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Dimensioning Studies for Reversible Hydro Power Plants in Portuguese Islands

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Abstract

This work is within the scope of set of consultancy studies made for Portuguese islands. It focuses on the integration of Pumped Storage Power in isolated islands. The paper starts to address several power systems circumstances about two Portuguese islands on the energetic level. For each of these islands, an independent examination of the conditions to install a reversible hydro power plant is accomplished. Therefore, the energy volume to be stored due to excess of renewable generation and the ideal power and number of the pumps and turbines to be installed were identified and evaluated for the sake of using the produced energy surplus as to be pumped and later generated. The paper enhances the importance of storing energy in the operation of isolated and small systems with considerable amount of intermittent power resources as well as the conditions for the viability of installing new exploitations of this kind.

Author Keywords. Pumped Storage Power, Unit Commitment Problem, Peak Shaving, Isolated Systems

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1. Introduction

The increasing penetration of wind power and other non-dispatchable renewable energy sources (RES) into power systems may lead to excess of produced energy in off peak periods and therefore to curtailment or exportation of this energy. The other option is store the energy surplus and return it to the system in periods with high consumption. Among several technologies that allow to store energy, a well-known possibility is to use reversible hydro power plants with sufficient reservoirs capacity (Pumped Storage Power – PSP) which stands an important instrument to support power/supply management. Besides, in a world increasingly concerned with greenhouse gas emissions, the use of PSP constitutes an advantage due it is used as a system that reuse water which is stored it in an upper reservoir until its delivery and therefore is a way to reduce environmental pollution. When the demand is high, the stored water is released through hydro turbines to generate electric power. The site characteristics, such as amount of water, topography and geology, influence the design of almost every PSP power plant. Pumped storage is usually seen as the most promising technology to increase renewable energy penetration levels in power systems and especially in small autonomous island grids and many times take part in hybrid power stations with wind energy systems. The PSP system is a hydroelectric type of power generation system used in power plants for peak load shaving (Rehman, Al-Hadhrami, and Alam 2015).

Pumped hydroelectric storage plants have several advantages mentioned in Hino and Lejeune (2012) which can be summarized as: flexible start/stop and fast response speed, ability to track load changes and adapt to drastic load changes, and ability to modulate the frequency and maintain voltage stability. A survey conducted in Kear and Chapman (2013) conclude that, in spite of their weighty costs, pumped hydro was almost unanimously viewed as technically capable of providing renewable support and peak power suitability. All these imply that PSP plants are useful tools in the electricity system.

In countries such as Portugal, Spain or Switzerland, PSP has high integration levels compared with other established technologies according to Filipe et al. (2016). Their usage may be an even more significant choice on small and energetic independent islands since they are usually reliant on thermal generation.

There are, in recent literature, several examples of works that have tried to tackle electrical energetic issues from different angles in isolated systems such as islands. Vasconcelos et al. (2015) present the main challenges and identifies possible solutions related to the operation of remote, isolated power systems with a large integration of renewable generation, taking as example the real case of the Portuguese-Atlantic islands. Authors looked for the support and improvement of robustness of the operation in terms of fast frequency and voltage control responses using islands of Madeira archipelago as case study. In this work the authors accomplished to size a flywheel energy storage system (FESS) aiming to avoid complications on frequency stability. Also, for Madeira island, there were quantified the technical benefits that result from variable speed hydro pumping stations that are able to provide primary frequency regulation services in the pump operation mode. In Cross et al. (2017) a detailed benchmarking exercise of islanded systems was performed using results of surveys for 28 islands and studying in detail 4 of those islands in terms of energy challenges related with interconnection, renewables and energy storage. They reached the conclusion that peak shaving approach through demand response could be useful in this type of systems. They advise also for the usage of energy storage since it can facilitate more efficient use of existing generation and it promotes the integration of a higher share of production from RES. In Bueno and Carta (2005) the authors discussed a technical and economic sizing of medium sized wind powered pumped hydro storage systems. This work was performed using an island from Canarian archipelago as case study. The possibility to penetrate about 68% of renewable energy after an analysis of economic point of view was estimated. Duić and Carvalho (2004) describe H2RES model for optimization of integration of hydrogen usage on an island of archipelago of Madeira. This model includes reversible hydro and batteries as storage technologies which may constitute an interesting tool for island energy planning. A comparison between batteries and pumped hydro storage is also made in Ma, Yang, and Lu (2014) on a remote island in Hong Kong. They reached the conclusion that the pumped storage combined with battery bank option conducts to lower operation costs compared to other options and the economic advantage of pumped storage is even more substantial in the case of purely pumped storage with hydraulic controller.

In this context, the technical circumstances of installing a reversible hydro power plant in each of two Portuguese islands were studied. Such a study need to bear in mind the conditions of the global system in the horizon of 2020 which corresponds to the year when the exploitations should start to operate. These islands are two of the largest in the corresponding archipelago, not only on area but also on energetic amount of resources. Because of their size and isolation, the two systems continue very dependents of thermal generation on account of security, stability and quality of supply issues, although there is an effort to promote the penetration of endogenous production in the region. The first island has about 402 km^2 of area with its most elevated point situated at 1021m height above sea. For 2020 horizon it is foreseen that the power system is composed by a thermal power plant of 61 MW, 2 wind farms with total of 12,6 MW installed, 3 hydro power plants with capacity of 1,4 MW, 3,5 MW of geothermal energy and 2,1 MW of installed capacity derived from burning of waste. The second island extends to over a surface of 746.82 km^2. In 2020 is was estimated that the power system will have a total of 98 MW of thermal power installed, 9 MW derived from wind power, capacity of 5 MW by hydro plants without pumping capacity, 7 MW from waste energy, almost 30 MW of geothermal power and about 1 MW resulting from biogas energy.

In this paper, a methodology used to face the problem is explained as well as the assumptions that were taken to fit the solution adopted to the case studies in analysis. Afterwards, some global results are showed using two different levels of detail. Finally, the results and solutions are discussed, and in the end, conclusions summarize what was achieved with this work.

2. Methodology

The proposed methodology adopts the analysis on specific days for each season of the year where the operation of the power system of each island is simulated. For both islands, future scenarios of generation capacity and consumption for the horizon of 2020 were defined according to estimated data from the operators of the network. The base temporal series correspond to the measurement series of 2015 with an interval of a half of hour, namely the speed of wind (m/s), the demand (MW) and the typical profiles of generation (MW). These series were then adjusted considering the necessary update of consumption and generation in order to fit these data to the projected consumption in 2020.

2.1. Procedure

A procedure was developed iteratively aiming to lead to final values of power in pumping mode, power in generating (turbine) mode, the energy to be pumped and energy to be generated. The following list corresponds to the steps of the approach used to achieve the results:

a) Identification of critical days for each season which are days with higher generation compared to consumption. These days may constitute as important measures to evaluate extreme conditions.
b) Thermal units dispatch and definition of load diagrams of the other technologies of generation.
c) Quantification of the surplus production that comes from renewable sources.
d) Establishment of the relations between pumping and generating modes and their periods. Assuming that the power to be generated and the pump power have similar values (pump/turbine with a typical value used in the literature of 70% of efficiency), the power to be generated was considered around the biggest surplus production from renewable sources.
e) Re-dispatch of thermal units considering that the hydro system is operating in turbine mode and taking into account the spinning reserve criteria.
f) Identification of the highest pumping power.
g) Compute the energy to be pumped at off-peak hours.
h) Distribution of energy to be generated in the peak periods considering a daily cycle which means that the energy stored at off-peak hours when the hydro system is

pumping mode is delivered to the system at the same say through turbines that generate the amount of energy necessary to cover the demand. The process of distributing the energy through the peak periods is accomplished by following a peak-shaving logic (detailed in 2.3).

2.2. The Unit Commitment problem

Points b) and e) mentioned in the last section requires the use of unit commitment problem (UCP) well described in Matos (2000) which is essentially an optimization problem aiming to satisfy the expected demand with a certain reserve, at minimum cost, respecting all the technical constraints. UCP is usually applied on thermal machines. The associated costs correspond to operation costs, typically nonlinear functions, and start-up and shut down costs of the machines used to produce electrical energy. The total power available in the system must be larger than the expected demand and the difference between these two values need to be higher than the spinning reserve defined for each interval of time (usually an hour). Thermal machines are subjected to individual constraints namely their minimum start time of operation, minimum stoppage times, minimum and maximum produced power and limits in their producing ramp rates (MW/h). Thus, for each period *i*, the following formulation has to be accomplished.

$$\min C = \sum_{i=1}^{h} C_i + T_i \tag{1}$$

$$\sum_{k=1}^{n} u_{ik}.P_k^{max} \geq P_i^{load} + P_i^{reserve} \qquad ,\forall i \tag{2}$$

$$\sum_{k=1}^{n} u_{ik}.P_{ik} = P_i^{load} \qquad ,\forall i \tag{3}$$

$$u_{ik}.P_k^{min} \leq P_{ik} \leq u_{ik}.P_k^{max} \qquad ,\forall i \tag{4}$$

In this formulation, C_i represents the operation costs of dispatching thermal units in the period *i* and T_i are the costs of transition between periods. The model aims to minimize the sum of these two costs during a total number of periods *h*. The total groups of thermal machines must have a sufficient installed power P_k^{max} to cover the consumption P_i^{load} and the reserve $P_i^{reserve}$. The binary variable u_{ik} is one if the group *k* in the period *i* is in service and is zero if it is turned off. P_{ik} corresponds to the effective power produced by group k in the period *i* and it is subjected to its technical minimum (P_k^{min}) and maximum (P_k^{max}) power.

There are several methods to dispatch the groups of thermal power, such dynamic programming, lagrangian relaxation, metaheuristics or evolutionary computation. However, since the number of thermal groups in these case studies is small, the option was to use a merit order. This option bases its decision on the indicator M_k presented in the next equation.

$$M_k = \frac{C_k^0 + C_k^V(P_k^{max})}{P_k^{max}} \tag{5}$$

The indicator corresponds to the total cost per unit of generated power. C_k^0 is the fixed cost of operation of group *k* while C_k^V is the equivalent variable cost. The groups are dispatched in ascending order of the respective M_k and removed by the inverse order. Together with this formulation there are some heuristics applied locally to eliminate situations of stoppage after starting up and other similar situations which replaces partially the model described in the first equations.

The requirement of spinning reserve in this case study obeys to constraints defined by the network operator. The amount of necessary spinning reserve varies with the speed of the wind in the period in analysis. For the cases where the operation of wind turbines is in its stable zone, less is the requirement of reserve (typically for speeds between 15 and 25 m/s). If the speed of wind is lower, wind turbines are operated within a more unstable zone which brings the necessity to the network operator to specify a higher requirement of spinning reserve. This requirement frequently comes in wind power produced percentages. For instance, for island 1, the requirement of spinning reserve is 100% of the generated wind power if the speed of the wind is lower than 15 m/s and corresponds to 50 % of the same generation if the speed of the wind is between 15 and 25 m/s.

2.3. Peak-shaving approach

As stated previously, it was admitted that the reversible hydro power plants to be installed would have a typical value of efficiency (pump and turbine) equal to 70%. Thus, part of the stored energy in the pumping hours was considered to generate in the rest of hours of the day. The distribution of the energy to generate during the day periods was done proportionally to the demand registered in these instants with the objective to smooth the load diagram (peak-shaving) as Figure 1 illustrates.

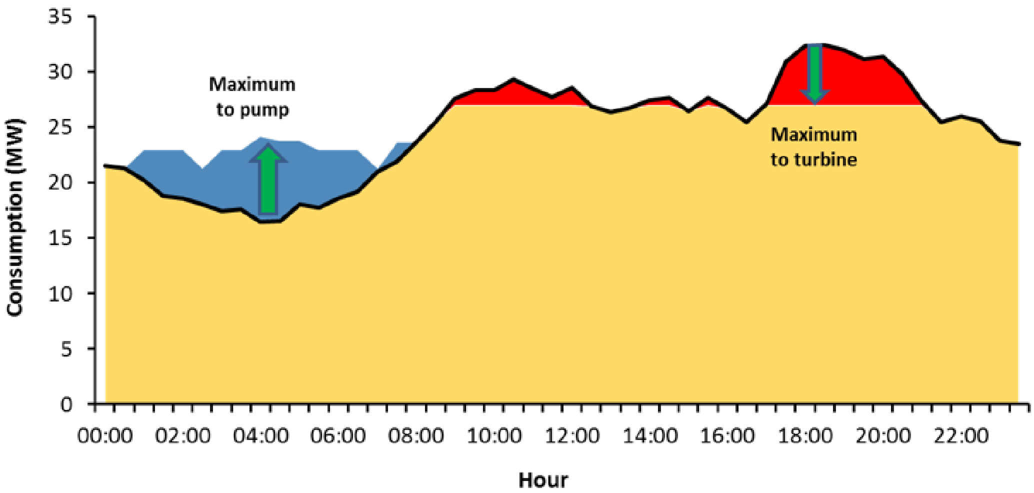

Figure 1: Example of the effect of distribution of pumping/generating energy in the load diagram

The hours which the blue area is above the black line (original load curve) correspond to the period when the pumping of production surplus should occur. If pumping did not happen, part of the generation would have to be cut, if this power comes from wind. The hours which the red area is below the black line are the hours when the stored energy should be delivered to the system by giving use to the turbines of the reversible hydro plants. In this period, the yellow area represents the consumption that all the remaining technologies would have to support. The energy above that area would be supported by the new hydro power plant operating in turbine mode.

3. Results

In this section some results will be presented using two different levels of detail. Firstly, examples of load diagrams for typical days of each island will be shown together with the results of using the methodology approached in this paper. Then, a statistical analysis covering all periods in the year will be performed.

3.1. Individual examples

Figure 2 shows one typical day of operation on winter for each Island. These days are previously chosen by the network operator for each season of the year because they have characteristics that represent the average behavior of the load diagrams.

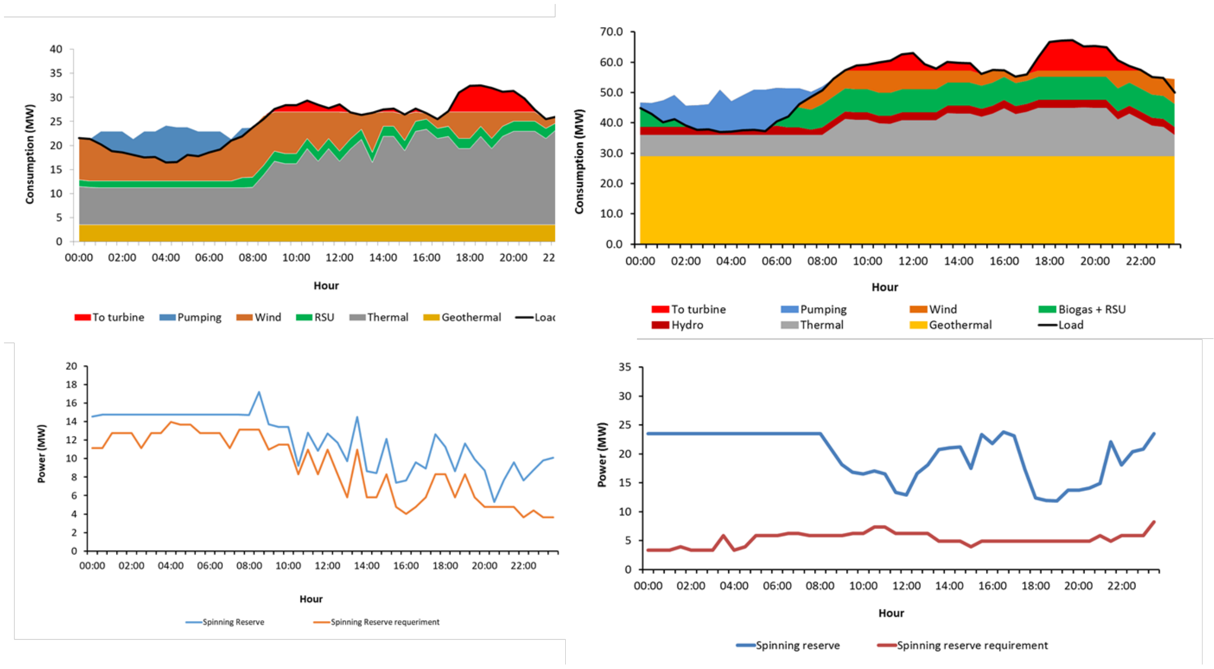

Figure 2: Left: Load diagram of a typical day of winter for island 1 and the corresponding spinning reserve requirement. Right: Load diagram of a typical day of winter for island 2 and the corresponding spinning reserve requirement

In the top of Figure 2, the outcomes of the methodology proposed in the previous sections for each island are presented over the load diagrams. Below the load diagrams, it is possible to see also the corresponding spinning reserve requirements and effective values during the same days.

As it is possible to observe in both cases, there is a surplus of production during the off-peak hours which can be pumped and later generated in its entirety during the peak hours at the same day. In the first island case, the required maximum pumping power would be 7.7 MW and the pumping energy would correspond to about 31 MWh while the maximum power generated in turbine mode would be about 5.5 MW and the energy stored in the upper reservoir would be around 26 MWh which is equivalent to roughly 22 MWh of energy turbined. In the second island case, the required maximum pumping power would be 14 MW and the pumping energy would correspond to about 67.2 MWh while the maximum power generated in turbine mode would be about 10 MW and the energy stored in the upper reservoir would be around 55.8 MWh which is equivalent to roughly 47.1 MWh of energy generated.

These scenarios configure an intermediary situation where all the energy previously pumped can be returned to the system in a daily cycle of operation. As mentioned before, also critical days were studied in this first phase of the work. At some of those scenarios, the energy stored due excess of renewable generation is so high that would not allow the operator to return it to the system in the same day.

3.2. Statistical analysis

Considering the results obtained for critical and typical days, a statistical analysis of the complete time series for the year was performed. This analysis was subjected to studies towards to identify the frequency of occurrences of the scenarios previously mentioned for a longer horizon. Therefore, it is possible to access to what extent these scenarios could be less common which will affect the solution of the dimensioning. A simplest scrutiny to critical days of the year would eventually lead to a situation where the dimensioning is exaggerated in view of the expected number of cases where such sizing is in fact justified. Thus, a simplified algorithm was created to perform the generation units dispatch aiming to quantify, for each day, the energy surplus in the off-peak periods and the energy that can be produced in the peak periods for all days in the year. This algorithm admits some assumptions namely the duration of the period to pump (00:00 to 07:30), the duration of the period to turbine (08:00 to 23:30), the operation of the hydro power plants corresponds to a daily cycle and there are no constraints of minimum uptime and downtime in the generation units dispatch.

Top left of the Figure 3 presents the histogram of necessary pumping power (MW) half-hourly in the off-peak period for island 1. This analysis permits to identify the number of times that a certain pumping power is necessary during the all off-peak periods. A similar examination was made for the powers in turbine mode, which result is presented in the top right of Figure 3. In bottom left of the same Figure is shown the histogram referred pumping energy (MWh), stored in the upper reservoir also for the first island. Finally, in the bottom right of Figure 3, is presented the histogram associated to the ability to deliver the stored energy to the system through operation of hydro power plant in turbine mode. The total number of occurrences (days) involve only the days that would have energy available to store which in the first island study corresponds to 228 days.

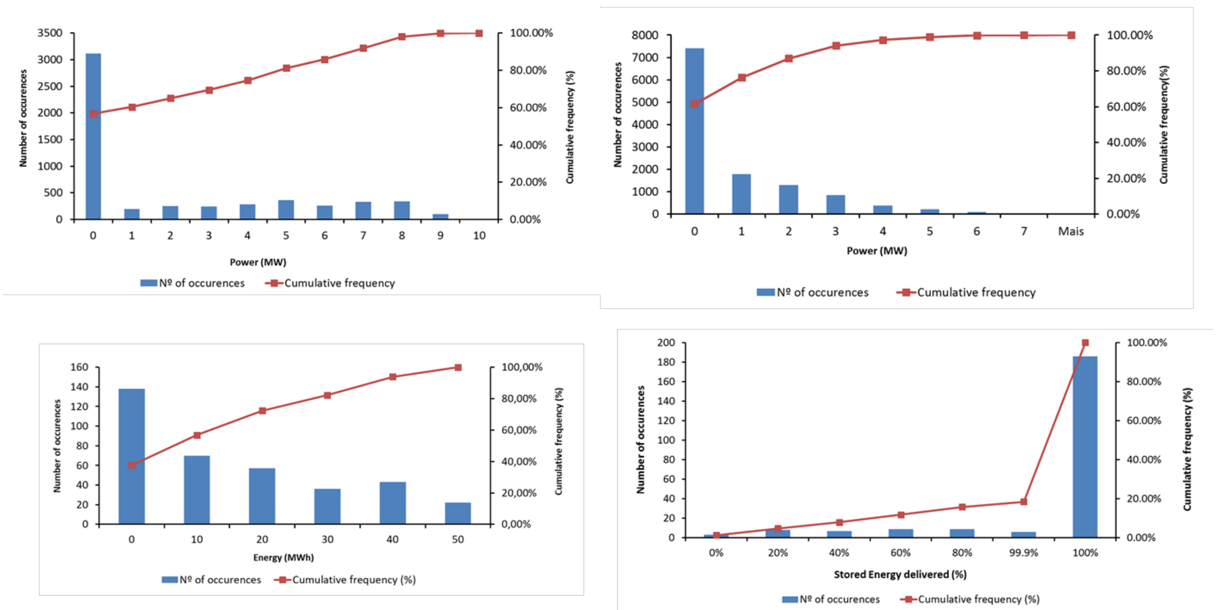

Figure 3: Top Left: Power in pumping mode (island1). Top Right: Power in turbine mode (island 1). Bottom Left: Stored energy (island 1). Bottom Right: capacity of returning stored energy to the system (island 1)

Identical assumptions were taken in order to produce similar histograms for the second island. Thus, Figure 4 shows an analogous analysis made for the first island. In this case, regarding the bottom right histogram, the total number of occurrences (days) involve all days in the year, because in all of them there would be energy to store.

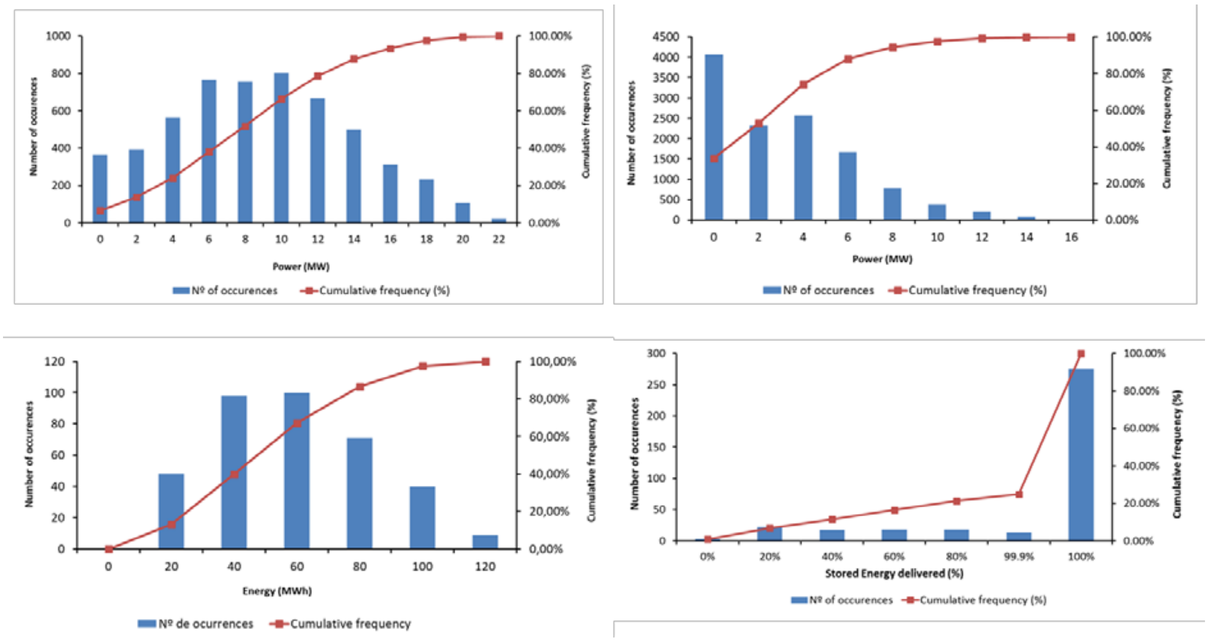

Figure 4: Top Left: Power in pumping mode (island2). Top Right: Power in turbine mode (island2). Bottom Left: Stored energy (island 2). Bottom Right: capacity of returning stored energy to the system (island 2)

3.3. Discussion of results and solutions

After the methodology that used critical and typical days was conducted and a statistical analysis was performed, it is possible to provide some suggestions regarding the future hydroelectric exploitations to be installed in the two islands.

For the first island, the maximum values obtained were 9,26 MW for the total pumping power, 6,29 MW for the total generated power and 63,56 MWh for stored energy. However, due issues of economical nature, it is not convenient to dimension a system to extreme conditions.

By means of statistical analysis carried out, it is possible to conclude that a pumping power around 8 MW would allow to cover a high percentage of occurrences and, therefore, it should not be economically interesting to consider higher pumping powers. Concerning the number and power of the pumps to consider in order to achieve a total pumping power between 7 and 8 MW, and considering the pumps available in the market, two options are suggested for pump powers to include in the hydroelectric exploitation:

- Include 6 pumps of 1.25 MW (total of 7.5 MW)
- Include 3 pumps of 1.25 MW plus 2 pumps of 2.3 MW (total of 8.35 MW)

The fractioning of the total pumping power will allow to follow the excess of generation from small values to high values with significant pumping efficiency. Regarding the total turbine power, a value around 4 MW would allow to cover an elevated number of occurrences. However, if it is intended to return all energy stored in a daily cycle but in a fewer number of hours, then a higher value of turbine power will be necessary (around 6 MW). Moreover, it makes sense to choose a value closer to the decided pumping power requirement. For the purpose of ensuring the ability to generate small powers and thus obtaining higher performance, an installation of two turbines of 3 MW (total of 6 MW) is recommended. Regarding the stored energy, it is suggested that 50 MWh is the most suitable value to consider with the view to choose an adequate reservoir volume since it will cover almost all the occurrences.

For the second island, the maximum values obtained were 20.47 MW for the total pumping power, 12.26 MW for the total generated power and 151.18 MWh for stored energy. By means of statistical analysis carried out, it is possible to conclude that a pumping power around 18 MW would allow to cover a high percentage of occurrences and, again as before, it should not be economically interesting to consider higher pumping powers. Concerning the number and power of the pumps to consider in order to achieve a total pumping power roughly between 16 and 18 MW, and considering the pumps available in the market, three options are suggested for pump powers to include in the hydroelectric exploitation:

- 4 pumps of 3.4 MW plus 2 pumps of 1.25 MW (total of 16.1 MW)
- 4 pumps of 3.4 MW plus 3 pumps of 1.25 MW (total of 17.35 MW)
- 4 pumps of 3.4 MW plus 2 pumps of 2.3 MW (total of 18.2 MW)

As before, the fractioning of the total pumping power will allow to follow the excess of generation from small values to high values with good performances. Regarding the total turbine power, a value around 12 MW would allow to cover an elevated number of occurrences. However, if it is intended to return all energy stored in a daily cycle but in a fewer number of hours, then a higher value of turbine power will be necessary (around 14 MW). In this case, one of the three following options is recommended:

- 1 turbine of 6 MW plus 2 turbines of 3 MW (total of 12 MW)
- 1 turbine of 7 MW plus 2 turbines of 3 MW (total of 13 MW)
- 1 turbine of 7 MW plus 2 turbines of 3.5 MW (total of 14 MW)

Regarding the stored energy, it is suggested that 120 MWh is the most suitable value to consider with the view to choose an adequate reservoir volume since it will cover almost all the occurrences. In this situation it is prudent to dimension the system for the worst case since a potential oversizing do not seem to lead to significant higher investment which is not the case for dimensioning of pumps and turbines.

4. Conclusions

This work involved an examination to the circumstances of installing a new reversible hydroelectric exploitation in each island subject of study. For each island, a methodology was considered to carry out an inspection of how to take advantage of the excess of generation coming from renewable resources. A dimensioning of ideal number and power of pumps and turbines as well as store capacity of reservoir were performed using results with two levels of detail. From the analysis of critical days of the year, maximum pumping and generating values of power and energy were retrieved. From the statistical analysis performed for all the periods in the year, it was possible to give more accurate suggestions to the decision maker regarding the ideal characteristics of the reversible hydro systems in order to face a sufficient number of expected occurrences.

The next step of this work will be a study involving dynamic simulation of the systems incorporating the hydro power plants towards to technically validate the dimensioning obtained in this study.

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