Pumped Storage as a complement for renewables

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Abstract

This work aims at evaluating if Pumped Hydro Storage (PHS) can be used to complement wind and solar generation in mainland Portugal. The 2018 energy Portuguese landscape was studied, and it was concluded that there is no substantial amount of excess energy. The PHS operation was simulated, and the results confirmed that when increasing generation by identified factors, installing PHS is viable and much needed to complement the renewable sources and satisfy 100% of demand. Possible locations to install PHS were identified. Future work should include the study of how increasing renewable sources capacity translates to increased generation.

Keywords: Pumped Hydro Storage, Renewable energy, Energy consumption, Wind Generation, Solar Generation.

I. Introduction

A. Motivation

With the increase in generation by renewable energy sources (RES), energy storage systems (ESS) are not only relevant but much needed. Besides helping integrate renewable sources in the grid, ESS help stabilize it, and solve power quality problems like frequency variations [1]. Portugal has set a number of goals in the National Energy and Climate Plan (PNEC) to obtain carbon emissions neutrality by 2050. One of the measures to be implemented is the increase of energy storage [2]. Pumped Hydro Storage (PHS) is considered a mature technology with high efficiency [3]. Other advantages are the long lifetime when compared to alternatives [4] [5], and the amount of energy it can store [6]. Among large scale ESS, pumped storage is described as the only viable one, being the best option for harnessing off-peak generation from renewable sources [7].

B. State of the art

C. Literature Review

Pumped Hydro Storage is an ESS that can be used to complement variable output sources such as wind and solar [8]. Integrating PHS with renewables can be challenging due to their low predictability [9]. To fully replace conventional sources with renewable energy, it is necessary to study grid connected RES-PHS systems [9] [8]. Critical parameters for the energy and economic viability of PHS installations include the total wind installed (or planned) capacity, and the storage capacity of the smallest reservoir [10]. Finally, pumped storage should be distributed to several sites, to maximize energy and economic efficiency, and new PHS investments can be planned and realized in parallel with the development of RES [10].

D. Existing Implementations

The Frades II power plant, visible in figure 1, uses existing dams to incorporate a configuration with variable-speed. It consists of two units of 383 MW each, and a maximum head of 441 m [11]. The Frades II power plant plays an important role in integrating the intermittent wind energy into the Portuguese grid [12] [13]. The Gouvães PHS power plant (PHSPP) is part of the Tâmega hydropower project. The PHSPP has 880 MW of installed capacity, distributed by 4 x 220 MW pump turbines, and a head equal to 660 m. The Tâmega scheme will complement electricity generation from wind [14].

Figure 1: Aerial view of the Frades II power plant.

E. Objectives and Contributions

The main objective of this dissertation is to determine the conditions in which pumped hydro storage can be used to complement wind and solar resources in order to meet energy consumption in mainland Portugal. The contributions of this work are the necessary modifications of the renewable energy scenario to justify the implementation of PHS in mainland Portugal and allow for all demand to be satisfied, the study of the constraints that the PHS facilities must respect in order to fully satisfy demand, and the study and selection of appropriate locations for facilities that satisfy those constraints.

II. Background

Renewable energy is generated from energy resources that can be replaced rapidly by a natural process, such as sunlight and wind, for example. Renewable energy sources can be divided into groups of technologies: Hydropower, Wind Power, Solar Energy, Geothermal Energy, Bio Energy, and Ocean Energy.

Energy storage systems allow the shift of excess energy to later periods in order to not waste energy. There are five types of ESS: Electro-Chemical, Electro-Mechanical, Chemical, Pumped Hydro Storage and finally Thermal Storage, with different storage capacity, efficiency, speed of response, among others.

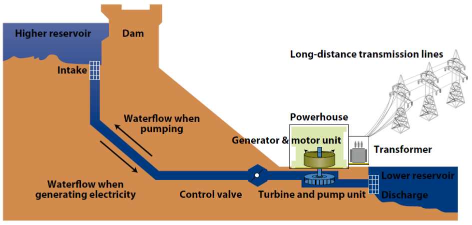
III. Pumped Storage

A. Background

PHS was traditionally used to smooth load variations on the power grid. This technology allowed, and to this day still does, base-load plants like nuclear power and coal power stations to continue operating at peak efficiency. Nowadays, with the increasing injection of renewable energy in the grid, pumped storage can also reduce the fluctuations introduced by intermittent renewable energy sources.

B. Operating Principle

The basic principle of PHS is to store energy in the form of gravitational potential energy of water, by pumping it from the lower reservoir to the higher one. When there is surplus energy from renewable energy sources, or when energy prices are lower, water can be pumped to the upper reservoir so that when demand increases or wind and solar production decreases, water can be released to the lower reservoir through a turbine in order to generate electrical energy. Figure 2 shows an example of a pumped storage scheme. Depending on the type of installation the reservoirs can be natural or man-made.



Source: Luo *et al.*, 2015.

Figure 2: Pumped Storage scheme.

C. Benefits and Challenges

Pumped storage is the ESS with the highest amount of installed capacity worldwide. Besides, PHS has an efficiency between 70% and 85% [3], and a very low self-discharge. The lifetime of a pumped storage facility is between 40 and 60 years, and if improvement measures are performed, it can be extended up to 100 years [15]. Finding suitable locations for the facilities is challenging due to the specific geotechnical conditions required. PHS has high investment costs related with land acquisition and mechanical/electrical machinery [16]. There are also environmental concerns associated with PHS facilities, over impacts like diversion of river flows, and creation of artificial water bodies [16].

D. Design Specifications

The installed capacity (power) of a PHSPP is calculated using equation 1. The most relevant variables are the head of the power plant (H) and the discharge flow (Q). There can be more than one reversible turbine in a pumped storage installation depending on the installed capacity to be implemented. Usually the turbines used, are reaction turbines like Francis turbines.

$$P = \gamma \cdot Q \cdot H_u \cdot \eta \tag{1}$$

The storage capacity (energy) of the upper reservoir of a PHS installation can be calculated using equation 2, that provides a solution in Joule (J). To convert the value to GW h one must divide the result by 3.6×10^{12}.

$$E = g \cdot \rho_{water} \cdot V_{res} \cdot H \cdot \eta \tag{2}$$

Every PHS project is different and have different total costs. The cost projection for a PHS facility in the $100 - 1000$MW range is between $600 - 1000$$ per kW and $10 - 15$$ per kW h [17].

D.1 Types of Installations

The types of pumped storage installations include Closed-Loop, Open-Loop and Seawater. Additionally, some potential technologies based on pumped storage are currently being studied, for example, Sea Bed Pumped Storage and Underground Pumped Storage.

E. Installed capacity around the world

Nowadays pumped storage provides about 96% of the total worldwide storage capacity, with a total of about 158 GW installed. Figure 3 shows the worldwide distribution of pumped storage capacity [18]. Pumped-Storage facilities in Portugal consist of dams with turbine/pump configurations, and currently there is a total of 2.82 GW pumped storage installed capacity in the country.

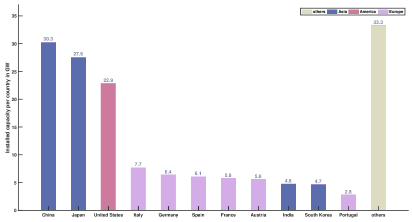


Figure 3: Installed Capacity in GW of the top ten countries, plus Portugal and the rest of the world.

IV. Electricity consumption and generation in Portugal

This section provides an overview of the electricity consumption and wind and solar generation in Portugal during 2018. Additionally, to justify the use of pumped storage, three scenarios are studied, in which the energy generation from the resources mentioned is increased. Finally, these scenarios are compared with the original data. All the data used for this chapter's analysis is provided by REN, the Portuguese transmission system operator [19].

A. Current state - base scenario

The energy consumption in Portugal during 2018 was 50.9 TW h, which represents a 2.5 % growth comparing to the previous year. Wind and solar installed capacity increased in 2018. Wind capacity increased 50 MW, while solar capacity increased 66 MW. Thus there is 5150 MW of installed wind capacity and 559 MW of installed solar capacity.

Figure 4 shows the monthly values of energy consumption, and wind and solar monthly generation during 2018. It can be confirmed that the total generation from these two types of renewable sources is not sufficient to meet demand. In regards to demand, it is possible to notice that energy consumption is quite similar monthly, the differences are mostly due to the fact that in winter months heating appliances are utilised. January is the month with the highest energy consumption, around 4.7 TW h, and the average consumption value per month is 4.24 TW h. In terms of energy generation, figure 4 shows that wind generation is more prolific than solar generation, since there is more installed wind capacity, and because there can be wind at any time of the day. Wind generation is highest during autumn and winter months, while solar power is highest during the spring and summer. It is also possible to verify high fluctuations of wind and solar generation throughout the year. September was the month with least wind and solar generation, around 0.5 TW h, while March was the month with highest generation, around 2 TW h.

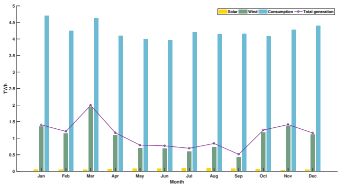
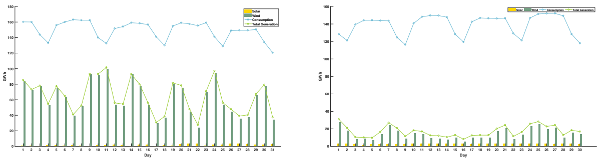


Figure 4: Consumption, wind, solar, and total generation in TW h per month.

Considering only wind and solar energy generation, the annual unsatisfied demand is equal to about 37 TW h, more than 70 % of the annual energy consumption. This value illustrates the magnitude of the problem, of considering only wind and solar energy to meet the country's energy needs, and justifies why PHS is needed.

Figure 5 shows the high volatility of wind and solar generation on a daily time frame during one month. It can also be verified that the month with higher total (wind plus solar) generation (March) has a lower solar contribution in comparison with the month with lower total generation (September) that has a greater contribution from solar generation. Increasing the installed capacity of both wind and solar sources is crucial since there are months with more sun and less wind, and months with less sun and more wind. Figure 6 shows the base scenario's residual profile for 2018. The residual profile is the difference between consumption and generation, represented here in an hourly time frame. As previously stated, 2018's wind and solar generation was not sufficient to satisfy in full every hour. This can be seen in figure 6, where the red bars represent the unmet demand of every hour of the year. Generation surpassed consumption during one hour, but the excess energy was so low it can not be seen in the residual profile. In this scenario total wind generation is equal to 12.21 TW h, and total solar generation is equal to 0.8256 TW h, adding to a total of about 13.03 TW h. The only excess energy



(a) March (best)

(b) September (worst)

Figure 5: Daily breakdown of the months with higher and lower wind and solar generation.

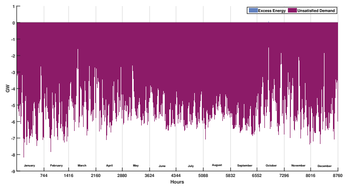


Figure 6: Residual profile in an hourly time frame during 2018, considering the base scenario

value registered is 58.5 MW h. In the base scenario, 99.99% of energy consumption hours are not satisfied by wind and solar generation alone, as well as 74% of demand. Without a significant increase in wind, and specially solar installed capacity, there is no need to implement energy storage systems like PHS, since there is barely any excess energy to reuse.

B. Increased scenarios

This section presents hypothetical scenarios where wind and solar installed capacity is increased, and it is assumed that the generation from these sources increases by the same factor. These scenarios are relevant, not only because more generation is needed to satisfy consumption, but also because to be able to integrate pumped storage, there must be excess energy to be stored. Equation $G_{Total} = (W_{Total} \cdot W + S_{Total} \cdot S)$ shows how total wind and solar generation is calculated, where W and S are the factors that multiply the current generation.

The factors used for scenario I ($W = 2, S = 14$) were based on two studies, one carried out by the National Laboratory of Energy and Geology (LNEG) [20] and the other inserted in the National Energy and Climate Plan (PNEC30) [2]. The other two (scenario II and III) are defined in the context of this work, and used the factors ($W = 3, S = 18$) and ($W = 3, = 25$), respectively.

B.1 Scenario I - (W=2, S=14)

Scenario I is increased by ($W = 2, S = 14$), making wind and solar installed capacity equal to 10 GW and 8.4 GW, respectively. Figure 7 (a) shows the monthly energy consumption, as well as the monthly increased wind and solar generation. In this scenario, there is still less energy generated than consumed in most months. In March, total wind and solar generation surpassed total energy demand. With this increase, during the summer, solar generation either surpasses wind generation or is very close to it. Annual unsatisfied demand is approximately 18 TW h, about 35% of the annual consumption (50.9 TW h).

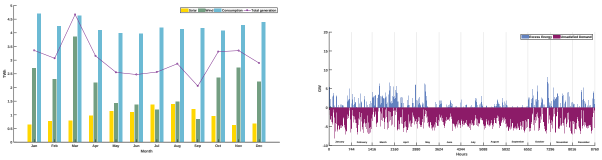

(a) Monthly profile (b) Annual residual profile

Figure 7: Monthly profile and annual residual profile. for scenario I.

Figure 7 (b) shows the residual profile, by hour. The blue bars correspond to excess energy, while the red bars correspond to unsatisfied demand. This scenario generated a total of 24.41 TW h and 11.56 TW h, wind and solar generation, respectively, which add up to 35.97 TW h. It is also possible to verify that total unsatisfied demand is 18.11 TW h and total excess energy is equal to 3.18 TW h. Total unsatisfied demand is greater than total excess energy which would not be enough to satisfy demand even if it could be stored by PHS. This scenario proves to be insufficient to justify using PHS to complement wind and solar generation. Additionally, an interesting metric that can be retrieved from the residual profiles is the number of consecutive unsatisfied hours, which in this case is 263 hours.

B.2 Scenario II - (W=3, S=18)

In the second scenario the factors are ($W = 3, S = 18$), making wind and solar capacity equal to 15 GW and 10.8 GW, respectively. Analysing figure 8 (a), it is possible to see that during six months of the year, combined wind and solar generation surpassed energy consumption. Months with lower combined generation are in general summer and spring months. For the present scenario, total wind and solar generation is equal to 36.62 TW h and 14.86 TW h, respectively. Total combined generation is equal to 51.48 TW h.

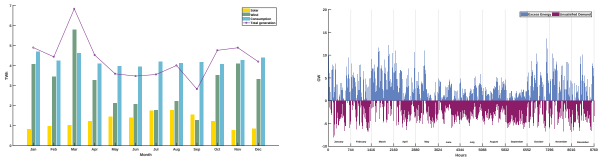
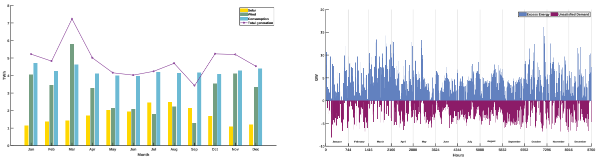

(a) Monthly profile (b) Annual residual profile

Figure 8: Monthly profile and annual residual profile. for scenario II.

The residual profile for scenario II is shown in figure 8 (b), and it is possible to verify that excess energy tends to be higher than unsatisfied demand. The longest streak of consecutive unsatisfied hours is 115. Total excess energy is equal to 11.96 TW h, and total unsatisfied demand is equal 11.38 TW h, which means that there is more excess energy than needed energy. If the surplus energy was stored by PHS, it could mitigate the remaining demand.

B.3 Scenario III - (W=3, S=25)

Scenario III is increased by ($W = 3, = 25$), making wind and solar capacity equal to 15 GW each. In this scenario, as seen in figure 9(a), combined wind and solar generation surpasses energy consumption during all months of the year, except September. Months in the beginning and ending of the year register higher generation than months in the middle. During July, August and September, solar gener-



(a) Monthly profile (b) Annual residual profile

Figure 9: Monthly profile and annual residual profile. for scenario III.

ation is higher than wind generation. Total combined generation is equal to 57.26 TW h, with wind and solar generation contributing 36.62 TW h and 20.64 TW h, respectively.

Figure 9(b) shows the residual profile, and it can be verified that there is much more excess energy than unsatisfied demand. In this scenario, energy surplus reaches a total of 16.71 TW h, and total unmet demand is equal to 10.35 TW h. The longest streak of unsatisfied hours is 63.

C. Results

Table 1 synthesizes the results for the studied scenarios. If there is no generation increase, it is impossible to satisfy demand, and to justify the use of pumped storage. Increasing installed capacity and consequently generation is crucial. The results from the base scenario can be marginally improved with a significant generation increase, going from $(W = 1, S = 1)$ to $(W = 2, S = 14)$, and only yielding one month in which combined generation is higher than consumption. Assuming a higher increase is possible, going from $(W = 2, S = 14)$ to $(W = 3, S = 18)$, the results improve substantially with six months with excess energy. Finally, taking an optimistic approach and further increasing solar generation (going from $S = 18$ to $S = 25$), only September is left with an energy deficit. In the last two scenarios the energy surplus is enough to justify the use of PHS.

Scenario	Multiplying Factors		Installed Capacity (GW)		Total Energy Consumption	Total Generation	Total Excess Energy	Total Unsatisfied Demand	Longest streak of consecutive
	Wind	Solar	Wind	Solar					
Base	1	1	5	0.6	50.9	13.03	0.0000585	37.87	6870
I	2	14	10	8.4		35.97	0.00318	18.11	263
II	3	18	15	10.8		51.48	11.96	11.38	115
III	3	25	15	15		57.26	16.71	10.35	63

Table 1: Summary of the results for the base scenario and scenarios I, II, and III.

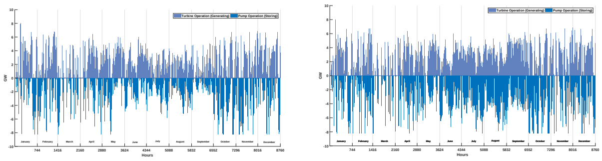
V. PHS to complement wind and solar generation in Portugal

In this section the PHS operation will be simulated to verify if it is viable to complement wind and solar generation. In this section, only the two scenarios that yielded enough excess energy (scenario II and III) to cover all demand will be considered.

A. Simulation of PHS operation

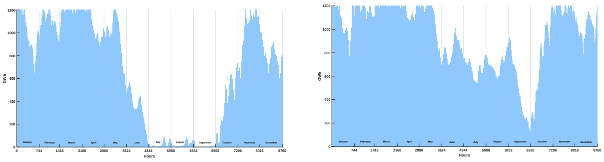
In an ideal situation the PHS operation profile should be opposite of the residual profile, so that all excess energy is stored and all demand is satisfied. In reality, not all of the excess energy can be stored, either because there is no storage space or not enough power to pump the excess. It is not feasible to limit installed capacity considering the peak of excess energy. In fact it is limited considering the peak of consumption, because the purpose, both economically and operationally, is to satisfy demand. Similarly, it is neither economically feasible nor sometimes possible to build reservoirs capable of storing all excess energy.

Figures 10 (a) and (b) show the PHS operation profiles, for both increase scenarios considered. These figures show how the pumped storage installation would operate. In figure 10, the dark blue areas represent hours when storage occurs (pumping mode), while the light blue areas represent hours of generation (turbine mode). Figures 11 (a) and (b) show the upper reservoir storage levels throughout the hourly simulation. The storage levels are in terms of stored energy (GWh) of the reservoir at a given time. During high excess energy periods, the reservoirs tend to be closer to maximum capacity, sometimes reaching maximum capacity, becoming unable to store the excess. These periods can last for months (March and April). During periods of low excess energy, the reservoir stores the surplus but soon after has to provide that energy, never equalling the storage levels of the periods of high excess energy. By comparing the residual profiles (figures 8 (b) and 9 (b)) with the PHS operating profiles (figure 10), it is possible to conclude that not all of excess energy has been stored. Firstly, pumping capacity is assumed to be equal to turbine capacity (8.2 GW), but there are hours with energy excess surpassing this value. Another issue,



(a) (3, 18) (b) (3, 25)

Figure 10: Annual pumped storage operation profiles in an hourly time frame.

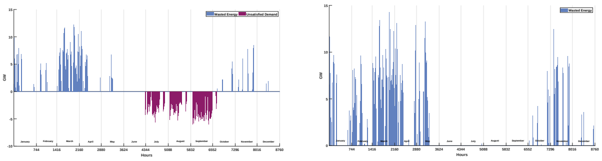


(a) (3, 18) (b) (3, 25)

Figure 11: Annual upper reservoir dynamics in an hourly time frame.

is that at a certain time instant the reservoir might already be at full capacity, so it is unable to store more energy.

Figure 12 shows the residual profiles resulting from the described PHS operation, for both increase generation scenarios. The first thing that can be verified is that not all excess energy is stored (blue area), confirming what was said in the previous paragraph. For scenario II (figure 12 (a)), it is also possible to see a red area from the end of June onwards, indicating that the energy reserve was exhausted, and it was not replenished in the storage system in sufficient quantities to satisfy the consumption of July, August, September and October completely. This can also be confirmed through figure 11 (a), that shows the evolution of stored energy in the upper reservoir, and for the unsatisfied hours of the year, shows that the stored energy is close to zero. On the other hand, for scenario III, there is no red area (12 (b)), since all demand is satisfied by generation plus PHS. Figure 11 (b) also confirms this, since throughout the year the reservoir is never empty. Figure 11 also helps visualize what was said about not being able to store all excess energy, since its is possible to see at several instants that the reservoir is full.



(a) $(3, 18)$ (b) $(3, 25)$

Figure 12: Annual residual profiles after PHS operation in an hourly time frame.

In conclusion, if pumped storage is used, then it is possible to relocate excess energy from plentiful hours to lacking hours, which translates into overall satisfied hour percentages of 88.29% and 100%, respectively for the multiplying factors $(3, 18)$ and $(3, 25)$. To summarise these results it can be said that if generation is increased, a technology like pumped storage must be used to take full advantage of the said increase. Only with an ESS it is possible to reach 100% (or close to 100%) of satisfied hours for 2018 using only solar and wind sources.

B. Implementation constraints

This section analyses how the storage capacity (energy) and installed capacity (power) influence the percentage of satisfied hours.

B.1 Storage Capacity

The PHS simulation considered a fixed value of 1.2 TW h for storage capacity. Now this value will be changed to identify the minimum storage capacity value that provides the highest percentage of satisfied hours. Figure 13 shows the variation in the percentage of satisfied hours with the increase in storage capacity, considering that the reservoirs start full. For this study only the upper range of satisfied hours will be considered $(80 - 100\%)$. As the storage capacity increases, the percentage of satisfied hours also increases. For both scenarios, the curves can be divided into two segments. In the first, a small increase in storage capacity causes a significant increase in the number of hours satisfied, and in the second to see a small change in the percentage of satisfied hours, the storage capacity needs to increase substantially. One can analyse, for example, the curves obtained for scenario II (purple line). To reach 80% of satisfied hours, the reservoir must have a storage capacity of 0.23 TW h. If 90% of satisfied hours is the goal (10% increase), the reservoir must have 1.5 TW h of storage capacity, which corresponds to an increase of six times.

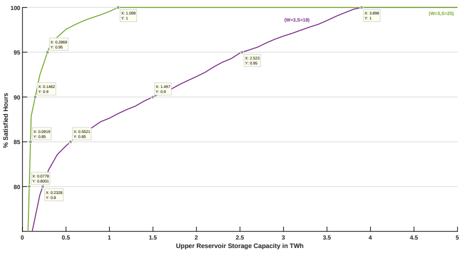


Figure 13: Percentage of satisfied hours in relation to the upper reservoir storage capacity.

Considering these scenarios of increased generation, it is possible to achieve 100% of satisfied hours if the reservoirs start full. However, each scenario requires reservoirs of different sizes to achieve this result: for scenario II, 3.9 TW h, and for scenario III, 1.1 TW h. The higher the increase factors, the smaller the reservoir have to be to satisfy all the hours of consumption.

B.2 Installed Capacity

Another aspect that must be considered is the installed capacity needed to assure that a certain percentage of satisfied hours is met. To satisfy 100% of 2018's consumption needs, the installed capacity must be at least 8.04 GW, as this is the power needed to cover the worst hour (the hour that requires the biggest PHS contribution). For others percentages of satisfied hours, the residual profile must be analysed to find the capacity value capable of providing energy to that percentage of hours.

Figure 14 shows for each percentage of unsatisfied hours, the power needed to assure that the percentage is met. In this approach the negative part of the residual profile is sorted from hours that need more energy to fully satisfy demand (worst hours), into the hours that require less energy (best hours). The

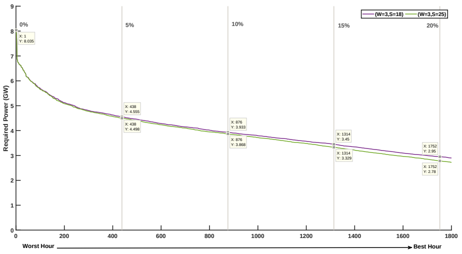


Figure 14: Required installed capacity according to the desired percentage of satisfied hours.

resulting array contains in the first cell the worst hour of the year, in the second cell the second worst, etc. For example, finding the power that satisfies 95% of the hours of 2018, is the same as finding the power that would leave 5% of the hours unsatisfied, and in this case 5% of 8760 is 438.

Analysing the required power for each percentage, it can be verified that from compromising 5% (95% of satisfied hours instead of 100%), the needed installed capacity drops to almost half (8.04 GW to 4.55 GW). This information is relevant because there is a hard limit to the capacity that can be implemented in a PHS installation, and it may not imply a serious compromise on the percentage of hours satisfied.

VI. Locations

The analysis of possible locations will focus on locations presented by the Australian National University in a study that aims to identify on a global scale, viable locations for implementation of PHS [21]. For each location, the study states, among other characteristics, the minimum altitude difference between the upper and lower reservoirs (head), minimum horizontal distance between the upper and lower reservoirs (separation), cost class, etc. Although the study includes locations of various storage capacities, this analysis will focus on the locations of 150 GW h, and 38 of these locations are found in Portugal. It should be noted that the possible locations are all in the north of the country, where there are more terrain elevations.

A. Number of Locations

The results from section V.B will be used to obtain the number of PHS installations needed.

A.1 Storage Capacity Restriction

The first restriction is the storage capacity. Figure 13 shows the storage capacity values needed for each desired percentage. Taking into account that the locations under study have a storage capacity of (150 GW h), the number of locations needed for each percentage were obtained. In the case of pair $(W = 3, S = 18)$, 2 PHS installations are needed to satisfy 80%, 4 to satisfy 85%, 10 to satisfy 90%, 17 to satisfy 95% and 26 to satisfy 100%. For the pair $(W = 3, S = 25)$ only one installation needs to be implemented to satisfy 90% of the hours, 2 to satisfy 95% and 8 to satisfy 100%. The results obtained prove what was previously mentioned, now in terms of number of facilities instead of storage capacity; to go from 80% to 90% the increase of the number of installations is lower, than the one needed to satisfy the next 10%. The results also show that in terms of storage capacity it is more viable to install PHS to complement scenario $(W = 3, S = 25)$, than scenario $(W = 3, S = 18)$, as the number of installations needed for the latter quickly becomes unfeasible.

A.2 Installed Capacity Restriction

In relation to the installed capacity restriction, figure 14 will be considered to obtain the required installed capacity for each desired percentage. To find how many facilities should be installed, it will be considered that each facility has 1.1 GW of installed capacity. For this restriction, the number of PHS installations needed is equal for both increase generation scenarios, and the values are: 3 to satisfy 80% of the hours, 4 to satisfy 85% and 90%, 5 to satisfy 95%, and 8 to satisfy 100%.

A.3 Results

In general, for the $(3, 25)$ scenario, the number of installations (N) is higher considering the installed power restriction rather than the storage capacity one. The opposite happens for the $(3, 18)$ scenario, where the storage capacity restriction will be the one to dictate the number of installations. The joined results are summarized in table 2.

	% of satisfied hours				
	80	**85**	**90**	**95**	**100**
(3,18)	3	4	10	17	26
(3,25)	3	4	4	5	8

Table 2: Number of PHS installations required for the two increase scenarios.

Table 2 shows that to satisfy 80% of hours, the minimum number of installations is equal to 3, for both scenarios. This means that if the goal is to satisfy 80% of hours, the generation increase can be $(3, 18)$ instead of $(3, 25)$. If 4 installations are considered, the percentage of satisfied hours can be equal to 85%, if the increase is $(3, 18)$, or equal to 90% if the increase is $(3, 25)$. To achieve percentages higher than 85%, with scenario $(3, 18)$, the number of installations is so high that, increasing generation according to scenario $(3, 25)$ should be considered instead, as this scenario can achieve 100% of satisfied hours by installing 8 PHSPP.

B. Location Selection

The location selection will consist in choosing possible sites presented by the AREMI study [21]. The criteria taken into account is the following:

- The reservoirs can not overlap with major populated areas or motorways;
- The location must have a proximity to transmission lines, power transformer substations or switching stations with the appropriate voltage level;
- The location should have a proximity to already implemented renewable sources sites;

Figure 15 shows the overlap of the national electricity transmission network with possible sites for implementing PHS, making it possible to check which sites are closest to transmission lines and connection points. Additionally, the locations were analysed on the map of Portugal, to verify if they are situated over populated areas or roads. Following the mentioned criteria, from thirty nine possible locations remained nine. Figure 16 shows the nine locations selected (numerical labelled yellow square), and an example of one location that proved to be unfeasible (red square).

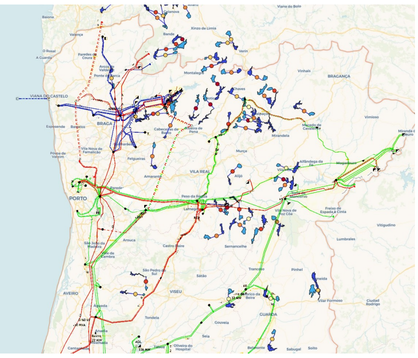


Figure 15: Part of the national very high voltage electricity transmission network and the possible locations.

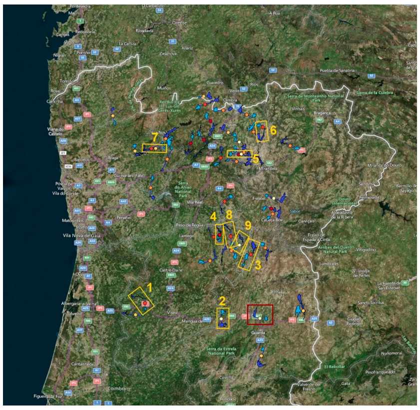


Figure 16: Selected locations, and an example of a non viable location in Portugal.

Figure 17 shows location one. This location is close to the Bodiosa substation (400 kV) and its lower reservoir would use part of the Vouga river. Regarding the other locations, these are some of their geographical characteristics: all locations are close to connection points; locations 4, 6, 7, 8 and 9 use part of a river as lower reservoir; locations 2, 3, 4, 7 and 9 are close to wind farms.

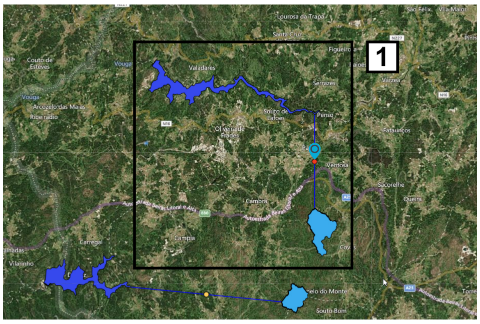


Figure 17: Aerial view of location number 1.

Figure 18 shows the close-up of the location that proved to be an unfeasible option, since the upper reservoir overlaps a village (yellow square) and the lower reservoir overlaps a motorway (red square). Table 3 shows for each chosen location some main features such as: the head (m), the separation between reservoirs (km) and the cost class (from A to E).

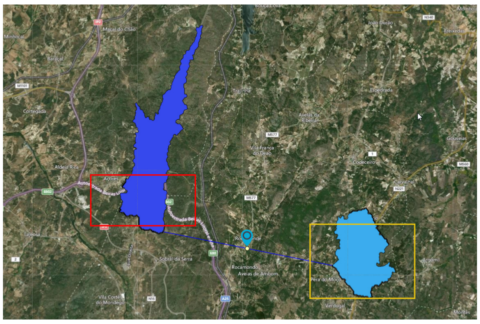


Figure 18: Aerial view of a non viable location.

	1	2	3	4	5	6	7	8	9
Head (m)	699	269	290	722	520	429	722	540	496
Separation (km)	5.3	5.1	2.8	2.3	7.7	3	10.1	7.1	5
Class	B	E	B	C	A	B	D	B	E

Table 3: Characteristics of the possible 9 locations.

C. Results

From section B it was possible to conclude that there are 9 locations available. Combining this result with the number of locations in table 2, it is possible to conclude that 8 locations must be selected. The selection is made considering the following criteria: Head, class, separation, and if the lower reservoir uses part of a river. To choose the locations, a classification function (3) was created and the locations with higher costs will be selected.

$$C = C_{Head} \cdot 1.1 + C_{Class} + C_{Sep} + C_{River} \qquad (3)$$

Figure 19 shows the score of each location after applying the cost function, and the cost breakdown per characteristic. Overall, locations with the most valuable set of features scored higher (4, 1, 6 and 8), and the locations remaining (5, 7 and 3) proved to be almost identical in their score. The last location to be chosen (9), had a higher score than location 2 mainly because it had a higher head.

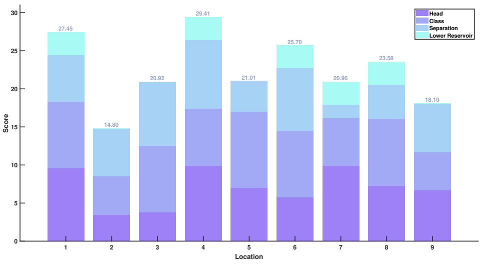


Figure 19: Scores breakdown of the 9 selected locations.

In conclusion, depending on the desired percentage of hours to satisfy, it is only feasible to choose 3, 4, 5 or 8 locations for PHS installations. The best locations are, from best to worst: 4, 1, 6, 8, 5, 7, 3 and 9.

VII. Conclusions

Analysing the Portuguese consumption and generation landscape during 2018, it was possible to verify that wind and solar generation varies a lot. Wind generation tends to be higher in the first and last three months of the year, and lower during the summer. Solar generation tends to be higher during spring and summer, and lower during autumn and winter. Both wind and solar generation can suffer great fluctuations from day to day. Considering an hourly time frame, solar generation is higher during the middle of the day, and wind generation can vary greatly each hour. In 2018, only one of the 8760 hours of the year had enough wind and solar generation to meet demand, making the total annual unsatisfied demand equal to 37.87 TW h, and making it unfeasible to install PHS if there is no increase in installed capacity.

Three scenarios where wind and solar generation were increased were considered, but only two proved to be sufficient to meet demand, and justify the use of PHS. In both, wind generation was tripled, but the first increased solar by factor of 18, and the second by a factor of 25. The $(W = 3, S = 18)$ scenario is more realistic, but the majority of its excess energy is from March, and to fully satisfy demand, the PHS reservoirs would have to be large enough to accommodate all that energy. In contrast, with the $(W = 3, S = 25)$ scenario most months have surplus energy, but it might be unfeasible to increase solar capacity by a factor of 25.

By simulating the PHS operation for the different scenarios considered, it was possible to validate that only with the increases of $(W = 3, S = 18)$ and $(W = 3, S = 25)$, implementing PHS is justifiable and needed. For scenario $(W = 3, S = 18)$, it is possible to reach 95% of satisfied hours with a total capacity of 2.6 TW h, and 100% with 3.9 TW h. For scenario $(W = 3, S = 25)$, it is possible to reach 100% of satisfied hours using a reservoir of 1.1 TW h. To guarantee that all hours are satisfied, installed capacity must cover the worst hour of the year, and be equal to 8.04 GW. However, a small compromise in the percentage of satisfied hours translates into a massive decrease in the required capacity. In this case by installing 4.55 GW instead of 8.04 GW, it is still possible to satisfy 95% of the hours.

Out of the 38 possible locations that were analysed, only 9 of them are viable as the others overlap with small towns or motorways. The number of locations required to complement wind and solar generation was determined according to the percentage of satisfied hours desired, following the storage and installed capacity restrictions studied. For scenario $(W = 3, S = 18)$, it is only possible to satisfy 85% of hours using 4 installations of PHS with 1.1 GW installed capacity. To satisfy over this percentage, more than 9 locations would be needed. For scenario $(W = 3, S = 25)$, it is possible to satisfy 100% using 8 PHS facilities. The 9 viable locations were classified using a cost function, and for each percentage of satisfied hours required, a set of locations was identified.

In summary, if Portugal increases its wind and solar generation, the implementation of PHS is not only viable, but a necessary step to satisfy demand relying exclusively on these resources.

A. Future work

This thesis allows for several paths of future work. First, the data considered in this dissertation is from 2018 because it was the most up to date year available in full. Since 2018, there has been a significant increase in wind and solar installed capacity, so part of this study could be extended with updated data. This work considered that the increase in installed capacity affects generation in the same way, but since this does not reflect reality, the true relationship between these two quantities should be studied. The Portuguese wind (on and off shore) and solar capacity potential should be studied to analyse whether the increase scenarios used in this work are implementable and, if they are not, other renewable resources should be considered to aid generation. Finally, a network including the PHS facilities and wind and solar parks could be created, and its respective power flow could be studied.

References

[1] Norang, Ingunn. (2015). Pump Storage Hydropower for delivering Balancing Power and Ancillary Services: A Case Study of Illvatn Pump Storage Power Plant. Norwegian University of Science and Technology.

[2] APA. (2019). Plano Nacional Energia e Clima 2021-2030 (PNEC 2030). Agência Portuguesa do Anbiente. Retrieved from `https://apambiente.pt/_zdata/Alteracoes_Climaticas/Mitigacao/PNEC/PNEC%20PT_Template%20Final%202019%2030122019.pdf`.

[3] Levine, Jonah G.. (2003).Pumped hydroelectric energy storage and spatial diversity of wind resources as methods of improving utilization of renewable energy sources. BSc. Thesis, Michigan Technological University.

[4] Pandey, Prashant & Srivastav, Anubhav & Kulmi, Pawan & Kumar Prasad, Amar. (2016). Sea water pumped storage power plant - concept paper.

[5] Akhil, Abbas A. & Huff, Georgianne & Currier, Aileen B. & Kaun, Benjamin C. & Rastler, Dan M. & Chen, Stella Bingqing & Cotter, Andrew L. & Bradshaw, Dale T. & Gauntlett, William D.. (2015). DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA. Sandia National Laboratories.

[6] Sultan, Hamdy M. & Diab, Ahmed A. Zaki & Oleg, N. Kuznetsov & Irina , S. Zubkova. (2018). Design and evaluation of PV-wind hybrid system with hydroelectric pumped storage on the National Power System of Egypt. Global Energy Interconnection. Volume 1. Issue 3. Pages 301-311, ISSN 2096-5117.

[7] Miller, Richard R. & Winters, Maureen. (2009).Energy Storage: Opportunities for Pumped Storage: Supporting Renewable Energy Goals. Hydro Review. Volume 28. Issue 5.

[8] Kelman, Rafael & Harrison, David. (2019). Integrating Renewables with Pumped Hydro Storage in Brazil:a Case Study. hal-02147740.

[9] Javed, Muhammad Shahzad & Ma,Tao & Jurasz, Jakub & Amin, Muhammad Yasir. (2020). Solar-wind-pumped hydro energy storage systems: review and future perspective. Renewable Energy. Volume 148. Pages 176-192. ISSN 0960-1481.

[10] Anagnostopoulos, John S. & Papantonis, Dimitris E. (2012). Study of pumped storage schemes to support high RES penetration in the electric power system of Greece. Energy. Volume 45. Issue 1. Pages 416-423. ISSN 0360-5442.

[11] Voith. Project Report: Frades II. Retrieved from `http://voith.com/ca-en/2012-10-12_Project_Report_Frades_II.pdf`

[12] Koutnik, Jiri. (2012). Frades II - variable speed pumped storage project and its benefit to the electrical grid. Voith

[13] Larson, Aaron. (2018). Award-Winning Pumped-Storage Hydro Facility a Modern Marvel. POWER. Retrieved from `https://www.powermag.com/award-winning-pumped-storage-hydro-facility-a-modern-marvel/`

[14] Bennati, Franco Michele. Gouvães - Portugal. Hydro News 30. Andritz Hydro. Retrieved from `https://www.andritz.com/resource/blob/74086/e5f1f8ddf3995090d192fc33f2eb189a/hy-hn30-11-gouvaes-portugal-data.pdf`

[15] IRENA. (2017). Electricity Storage and Renewables: Costs and Markets to 2030. International Renewable Energy Agency. Abu Dhabi.

[16] Sabihuddin, Siraj & Kiprakis, Aristides & Mueller, Markus. (2015). A Numerical and Graphical Review of Energy Storage Technologies. Energies. Volume 8. Pages 172-216.

[17] Farret, F.A. & Simoes, M.G.. (2006). Integration of Alternative Sources of Energy. Wiley.

[18] IHA. (2020). Hydropower Status Report: Sector trends and insights. International Hydropower Association. United Kingdom.

[19] REN. (2018). Technical Data Report. Redes Energéticas Nacionais. Portugal. Retrieved from `https://www.centrodeinformacao.ren.pt/PT/InformacaoTecnica/DadosTecnicos/Dados%20T%C3%A9cnicos%202018.pdf`

[20] Costa, Paula & Couto, António & Silva, João & Esteves, Teresa & Estanqueiro, Ana. (2018). Reavalição do potencial eólico sustentável em Portugal Continental. Laboratório Nacional de Energia e Geologia.

[21] Stocks, Matthew & Stocks, Ryan & Lu, Bin & Cheng, Cheng & Nadolny, Anna & Blakers, Andrew. (2019). A global atlas of pumped hydro energy storage. Australian National University. Retrieved from `http://re100.eng.anu.edu.au/global/`