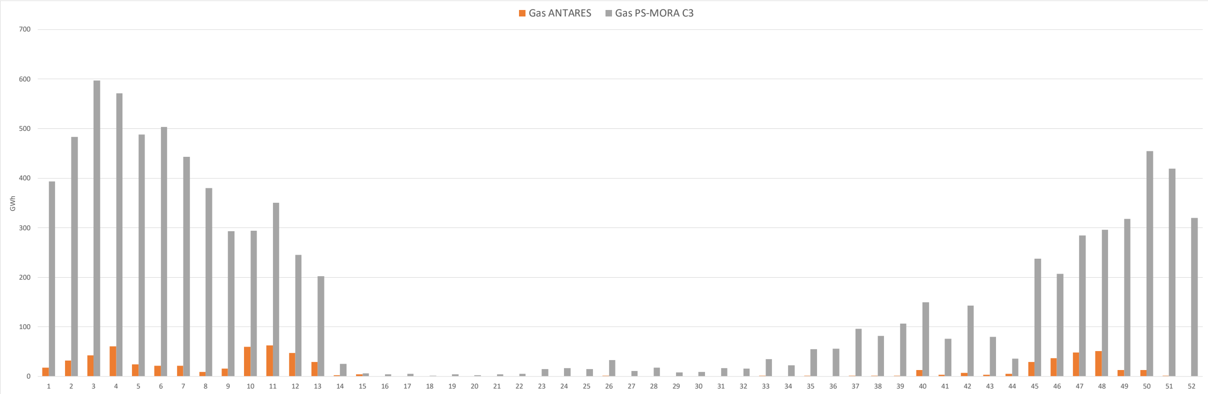
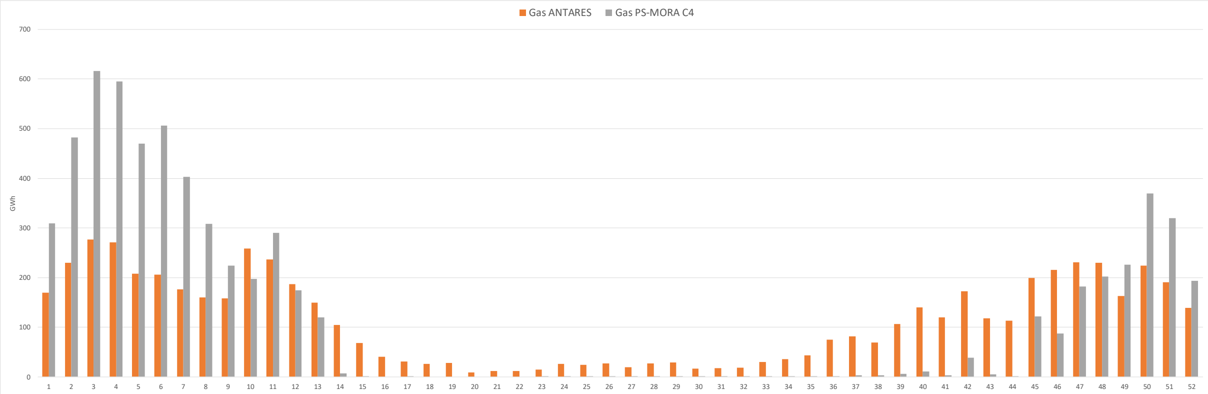


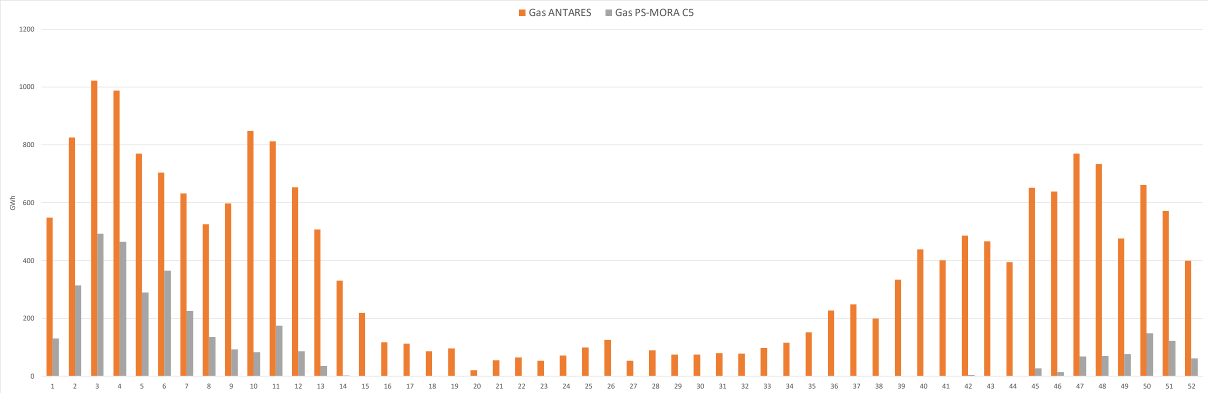
Figure 24 – Hydro Pump Production Comparison between ANTARES and PS-MORA

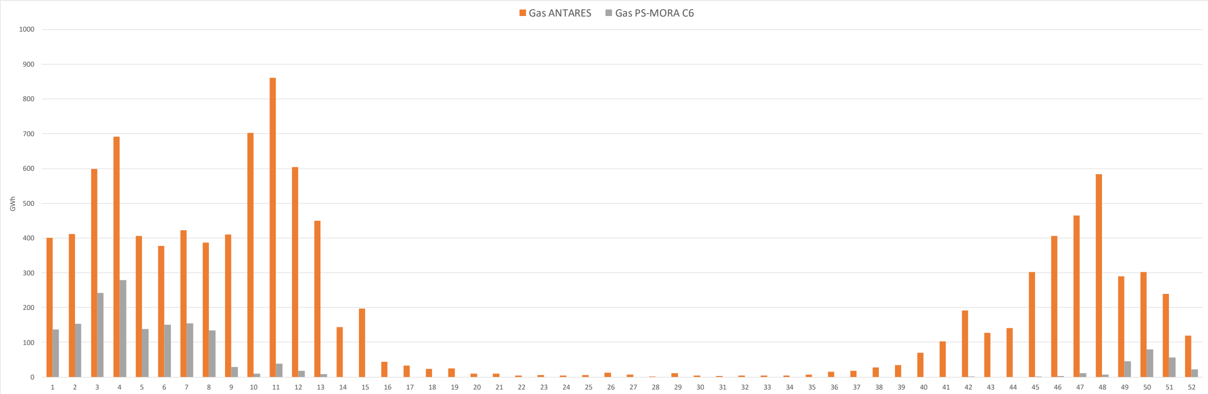
6.1.3 Natural Gas




Gas ANTARES
Gas PS-MORA C3
GWh


Gas ANTARES
Gas PS-MORA C4
GWh


Gas ANTARES
Gas PS-MORA C5
GWh


Gas ANTARES
Gas PS-MORA C6
GWh

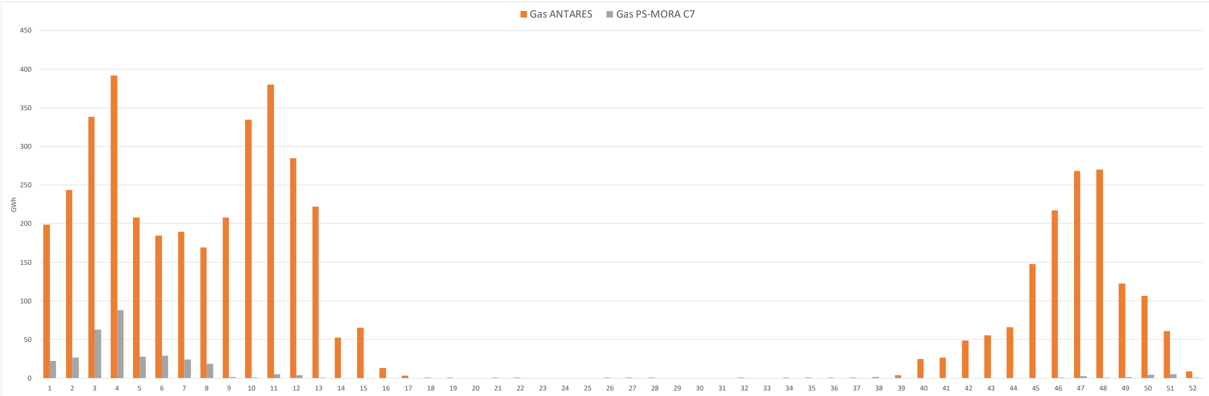
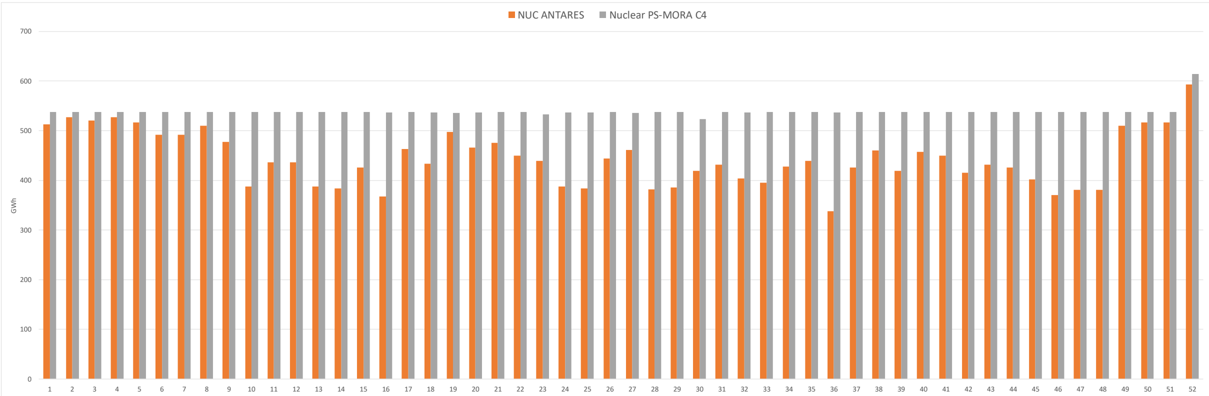
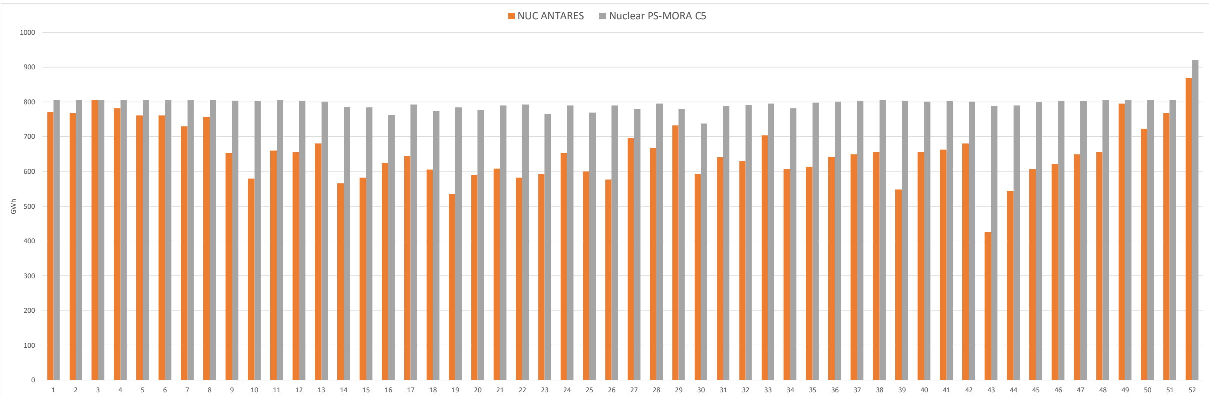
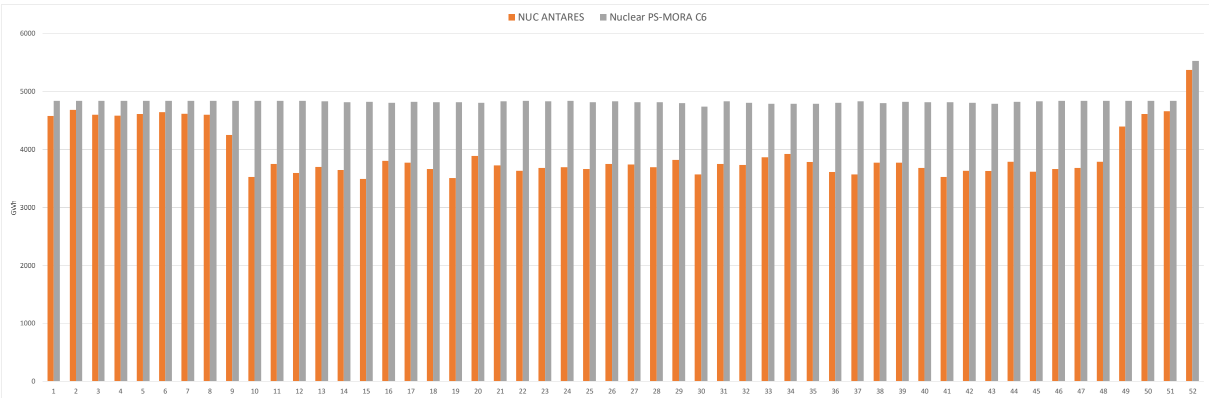


Figure 25 – Natural Gas Production Comparison between ANTARES and PS-MORA

6.1.4 Nuclear







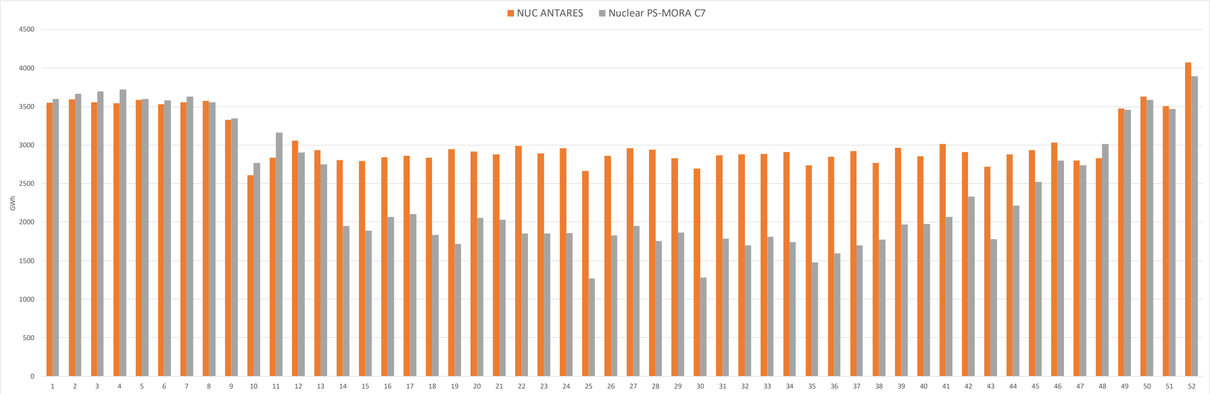
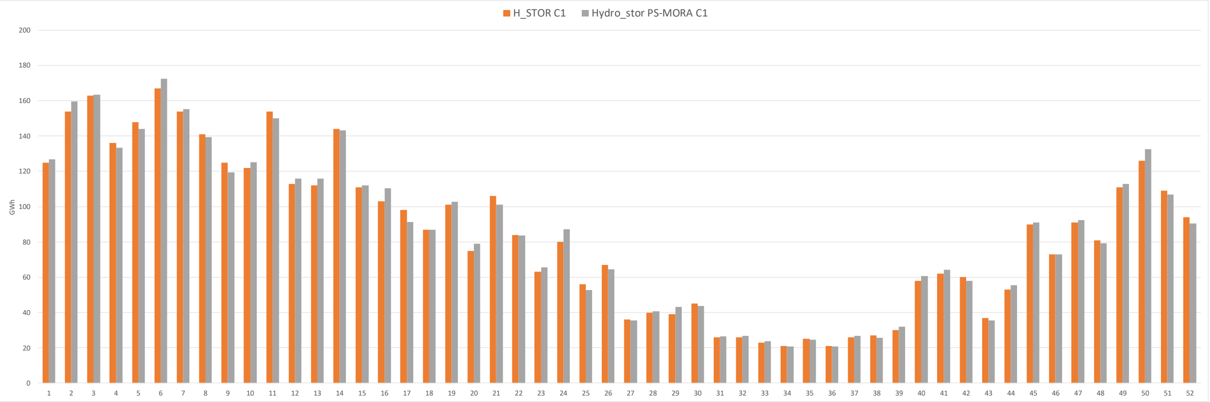
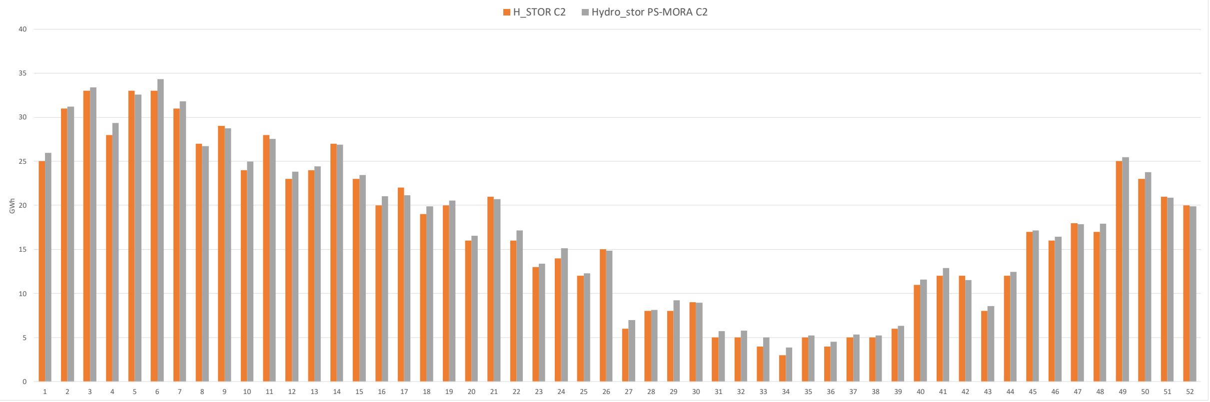


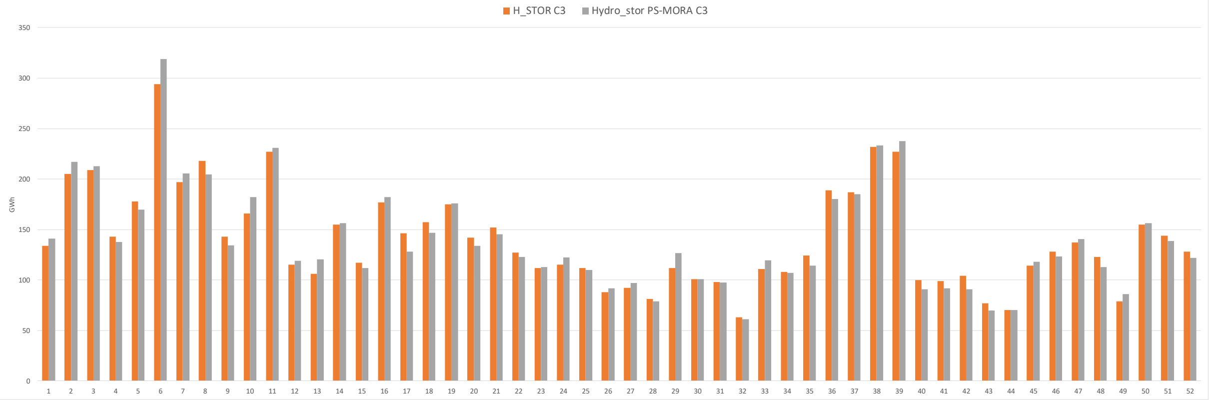
Figure 26 – Nuclear Production Comparison between ANTARES and PS-MORA

6.2 Weekly hydro production comparison per cluster and technology between ANTARES and PS-MORA, considering hydro production costs = 0

6.2.1 Hydro Storage







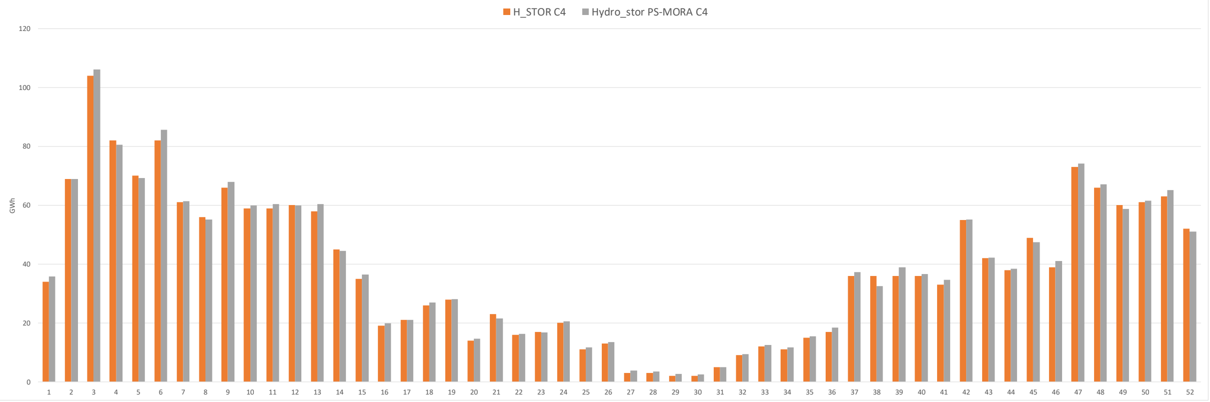
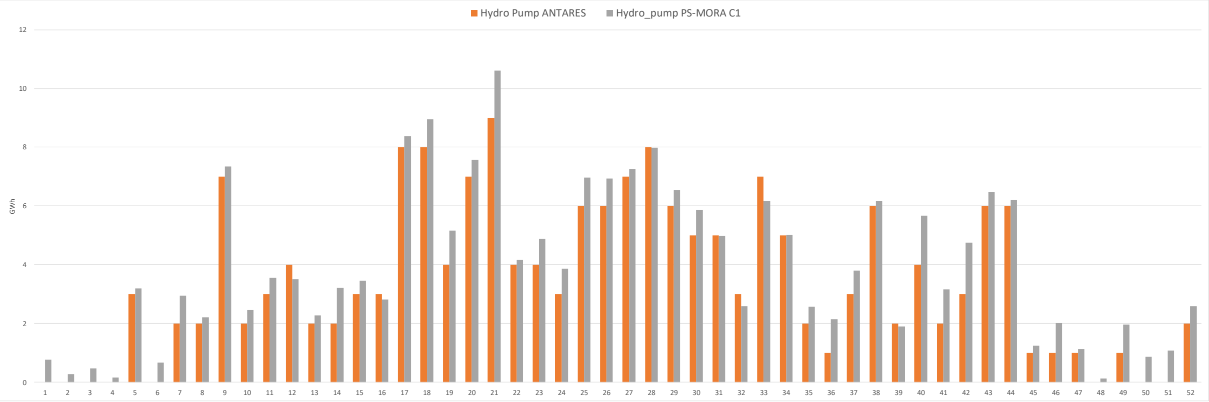
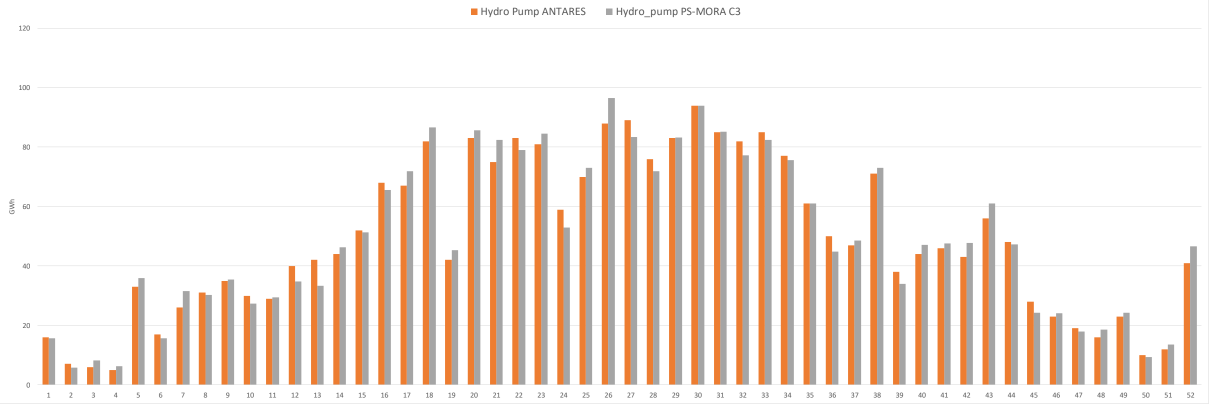
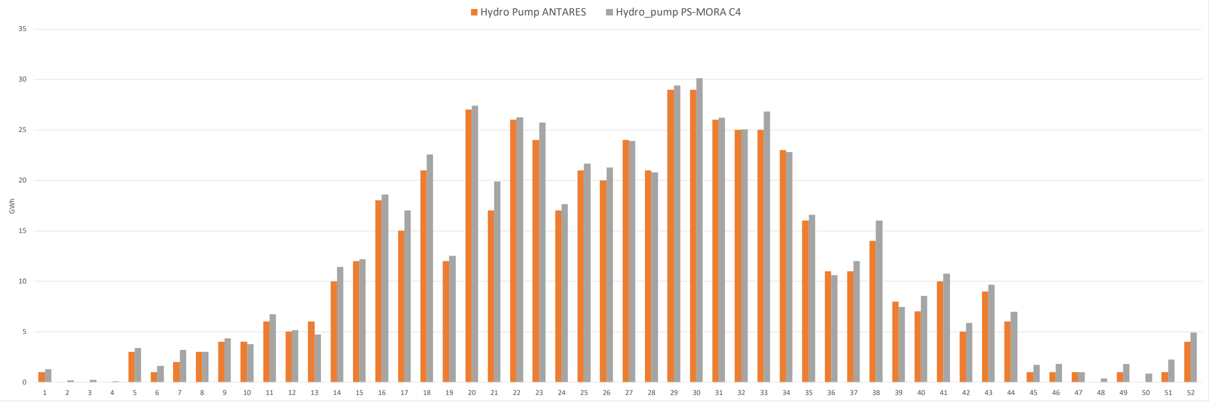


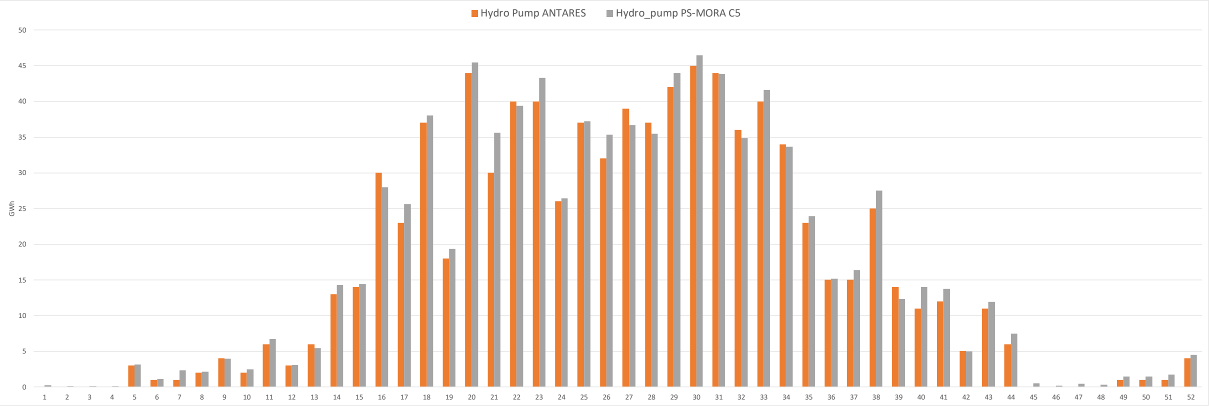
Figure 27 – Hydro Storage Production Comparison between ANTARES and PS-MORA using market bid price = 0€/MWh

6.2.2 Hydro Pump









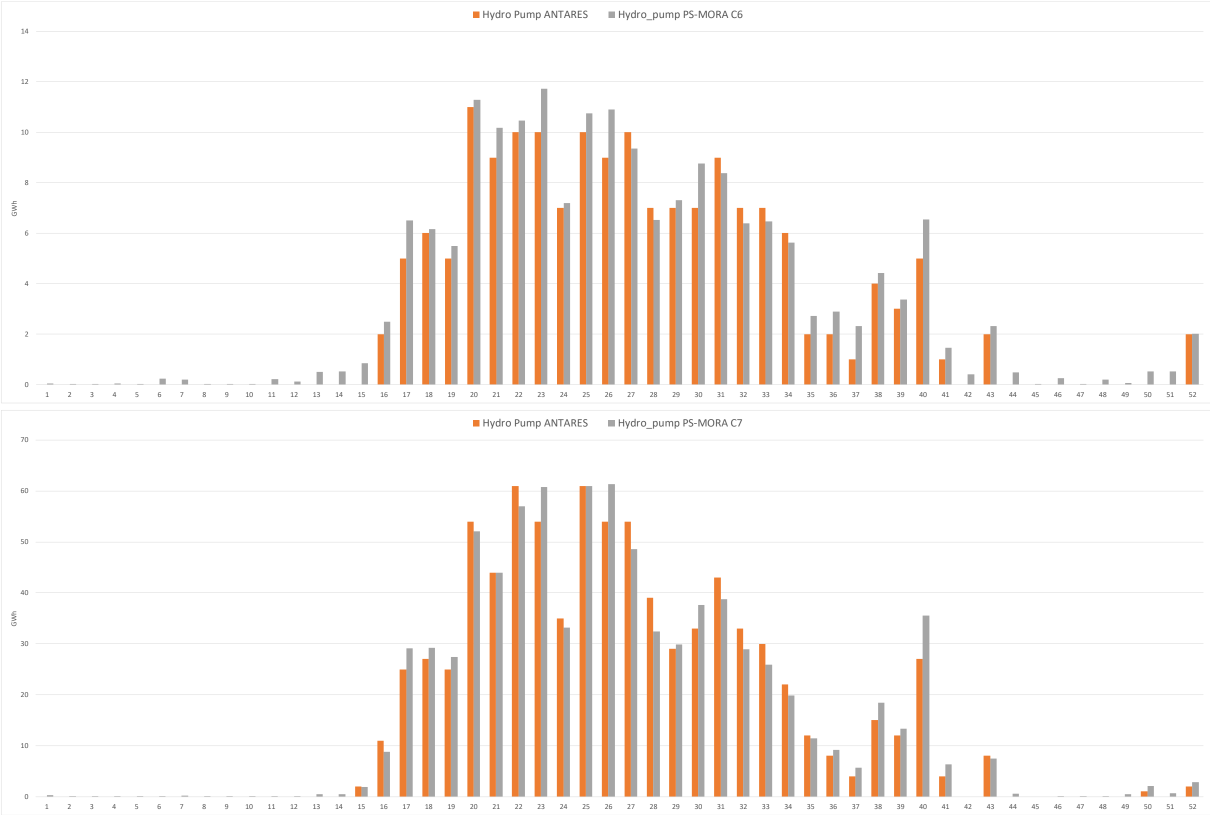


Figure 28 – Hydro Pump Production Comparison between ANTARES and PS-MORA using market bid price = 0€/MWh