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# **Pumped Storage as a complement for renewables**

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### **Declaration**

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.



In memory of my sister Micaela.

To my mother São,  
my father Fernando,  
and my nephew Matthew.

To Antonio and his family.



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## Resumo

Este trabalho visa avaliar se o armazenamento hidráulico por bombagem (PHS) pode ser utilizado para complementar a geração eólica e solar em Portugal Continental. Para tal, o consumo e a geração de 2018 são estudados e a operação de PHS é simulada usando esses dados. Adicionalmente, são estudados possíveis locais para a instalação de PHS. Os dados mostram que para o consumo de 2018, se apenas se considerar a geração eólica e solar, só existe excesso numa hora do ano. Assim, para o panorama atual o uso de PHS é descartado. Consideraram-se diferentes cenários com geração aumentada, e dois permitiriam que 100% das horas fossem satisfeitas: em ambos a geração eólica é aumentada em 3, e a solar é aumentada em 18 e 25. O uso de PHS foi simulado e os resultados confirmaram que ao aumentar a geração em (3, 18) e (3, 25), instalar PHS é viável e necessário para complementar as fontes renováveis e satisfazer 100% do consumo. De 38 localizações possíveis para a instalação de PHS, 29 sobrepõem-se a áreas povoadas ou autoestradas, e assim apenas 9 são viáveis. A partir dos resultados das simulações, e considerando as características dos locais, conclui-se que se a geração for aumentada em (3, 18), 85% de horas são satisfeitas requerendo 4 instalações, e se for aumentada em (3, 25), 100% das horas são satisfeitas utilizando 8 localizações. O trabalho futuro deve incluir o estudo de como o aumento da capacidade das fontes renováveis se traduz no aumento da geração.

**Palavras-chave:** Armazenamento de Energia, Armazenamento hidráulico por bombagem, Energia Renovável, Consumo de Energia, Geração Eólica, Geração Solar.



## Abstract

This work aims at evaluating if Pumped Hydro Storage (PHS) can be used to complement wind and solar generation in mainland Portugal. To achieve this goal, 2018's consumption and generation is studied and the PHS operation is simulated using this data. In addition, possible locations for installing PHS are studied. The data shows that for 2018's consumption, if only wind and solar generation are considered, only 1 hour of the year has excess energy, discarding the use of PHS, as PHS is used to store and redistribute surplus energy. Therefore, different scenarios with augmented generation were considered, and two of those would allow for 100% of hours to be satisfied: in both wind generation is increased by 3, and solar generation is increased by 18 and 25. By simulating the PHS operation, the results confirmed that when increasing generation by (3, 18) and (3, 25), installing PHS is viable and much needed to complement renewable sources and satisfy 100% of demand. From 38 possible locations to install PHS, 29 overlap major populated areas or motorways, meaning only 9 are viable. From the simulations' results, and considering the locations' characteristics, it is concluded that if generation is increased by (3, 18), only 85% of hours can be satisfied using 4 locations (90% of hours would require 10), and if generation is increased by (3, 25), 100% of hours can be satisfied by using 8 locations. 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.



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# Abbreviations

**PHS** Pumped Hydro Storage

**RES** Renewable Energy Sources

**VRE** Variable Renewable Energy

**PHSPP** Pumped Hydro Storage Power Plant

**TSO** Transmission System Operator

**IHA** International Hydropower Association

**IRENA** International Renewable Energy Agency

**ESS** Energy Storage System

**APREN** Associação Portuguesa de Energias Renováveis (Portuguese Renewable Energy Association)

**LNEG** Laboratório Nacional de Energia e Geologia (National Laboratory of Energy and Geology)

**PNEC30** Plano Nacional Energia e Clima 2021-2030 (National Energy and Climate Plan)

**US DOE** United States Department of Energy



# Chapter 1

## Introduction

### 1.1 Motivation

Energy storage is a relevant subject of the current electricity generation and consumption landscape.

The increase of energy generation by renewable sources, in specific wind and solar sources, supports the importance and necessity of energy storage, both now and in the future. Besides helping integrating renewable sources in the grid by storing its surplus energy, energy storage systems can aid in stabilizing the electrical grid, and solve power quality problems such as voltage sags [1] and frequency variations [2].

Portugal, in order to fulfil its commitment to the Paris Agreement, has set for itself a number of goals in the National Energy and Climate Plan (PNEC) to obtain carbon emissions neutrality by 2050. To achieve this goal, one of the measures to be implemented is the increase of energy storage [3].

A possible way to store energy, to complement renewable sources, is Pumped Hydro Storage (PHS). PHS is considered a mature system of energy storage, which means that it is a well established technology with an extensive record of installations, and most of its faults have been mitigated. Another advantage of this technology is its efficiency that ranges between 70% and 85% [4]. The biggest advantages of pumped storage are its long lifetime when compared to alternatives [5] [6], and the amount of energy it can store [7]. Among large scale energy storage systems, pumped storage is described as the only viable one, being the best option for harnessing off-peak generation from renewable sources [8].

While installing PHS can be difficult due to specific geographic needs [1], considering Portugal's topology there is a multitude of possible locations [9].

With the implementation of measures, on a global scale, that envision a more sustainable future, both in increasing renewable capacity and in decreasing carbon emissions, the need to implement energy storage systems is imperative, and pumped hydro storage shows to be a strong candidate [10].

## 1.2 State of the art

This chapter addresses the literature review, as well as current implementations of pumped hydro-electric storage systems.

### 1.2.1 Literature Review

#### Pumped Storage

Pumped Hydro Storage takes advantage of the potential gravitational energy of water to generate electricity [11][12].

PHS is a proven and reliable technology energy storage system with implementations all over the world, either to complement other storage options, or to provide capacity to integrate VRE's [13]. PHS projects require considerable time for both the authorization and construction [14] [15].

To operate, facilities need two reservoirs that can be natural or man-made [16]. Over the last years, there has been an increasing interest in sub-surface PHS [17]. These projects are attractive since they have less environmental impacts and can offer a way to reuse abandoned man-made facilities like coal mines [18], reducing costs of construction, and allowing high water heads.

To overcome difficulties related to finding suitable locations for PHS facilities and their high capital cost, upgrading existing hydro stations to pumped hydro storage is a possible way forward [14] [15] [27]. Additionally, there is a need for new and effective methods/tools identify feasible sites for PHS [14].

Recently, there have been studies regarding the use of underwater reservoirs [19]. In these configurations hollow spheres serve as the lower reservoirs while the water surrounding them acts as the upper. Electric energy is generated by allowing the spheres to be filled with water, and surplus energy is consumed when the spheres are drained. While the tests for this technology were performed in a lake, the technology is to be used in the sea.

Also related to the use of seawater in pumped hydro storage, is the use of the sea as the lower reservoir of a PHS facility [5] [20] [21]. This configuration has advantages in terms of construction, but suffers from problems associated with the use of seawater, for example turbines cannot be the same used in fresh water configurations [22].

The traditional configuration of a PHS facility makes use of a reversible pump-turbine, however configurations with variable speed pump-turbines were also found in the literature [23] [24] [25], and are already in use [26]. The variable speed configuration allows an operation at a wider range, but it is also more costly than the traditional one.

Finally, pumped storage should be distributed to several hydroelectric sites, in order to maximize the energy and economic efficiency of excess energy exploitation, and new pumped storage investments can be planned and realized gradually in parallel with the development of RES [27].



## Pumped Storage as a complement to renewables

Pumped Hydro Storage is an ESS that can be used to complement variable output sources such as wind and solar [13]. Integrating pumped hydro storage with renewables can be challenging due to the low predictability of timing, amount and duration of excess renewable energy [14].

At a small scale of an hybrid wind-hydro power station used to meet energy demand of irrigation pumps, pumped storage systems show to be suitable used together with wind power plants [28].

It is also mentioned that imbalances caused by errors in the wind power forecasting when participating in an electricity market could be fully avoided by the action of a PHSP [29].

To fully replace conventional sources with renewable energy, it is necessary to study grid connected RE-PHS systems [14] [13].

Critical parameters for the energy and economic viability of PHS installations to complement wind generation include the total wind installed (or planned) capacity, and the storage capacity of the smallest reservoir [27].

### 1.2.2 Existing Implementations

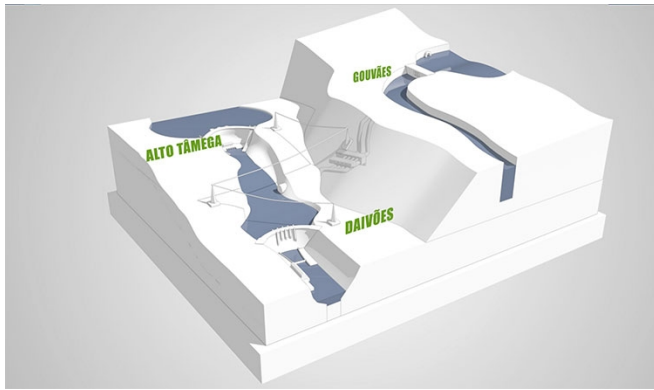
This section presents different implementations of pumped storage around the world. Currently Portugal does not have closed-loop pumped hydro storage facilities, yet it has dams with a turbine/pump configuration.

The Frades II power plant, visible in figure 1.1, is located in the northern region of Portugal and takes advantage of existing dams to incorporate a configuration with variable-speed. It consists of two units of 383 MW each, a maximum head of 441 m, and a nominal rated flow of  $100 \text{ m}^3 \text{ s}^{-1}$  [30]. The Frades II power plant plays an important role in integrating the intermittent wind energy into the Portuguese grid [26] [31]. The Gouvães PHSP is part of the Tâmega hydropower project that its being developed

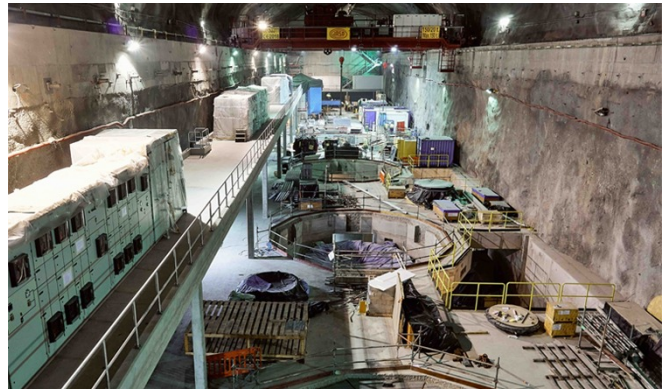


Figure 1.1: Aerial view of the Frades II power plant upper reservoir and dam.

in the Tâmega river in northern Portugal. The pumped storage power plant has 880 MW of installed capacity, distributed by four 220 MW pump turbines, and a head equal to 660 m, to cover the need for peak-load energy and provide fast-responding regulating power. The Tâmega scheme will complement electricity generation from wind power [32]. Figure 1.2(a) shows a scheme of the Tâmega project, and figure 1.2(b) shows the inside of the Gouvães powerhouse. To this day, the only PHS facility in the



(a) Tâmega Project Scheme



(b) Inside of the Gouvães Powerhouse

Figure 1.2: Tâmega project and powerhouse detail.

world to use seawater was the Okinawa Yanbaru power station, located in Japan, which can be seen in figure 1.3. It was built in 1999 and dismantled in 2016, due to not being a profitable business since the electric power demand in the island of Okinawa did not grow as predicted [33]. The power plant had a capacity of 30 MW, an effective head of 136 m, and a maximum discharge flow of  $23 \text{ m}^3 \text{ s}^{-1}$  [34]. The Goldisthal Pumped-storage Power Plant, in figure 1.4 is located in Germany and at 1060 MW is



Figure 1.3: Aerial view of the Okinawa Yanbaru power station.

the largest of the country and one of the largest in Europe. The power plant is the first variable speed pumped storage unit in Europe, and consists of two synchronous and two asynchronous pump-turbines. This configuration allows a high level of control of power delivery, for grid stabilization applications, and a higher efficiency than other PHS designs [35]. Other characteristics of the power plant are: a head of 302 m, a water discharge flow per pump-turbine of  $103.3 \text{ m}^3 \text{ s}^{-1}$ , and an artificial reservoir with a capacity for  $13\,000\,000 \text{ m}^3$  of water [36]. The world's largest pumped storage hydroelectric power station is the Bath County Pumped Storage Station, visible in figure 1.5, located in the United States. It has an installed capacity of 3000 MW, an hydraulic head of 385 m, the water flow can be of  $850 \text{ m}^3 \text{ s}^{-1}$  when generating energy, and when storing it can be of  $800 \text{ m}^3 \text{ s}^{-1}$  [37]. There are many pumped-storage facilities all over the world, and this number is ever evolving.

"More than 100 pumped storage hydropower projects totalling 75 GW of new capacity are in



Figure 1.4: Aerial view of the Goldisthal Pumped Storage Power Plant.



Figure 1.5: Aerial view of the Bath County Pumped Storage Power Plant's lower and upper reservoirs.

the pipeline. These projects will increase existing global storage capacity by 50 per cent to almost 225 GW by 2030."

International Hydropower Association, 2018 Hydropower Status Report.

### 1.3 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.

First, the portuguese electricity consumption and renewable generation must be analysed, and it must be determined if the current situation justifies the use of pumped storage, and if it does not, what are the necessary changes to justify it. Second, the constraints that need to be respected by the pumped storage installations must be identified. These constraints are the storage and installed capacities. Afterwards, possible locations for installing PHS facilities, must be presented and analysed. Finally, based on the study of locations, and considering the PHS constrains identified, a set of suitable locations must presented.

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 constraints that PHS facilities must respect in order to fully satisfy demand, and the study and selection of appropriate locations for facilities that satisfy those constraints.

## 1.4 Outline

The remaining content of this dissertation goes from chapter 2 to chapter 7. Chapter two presents a brief introduction on renewable energy and energy storage systems.

Chapter three provides a brief study of pumped hydro storage, including the background of the technology as well as its description.

Chapter four provides an overview of the portuguese electricity consumption and generation landscape during 2018. First, the current state of electricity consumption and generation in the country, is analysed. Next, three scenarios are presented where wind and solar generation are increased in order to satisfy demand, and justify the use of pumped storage. Finally, the different scenarios are compared, and the viable ones are pointed out.

Chapter five focuses on simulating the PHS operation for different scenarios, in order to analyse the viability of installing pumped storage, and to identify under which conditions it is viable. At the end of the chapter there is a study on how the size reservoir and installed capacity influence the number of satisfied hours.

Chapter six analyses possible locations to install PHS facilities in Portugal, following the AREMI study [9]. First, the number of required PHS installations is determined. Then possible locations are studied, and a set of feasible locations is presented.

In chapter seven, conclusions of the dissertation are drawn and possible future work is laid out.

# Chapter 2

## Background

This chapter offers an introduction to the main concepts of this thesis: renewable energy and energy storage systems.

### 2.1 Renewable Energy

Renewable energy is generated from energy resources that can be replaced rapidly by a natural process, such as sunlight and wind, for example. This clean energy is utilized in areas like electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services.

Renewable energy sources can be divided into groups of technologies: Hydropower, Wind Power, Solar Energy, Geothermal Energy, Bio Energy, and Ocean Energy.

Hydropower consists of power derived from the energy of falling water or fast running water. Its most relevant technologies are: hydroelectric dams, run-of -the river stations, small-hydro dams, and pumped-storage facilities.

Wind power utilizes the air that flows through a wind turbine to feed electric generators with mechanical power. This technology can be divided in onshore and offshore wind power. Onshore wind turbines is a cheaper alternative than offshore, however the offshore applications have at their disposal stronger and steadier wind.

Solar Energy is the product of harnessing radiant light and heat from the sun. It is possible due to technologies like solar photovoltaic and solar thermal energy.

Geothermal Energy is related to the temperature of matter, generated and stored in the earth. This type of energy appears in vapor-dominated or liquid-dominated forms.

Bio Energy is created from materials derived from biological sources, and it can be retrieved from: biomass, biofuel and biogas. Biomass consist of waste material from plants and animals. Biofuel is fuel created through biological processes, such as agriculture or anaerobic digestion. Biogas consists of a mixture of gases produced through the breakdown of organic matter in anaerobic processes.

Ocean Energy relates to Wave Power and Tidal Power. Wave Power refers to the capture of wind waves in order to generate useful work like electricity generation, while on the other hand, Tidal Power utilizes the energy obtained from tides to generate electricity.

Figure 2.1 shows the global installed capacity of renewable energy sources. It can be verified that there is an increasing trend in the overall installed capacity, and that this increase is mostly due to the increase in wind and solar resources.

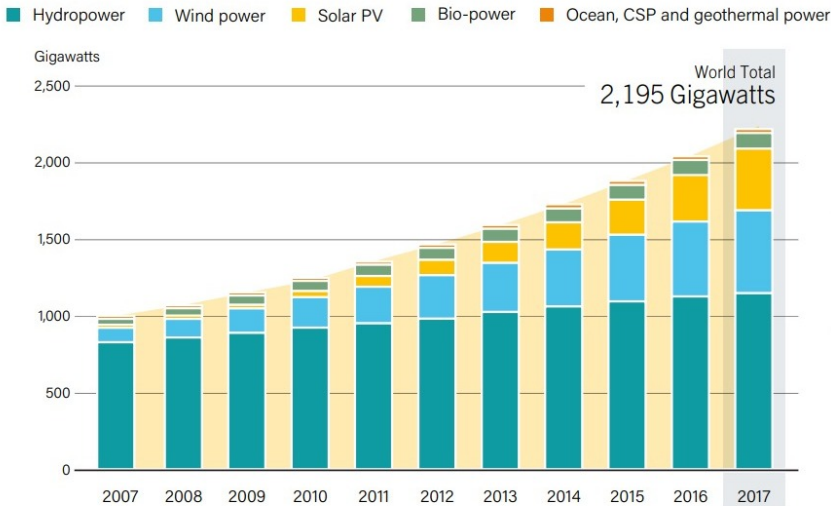


Figure 2.1: Global Renewable Power Capacity 2007-2017, according to REN21’s Renewables 2018 Global Status Report.

This thesis will focus on renewable generation by wind and solar photovoltaic resources.

## 2.2 Types of Energy Storage Technologies

As it was referred before, energy storage is becoming a crucial technology, as it contributes to better electrical power quality, and also to decentralized energy conversion. Energy storage allows the shift of excess energy (surplus) to later periods in order to not waste energy. Currently there are various technologies, with different storage capacity, efficiency, speed of response, and other characteristics. It is important to notice that a certain technology may be better in some aspects but not so good in others, so a balance between their characteristics is important. The different energy storage systems can be divided into four categories according to their application [38].

1. Low-power application in isolated areas, feeding of transducers and emergency terminals.
2. Medium-power applications in isolated areas, for example, town supply, individual electrical system.
3. Network connection application with peak leveling.
4. Power-quality control applications.

Technology Type	Subtechnology Type
Electro-chemical	Electro-chemical capacitor, lithium-ion battery, flow battery, vanadium redox flow battery, lead-acid battery, metal air battery, sodium-ion battery
Electro-mechanical	Compressed air storage, flywheel
Chemical	Hydrogen storage, liquid air energy storage
Pumped hydro Storage	Closed-loop pumped hydroelectricity storage Open-loop pumped hydroelectricity storage
Thermal Storage	Chilled water thermal storage, concrete thermal storage, heat thermal storage, ice thermal storage, molten salt thermal storage

Table 2.1: Electricity storage family nomenclature according to the United States Department of Energy Storage Database, mid-2017

There are five types of energy storage technologies: Electro-Chemical, Electro-Mechanical, Chemical, Pumped Hydro Storage and finally Thermal Storage, as table 2.1 demonstrates. The global operational energy storage capacity by technology is presented in figure 2.2, and it can be verified that pumped storage is the technology with the largest-capacity of energy storage available. In figure 2.3 the power capacity of Thermal, Electro-Chemical and Electro-Mechanical can be seen with more detail.

Lithium-ion Batteries is the electro-chemical technology with the highest power capacity global distribution, which means that it is the most used type of batteries. Figure 2.4 shows the distribution of the

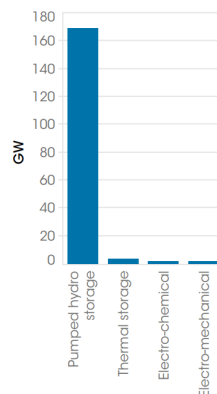


Figure 2.2: Global operational energy storage power capacity by technology group, mid-2017 (US DOE 2017).

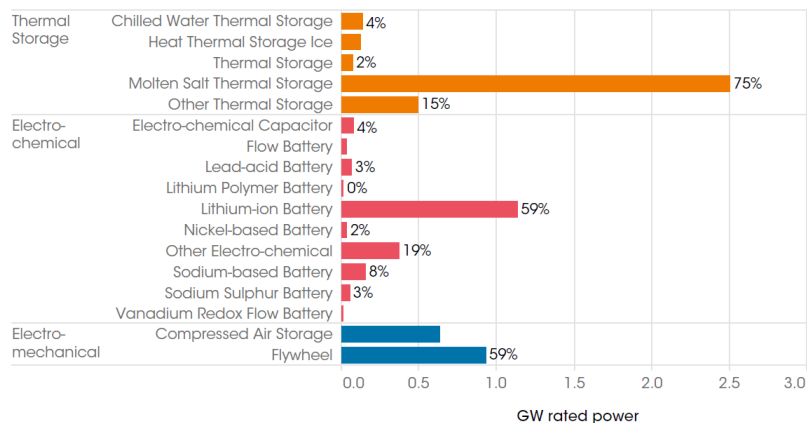
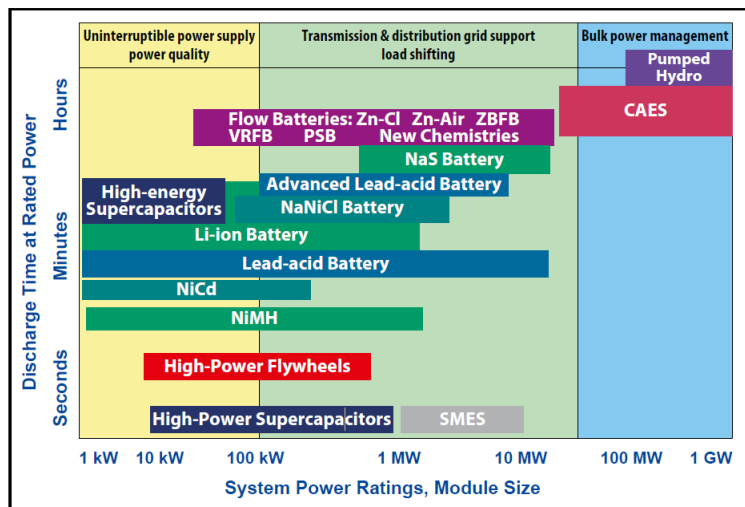


Figure 2.3: Thermal, electro-chemical and electro-mechanical energy storage power capacity by technology, mid-2017 (IRENA).

different systems of energy storage according to their rated capacity and discharge time at rated power. It can be verified that pumped-storage technologies are utilized for bulk power management, since these can discharge for hours economically.



Source: US DOE/EPRI, 2015.  
 Note: Zn-Cl = zinc chlorine flow battery; Zn-Air = zinc air flow battery; ZBFB = zinc bromine flow battery; VRFB = vanadium redox flow battery; PSB= polysulfide bromine flow battery; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; NiCd = nickel cadmium; NiMH = nickel-metal hydride; SMES = superconducting magnetic energy storage.

Figure 2.4: Positioning of diverse energy storage technologies per their power rating and discharge times at rated power (IRENA).

Figure 2.5 shows that PHS has low energy density and also low power density, which can be explained by the fact that potential gravitational energy is much weaker than chemical energy – "(...)the energy contained in 1 litre of gasoline is the same as 7 tonnes of water raised 500 meters" [39].

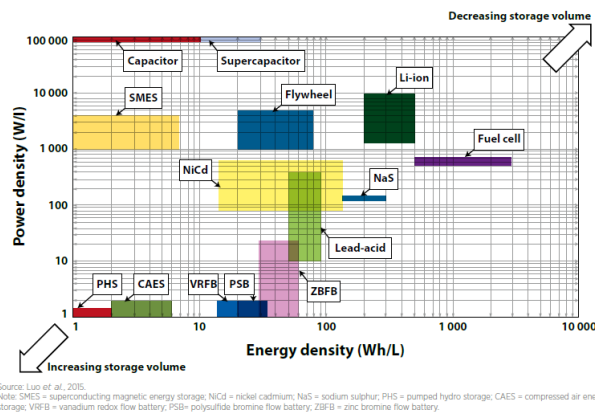


Figure 2.5: Comparison of power density and energy density for selected energy storage technologies (US DOE).

When choosing a energy storage system for a certain project, the following characteristics must be considered [38]: maximum output, storage capacity, speed of response, lifetime, need for AC/DC (DC/AC) converters, accessibility, and capital and operating costs.

This thesis will focus on pumped hydro storage as the energy storage system that complements wind and solar photovoltaic sources.



# Chapter 3

## Pumped Storage

The current chapter presents a study of pumped hydro storage, the technology that will be used in this thesis to complement wind and solar generation.

### 3.1 Background

It is believed that the first demonstration of an hydro-mechanical storage system, that operated a pump and a turbine in a small reservoir, occurred in 1882 near Zurich, Switzerland. A few years later, in 1909, the first commercial pumped storage plant, with a rated capacity of 1.5 MW, was installed in Schaffhausen, Switzerland. This plant used a pump to store water and a turbine to generate energy. The first pumped storage installation in the US was the Rocky River plant, it started operating in 1929 and by this time, there were more than 40 plants installed in Europe.

The traditional use for pumped storage plants was 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. This reduces the need for peak power plants, like Combined Cycle Gas Turbine (CCGT) plants that use natural gas to operate. This type of plants have a very high variable cost because the necessary fuel is expensive, and also have additional costs due to carbon emission fees. To sum, pumped storage offers a reliable and clean solution to variations on the demand curve that thermal base load plants cannot satisfy. Nowadays, with the increasing injection of renewable energy in the grid, pumped storage can also reduce the fluctuations introduced by intermittent renewable energy sources. Furthermore, it is important to refer that renewable energy sources guarantee energy, and PHS guarantees power. Energy is the ability to do work, for instance generating electricity, which can be stored. Power is the measurement of energy, being the rate at which energy is delivered, and cannot be stored since it is an instantaneous quantity. Pumped storage takes advantage of surplus energy during periods of low demand, for instance at night time, using that energy to pump water from the lower to the upper reservoir, so later when it is needed the pumped storage

installation can generate energy.

## 3.2 Operating Principle

Pumped hydro storage is often called a natural battery because of the way it performs. Its basic principle 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 ( example: during valley hours), 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. This energy is then transmitted to an electrical substation where voltage is transformed and distributed to consumers or other substations. This can be seen in figure 3.1 that shows an example of a pumped storage scheme. A pumped storage installation has two reservoirs as previously mentioned, the upper reservoir (in an

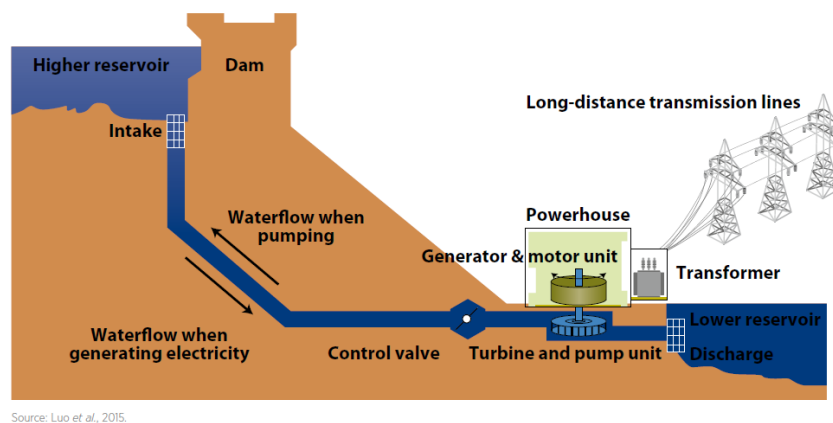


Figure 3.1: Pumped Storage scheme.

elevation), and the lower reservoir, and depending on the type of installation the reservoirs can be natural or man-made. In terms of comparison, these reservoirs are quite smaller than the ones used in conventional hydroelectric dams of similar power capacity. For example, the pumped storage power station of Okutataragi (1.932 GW) in Japan has a upper reservoir with 33 387 000 m<sup>3</sup> capacity, and the Ahai Dam (2 GW) in China has as reservoir with 8 820 000 000 m<sup>3</sup> capacity.

## 3.3 Benefits and Challenges

As all energy storage technologies, pumped hydro storage has advantages and disadvantages. Table 3.1 expresses advantages and disadvantages of pumped storage installations [40].

Pumped hydro storage is the energy storage system with the highest amount of installed capacity worldwide. It was developed in the beginning of the 20<sup>th</sup> century, and to this day it is still a relevant energy storage system. The self-discharge of a pumped storage facility is very low, because it is only due to water evaporation. Pumped storage facilities have an efficiency between 70% and 85% [4], which is a reasonable range. The amount of energy stored only depends on the volume capacity of the upper

<b>Advantages</b>	<b>Disadvantages</b>
Established technology with high technical maturity and extensive operational experience	Geographic restrictions, since a suitable site with large land use is needed
Very low self-discharge	Low energy density (large footprint)
Reasonable round-trip efficiency	High initial investment costs, long construction period and long time to recover investment
Large volume storage and long storage periods are possible	Environmental concerns
Low energy installation costs	
Good start/stop flexibility	
Long life and low costs of storage	

Table 3.1: Advantages and Disadvantages of a Pumped Storage installation according to the International Renewable Energy Agency.

reservoir, and due to the low self-discharge of the facilities, water can be stored for long periods of time without suffering significant losses. The lifetime of a pumped storage facility is between 40 and 60 years, however if improvement measures are performed, the lifetime can be extended up to 100 years [40].

Finding a suitable location for the facility constitutes a disadvantage, since finding locations with good geotechnical conditions, and high head height between two settings that can be used or transformed in reservoirs is challenging, though considering Seawater or Underground PHS facilities can mitigate this difficulty. A pumped storage facility has high investment costs related with land acquisition, civil works, steel structures and mechanical/electrical machinery [41], which poses a challenge regarding potential investments for a project. However the capital costs can be mitigated due to their long service lifetime. There are also environmental concerns associated with PHS facilities, over impacts such as diversion of river flows, creation of artificial water bodies, water quality, mosquito plagues, bursting dam risks and earthquake risks [41].

## 3.4 Design Specifications

### Efficiency

The efficiency of pumped storage power plants can be calculated using equation (3.1). The overall efficiency is a product of the efficiencies of the two operations performed by PHS, storing energy (charging efficiency) and generating energy (discharging efficiency).

$$\eta = \eta_c \cdot \eta_d = [\eta_p \cdot \eta_M (H - \Delta H_p \cdot H)] \cdot [\eta_t \cdot \eta_G (H - \Delta H_p \cdot H)], \quad (3.1)$$

where:

$\eta_c$ : charging efficiency;

$\eta_d$ : discharging efficiency;

$\eta_p$ : pumping efficiency;

$\eta_t$ : turbine efficiency;

$\eta_M$ : motor efficiency ;

$\eta_G$ : generator efficiency;

$H$ : head ( m);

$\Delta H_p$ : loss head of water way in pumping operation;

$\Delta H_t$ : loss head of water way in turbine operation.

Some reference values of the efficiency of all the equipment related to a pumped storage facility are summarized in table 3.2:

Equipment	Efficiency $\eta$
Motor and Generator	96%
Pump and Turbine	77%
Pipeline and tunnel	97%
Transmission	95%

Table 3.2: Efficiency reference values (in %) for the equipment used in PHS facilities.

### Installed Capacity (Power)

The installed capacity of a PHSP is calculated using equation 3.2. The most relevant variables are the head of the power plant ( $H$ ) and the discharge flow ( $Q$ ). The specific weight and turbine efficiency (depends on the chosen turbine) are constants. Since power is directly proportional to the head ( $H$ ) and to the discharge ( $Q$ ), it will increase as the head and discharge increase. This result can lead to the false assumption that these two variables are interchangeable to obtain the same installed capacity. In theory, head and discharge flow seem substitutable variables in the installed capacity equation, since a high head and a low flow can result in the same installed power as a low head and a high flow. However, considering a low head, implementing a sufficient flow to translate into the same installed capacity is not feasible, since the size of the pipe needed to obtain said installed capacity would have to be of enormous proportions. This would not be economically feasible and that is why PHS plants generally have a high head [42]. 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. These types of turbines are typically used with medium heads up to 800 m and large flows. There is also the possibility of having variable speed hydro generators in a pumped storage facility, which enable a wider operating speed range.

$$P = \gamma \cdot Q \cdot H_u \cdot \eta \quad (3.2)$$

where:

$P$ : installed power (kW);

$\gamma$ : specific weight of fluid ( $\text{N m}^{-3}$ );

$Q$ : discharge ( $\text{m}^3 \text{s}^{-1}$ );

$H_u$ : head (m);

$\eta$ : turbine-generator efficiency.

## Storage Capacity (Energy)

The storage capacity of the upper reservoir of a PHS installation can be calculated using equation 3.3, that provides a solution in Joule (J). In order to convert the value to GW h one must divide the result by  $3.6 \times 10^{12}$ .

$$E = g \cdot \rho_{water} \cdot V_{res} \cdot H \cdot \eta \quad (3.3)$$

where:

$g$ : is the gravitational acceleration that is approximately  $9.81 \text{ m s}^{-2}$ ;

$\rho_{water}$ : is the water density that is approximately  $1000 \text{ kg m}^{-3}$ ;

$V_{res}$ : is the volume of the upper reservoir ( $\text{m}^3$ );

$H$ : is the head (m);

$\eta$ : is the efficiency of energy conversion, and should consider turbine and generator efficiency, and the hydrodynamics losses.

Since the gravitational acceleration and water density are constants, and the efficiency does not vary significantly, the stored energy mainly depends on the volume of the reservoir and the head.

## Costs

Every PHS project is different because of the specific geographical requirements, so different projects have different total costs. The cost projection for a pumped storage installation can be as table 3.3 [42]. Table 3.4 shows the indicative cost breakdown of a PHS project, in which the lower reservoir is an

Typical Size Range (MW)	\$\text{kW}	\$\text{kWh}
100-1000	600-1000	10-15

Table 3.3: Cost projection of pumped storage.

existing lake or river. Since pumped hydro storage is a very site specific technology, the costs may vary considerably from project to project, specially the reservoir construction costs and the engineering, procurement and other construction costs. Considering a seawater pumped storage installation can reduce these costs, since the sea can act as the lower reservoir. However, seawater PHS has higher maintenance costs, due to corrosion issues and marine growth on hydraulic components, which can offset the savings of not having to build a lower reservoir [40].

Subcomponent	Share of Total Costs , 2016 (%)
Powerhouse	37
Upper Reservoir	19
Engineering, procurement, construction, and management	17
Onwer's costs	17
Tunnels	6
Powerhouse excavation	4

Table 3.4: Indicative cost breakdown for a pumped hydro storage system.

### Types of Installations

The types of pumped storage installations include:

- **Closed-Loop** configurations occur when both reservoirs are not connected to a naturally flowing water source;
- **Open-Loop** facilities, where the lower reservoir is replenished by natural inflows, while the upper reservoir may or may not be isolated. If it is isolated, then it is a **off-stream** pumped storage facility, otherwise it is consider a **pump-back** plant, like the ones present in Portugal.
- **Seawater** configurations that take advantage of the sea, making it the lower reservoir of the power plant. This results in lower costs, and also a reduced construction time.

Additionally, some potential technologies based on pumped storage are currently being studied, for example, Sea Bed Pumped Storage and Underground Pumped Storage.

## 3.5 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, according to International Hydropower Association, as shown in figure 2.2. This number is in constant change , since every year there are more projects in the process of construction, or of being approved.

Figure 3.2 shows the worldwide distribution of pumped storage capacity [43]. The values shown

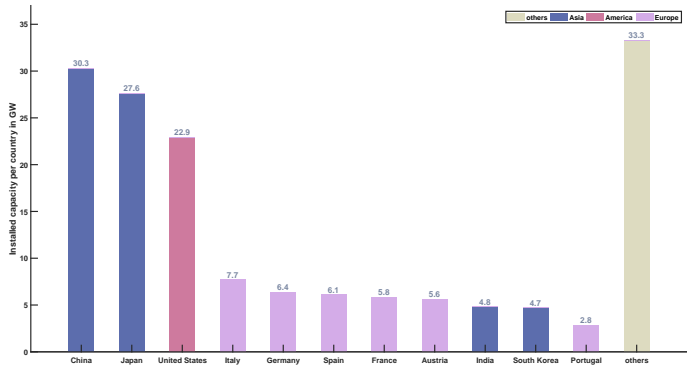


Figure 3.2: Installed Capacity in GW of the top ten countries, plus Portugal and the rest of the world.

in figure 3.2 account for all types of pumped storage installations, such as closed-loop and open loop power plants. 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.

# Chapter 4

## Electricity consumption and generation in Portugal

This chapter provides an overview of electricity consumption, and wind and solar generation of the Portuguese energy landscape, in 2018. Additionally, to justify the use of pumped storage, three scenarios are created, in which energy generation from the resources mentioned is increased. Finally, these scenarios are compared with the original data taking into account some defined metrics. All data used for this chapter's analysis is provided by REN, the Portuguese transmission system operator (TSO) [44].

### 4.1 Current State - Base Scenario

The annual energy consumption in Portugal during 2018 was 50.9 TWh, which represents a 2.5% growth comparing to the previous year. Peak consumption occurred in the 7<sup>th</sup> of February at 7:45 pm with a value of 8794 MW. On the other hand, peak generation occurred in the 7<sup>th</sup> of March at 8:00 pm with a registered value of 11 995 MW.

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. Although the data used in the actual study is from 2018, it is important to note that in the year 2019 installed wind capacity increased by 279 MW and solar capacity by 269 MW, equalling a total of 5429 MW and 828 MW of wind and solar capacity, respectively.

In 2018, renewable energy satisfied 52.6% of the energy demand, 12% more than in 2017, and in 2019, satisfied 51%.

#### Monthly Analysis

Figure 4.1 shows the verified monthly values of energy consumption, and the verified 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 values, it is possible to notice that energy consumption is quite similar monthly, the differences between values are mostly due to the fact that in winter months heating appliances are utilised, and although in the summer there is a need for cooling solutions these do not utilize as much electricity as heating solutions. January was 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 figure 4.2 it is possible to observe the variations in consumption throughout January

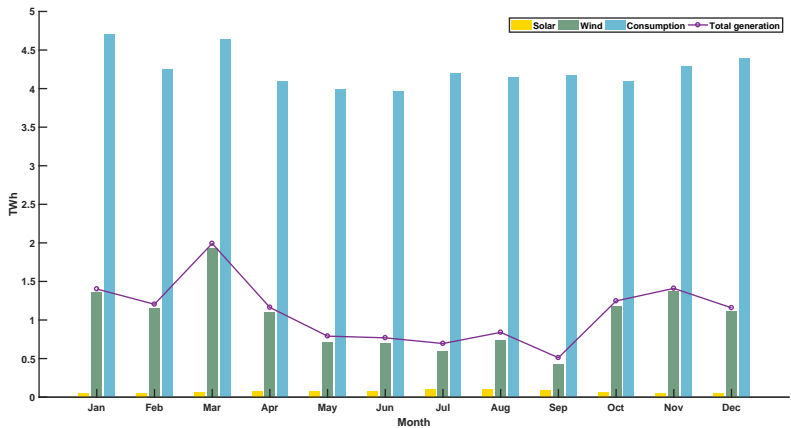


Figure 4.1: Verified Consumption, wind, solar, and total generation in TW h per month, considering the base scenario.

(more demand) and June (less demand). The difference between the two graphs is mostly limited to the different consumption values for each month. It is possible to observe a higher consumption pattern during the five weekdays and a lower one during the weekend.

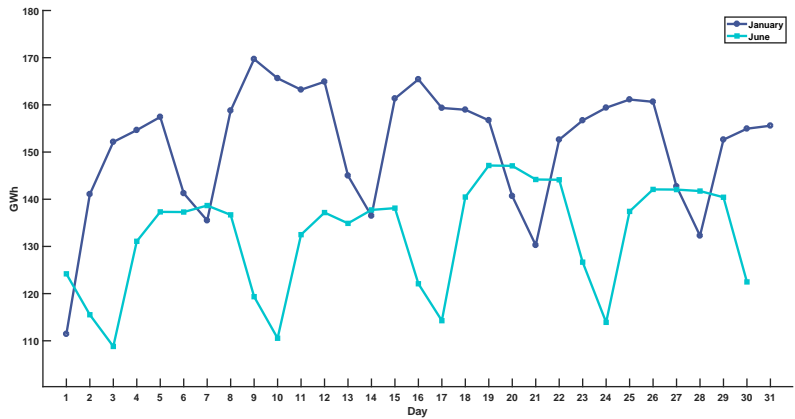


Figure 4.2: Daily breakdown of the highest (January) and lowest (June) verified electricity consumption month in 2018.

In terms of energy generation, figure 4.1 shows that wind generation is more prolific than solar generation, which results from the fact that there is more installed wind capacity, and also, there can be wind at any time of the day, unlike solar energy. Wind generation is highest during the autumn and winter months, while solar power is highest during the spring and summer months. It is also possible to verify high fluctuations of wind and solar generation throughout the year. September was the month with the



least wind and solar generation, around 0.5 TW h, while March was the month with highest generation, around 2 TW h, making it a value four times higher than the one registered in September.

The monthly consumption values and the total wind and solar generation values can be found in table 4.1. In addition, the difference between consumption and generation is also shown. This quantity represents the unsatisfied demand, if only wind and solar energy sources were used in the country for electricity generation.

	Consumption (GWh)	Wind Generation (GWh)	Solar Generation (GWh)	Wind + Solar Generation (GWh)	Unsatisfied Demand (GWh)	% Unsatisfied Demand
January	4700	1356	46	1402	3298	70%
February	4246	1149	55	1204	3042	74%
March	4632	1935	57	1992	2640	58%
April	4099	1094	69	1163	2936	75%
May	3987	710	81	791	3196	83%
June	3966	691	78	769	3197	84%
July	4199	597	98	695	3504	85%
August	4140	741	99	840	3300	82%
September	4166	425	86	511	3655	89%
October	4090	1179	68	1247	2843	73%
November	4282	1366	44	1410	2872	70%
December	4398	1110	48	1158	3240	75%

Table 4.1: Electricity consumption, wind and solar generation, and unsatisfied demand in per month for the year 2018.

All mentioned unmet consumption values are positive which means that in no month of 2018 was there enough wind and solar generation to satisfy energy consumption. 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 an increase in generation by these resources is required.

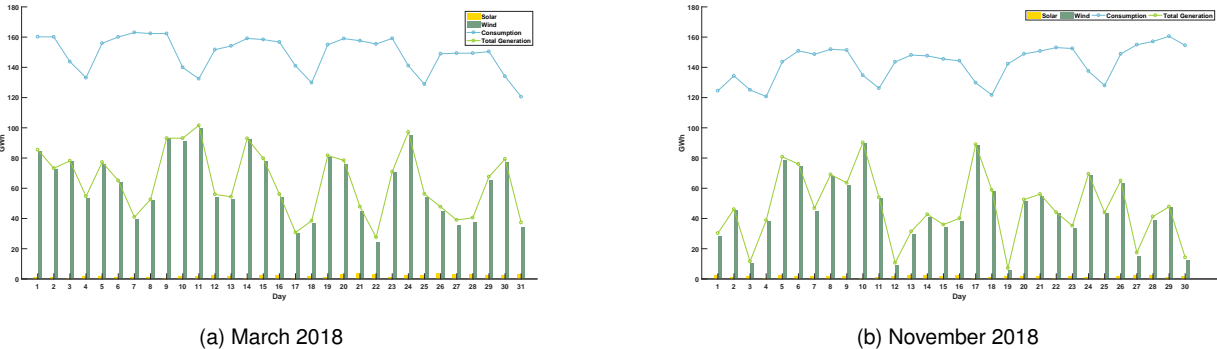


Figure 4.3: Daily breakdown of the months with higher wind and solar generation.

Figures 4.3 and 4.4 show the high volatility of wind generation on a daily time frame during one month. During March, the month with highest wind generation, there are days with high generation followed by days with low generation. The same occurs in the other months represented in the figures 4.3 and 4.4. In regards to solar generation, one can conclude that on a daily scale this resource is as variable as wind, since there can be days when there is less sunlight and days when there is plenty. It can also be verified that months with higher total (wind plus solar) generation (March and November) have a lower solar contribution in comparison with months with lower total generation (July and September) that have

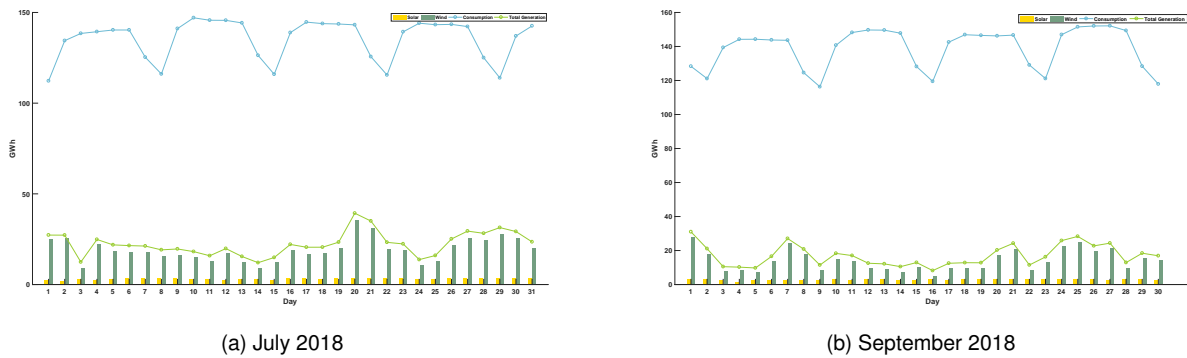


Figure 4.4: Daily breakdown of the months with lower wind and solar generation.

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.

### Weekly Analysis

Figure 4.5 shows the variation in consumption, and in wind and solar generation per week, throughout 2018. As expected from the monthly analysis, electricity consumption is higher in winter and autumn weeks and lower in summer and spring weeks. The weekly peak consumption occurred in the sixth week of the year, the same week as the daily peak consumption occurred. The peak value was 1.12 TW h and the average weekly demand value was 0.98 TW h.

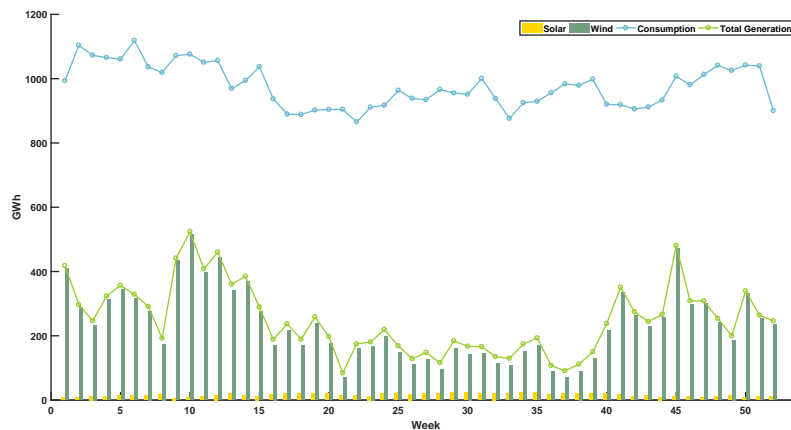
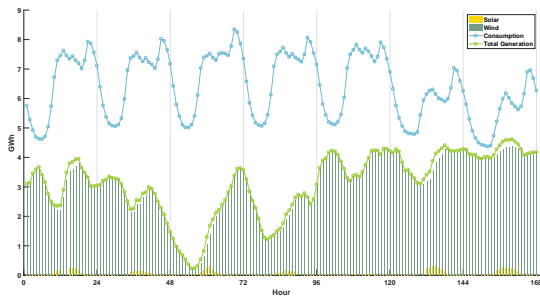


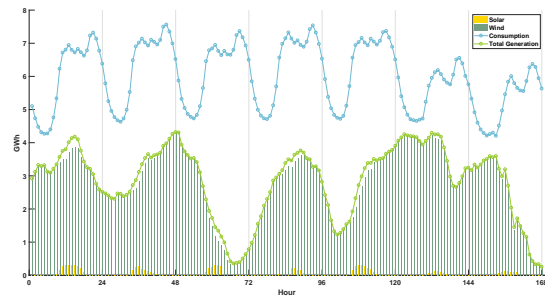
Figure 4.5: Weekly energy consumption, wind and solar generation in GWh during the 52 weeks of 2018.

Figures 4.6 and 4.7 represent the most and least prolific weeks in terms of wind and solar generation and their consumption on an hourly time frame, respectively.

It is possible to see that electricity consumption decreases during the weekend compared to the other days of the week. A 24-hour consumption pattern can also be checked, i.e. from day to day. Electricity consumption is lower at night, as the largest share of the population is inactive, and as morning hours

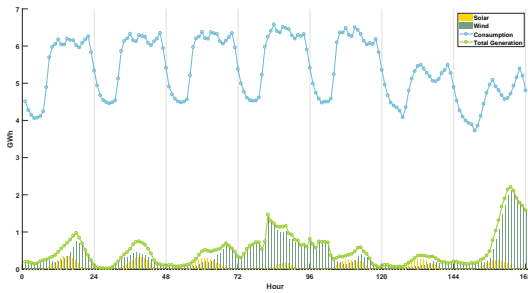


(a) Week 10

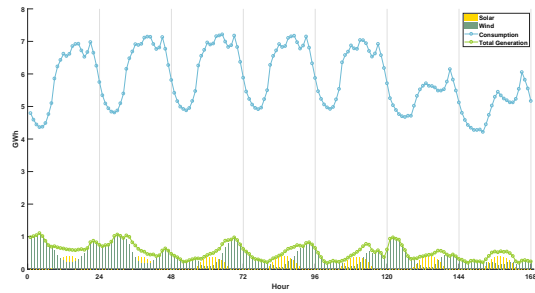


(b) Week 45

Figure 4.6: Electricity consumption and wind and solar generation during every hour of week 10, and week 45, of 2018



(a) Week 21



(b) Week 37

Figure 4.7: Electricity consumption and wind and solar generation during every hour of week 21, and week 37, of 2018.

approach consumption begins to increase. In the afternoon, consumption decreases and then increases during the evening.

Regarding wind and solar generation during the weeks represented in figures 4.6 and 4.7, it is possible to notice that during one week wind generation varies significantly, both in terms of intensity and time, while solar generation is more constant. As solar energy depends on the amount of sunlight it is natural that during the hours of the day when the sun is higher, solar generation is more prolific. Usually between 12h and 15h is when there is more solar generation, as can be seen in figures 4.7 (a) and (b) .

Table 4.2 shows the energy consumption, wind and solar generation and the unsatisfied consumption values for the more relevant weeks of the year, the weeks of higher consumption, higher generation and lower generation. By analysis of the table 4.2, it can be seen, in terms of wind and solar generation, that in the best weeks of the year, the percentage of consumption not satisfied is 52%, while in the worst weeks is 91%. This disparity results from the volatility of the sources used and the large difference in installed capacity of each source. The times of the year when there is more wind do not necessarily coincide with the times of the year when there is more sunlight, so increasing the capacity of both sources is imperative, not only to increase renewable generation but also so that at times when one of the resources is more scarce the other resource can mitigate this lack.

	Week	Consumption (GWh)	Wind Generation (GWh)	Solar Generation (GWh)	Wind+Solar Generation (GWh)	Unsatisfied Demand (GWh)	% Unsatisfied Demand
Highest Consumption Week	6 (February 5 to 11)	1120	320	10	330	790	71%
	10 (March 5 to 11)	1080	510	9	520	560	52%
Highest Generation Weeks	45 (November 5 to 11)	1000	470	10	480	520	52%
	21 (May 21 to 27)	900	70	15	85	818	91%
Lowest Generation Weeks	37 (September 10 to 16)	980	70	20	90	890	91%

Table 4.2: Values of consumption, wind and solar generation and unsatisfied demand of the highest consumption, and highest and lowest generation weeks of 2018.

## Daily Analysis

The daily analysis refers to the days when there were registered the highest and lowest values of wind and solar generation, in 2018. Table 4.3 shows the values of consumption, wind and solar generation and unsatisfied demand for the days: March 11 (highest wind generation), May 26 (lowest wind generation), July 29 (highest solar generation) and January 9 (lowest solar generation).

	Day	Consumption (GWh)	Wind Generation (GWh)	Solar Generation (GWh)	Wind + Solar Generation (GWh)	Unsatisfied Demand (GWh)	% Unsatisfied Demand
Highest value of wind generation	March 11	132.4	99.7	1.8	101.5	30.9	23%
Lowest value of wind generation	May 26	119.1	2.8	2.1	4.9	114.2	96%
Highest value of solar generation	July 29	113.8	27.8	3.7	31.4	82.4	72%
Lowest value of solar generation	January 9	169.7	54.9	0.15	55.05	114.6	68%

Table 4.3: Values and correspondent days of highest and lowest wind and solar generation in 2018.

In figures 4.8 and 4.9 the hourly values of consumption, and wind and solar generation for the mentioned days, can be observed.

On March 11<sup>th</sup>, wind generation was almost enough to satisfy consumption. Wind generation was high enough, that if only wind and solar sources were used to satisfy consumption, the percentage not be satisfied would be 23%. This day was particularly prolific with regard to wind generation, which was almost constant on an hourly scale, generating approximately 4 GW h of energy every hour, as can be observed in figure 4.8 (a). On the other hand, May 26, was the day with lowest wind generation value. Wind generation varied significantly during the day, being more prolific during the early morning hours

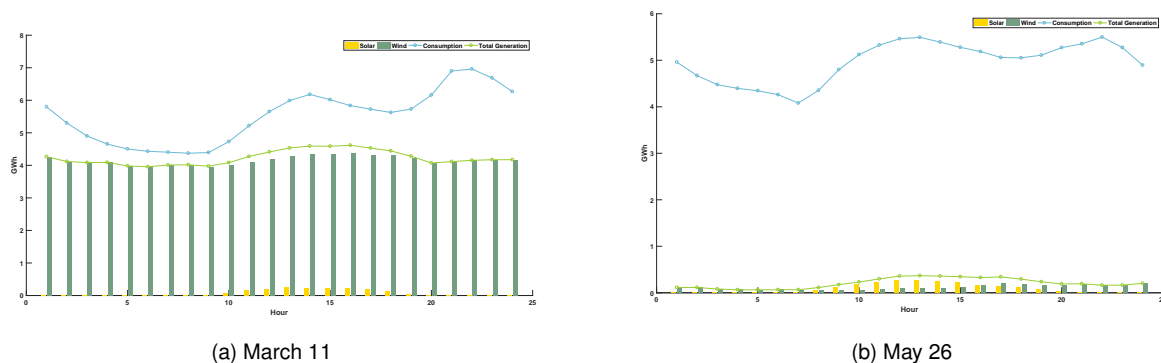


Figure 4.8: Hourly electricity consumption and wind and solar generation during the highest (March 11) and lowest (May 26) wind generation days.

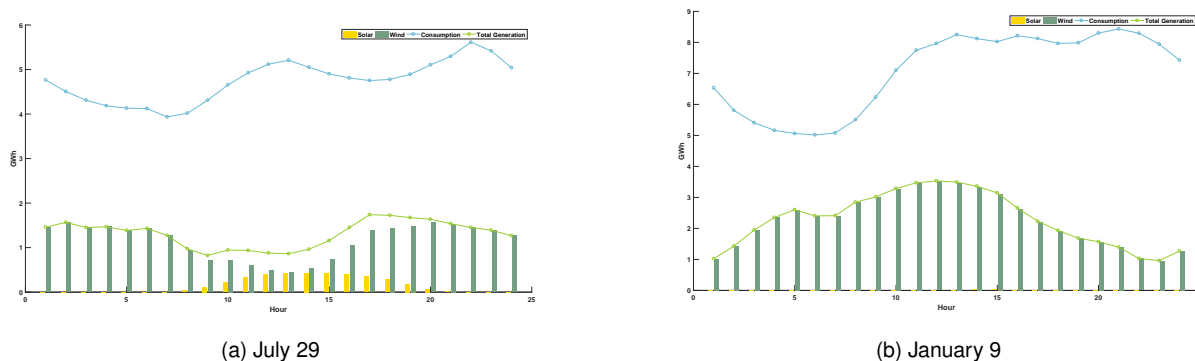


Figure 4.9: Hourly electricity consumption and wind and solar generation during the highest (July 29) and lowest (January 9) solar generation days.

and almost non-existent during the rest of the day, as it can be seen in figure 4.8 (b). On this day, if only wind and solar sources were used, 96% of energy consumption would not be satisfied. Wind power generation during March 11 was almost 30 times the wind power generation of May 26. These two examples reinforce the high volatility of wind energy on a daily and even hourly time frame.

Maximum solar generation occurred on July 29. By analysis of table 4.3 the maximum value of solar generation, 3.7 GWh is almost equal to the minimum value of wind generation 3.5 GWh. This can be explained by the large difference between the installed capacity of each resource, as already mentioned in this chapter. Solar generation is less variable, in a temporal scale, than wind generation as can be seen in figures 4.9 (a) and (b), since solar generation has an almost equal behaviour in the same hourly period on both highest and lowest generation days. Another characteristic of solar generation is that the highest generation is closer to the lowest value, 3.7 and 0.15 GWh, than what happens with wind generation, 99.7 and 2.1 GWh. This shows the high variation of wind generation intensity and the lower variation of solar generation intensity.

## Residual Profile

Figure 4.10 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, the verified wind and solar generation of 2018 was not sufficient to satisfy in full every hour of energy consumption. This can be seen in figure 4.10, where the red bars represent the unmet demand of every hour of the year. Generation surpassed consumption during one hour of the year, and since the excess energy generated during that hour is so low, it can not be seen in figure 4.10. This case will be further analysed in chapter 5. In this scenario total wind generation is equal to 12.21 TWh, and total solar generation is equal to 0.8256 TWh, adding to a total of about 13.03 TWh. The only excess energy value registered is 58.5 MWh, and total unsatisfied demand is equal to 37.87 TWh. Total excess energy is calculated by adding all the positive values of the residual profile (blue bars), while unsatisfied demand is calculated by adding all the negative values of the residual profile (red bars). In the base scenario, 99.99% of energy consumption hours are not satisfied by wind and solar generation alone, as well as

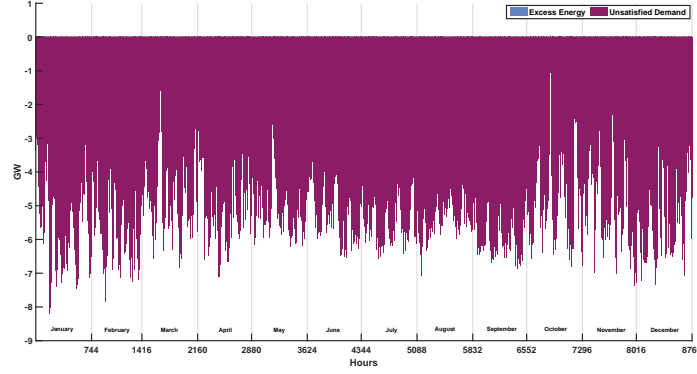


Figure 4.10: Residual profile in an hourly time frame during 2018, considering the base scenario

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.

## 4.2 Increased Scenarios

As mentioned in section 4.1, the installed solar and wind power capacity in the year 2018 would not be sufficient to satisfy electricity consumption on its own. This section presents hypothetical scenarios where the installed capacity of wind and solar sources is increased and it is assumed that the generation from these sources increases by the same factor. Equation 4.1 shows how total wind and solar generation is calculated.

$$G_{Total} = (W_{Total} \cdot W + S_{Total} \cdot S); \quad (4.1)$$

where:

$G_{Total}$  is the total wind and solar generation;

$W_{Total}$  is the total wind generation;

$W$  is the wind increasing factor;

$S_{Total}$  is the total solar generation;

$S$  is the wind increasing factor;

The increased generation scenarios are relevant, not only because more generation is needed to satisfy consumption, but also because to be able to integrate energy storage systems, such as pumped storage, there must be excess energy to be stored. As it was referred in section 4.1, in 2018 the installed wind capacity was around 5 GW and solar capacity was around 0.6 GW. Since the consumption and generation data is from 2018, the considered installed capacity corresponds to the one existing in 2018.

The theoretical increase of wind and solar sources cannot be unmeasured and one must take into account the country's potential for the implementation of more wind and solar resources. To decide the factors used to increase wind and solar resources two studies were considered, one carried out by the National Laboratory of Energy and Geology (LNEG) [45] and the other inserted in the National Energy

and Climate Plan (PNEC30) [3]. According to the study conducted by LNEG in 2018, the main land portuguese wind capacity potential was 13.7 GW. Additionally, by 2030 according to the National Energy and Climate Plan (PNEC30) [3], Portugal has the goal of having between 8.1 –9.9 GW of solar installed capacity.

Taking into account the mentioned wind potential and the PNEC30 objectives, one increase scenario is defined (scenario I), while the other two (scenario II and III) are defined in the context of this work. The first considers that wind capacity is increased by a factor of two (2) and solar capacity was increased by a factor of fourteen (14), making wind and solar installed capacity equal to 10 GW and 8.4 GW, respectively. In the second scenario, wind capacity is increased by a factor of three (3) and solar capacity is increased by a factor of eighteen (18), making wind and solar capacity equal to 15 GW and 10.8 GW, respectively. In the third and final scenario, wind capacity is increased by a factor of three (3) and solar capacity is increased by a factor of twenty-five (25), making wind and solar capacity equal to 15 GW each.

Scenario I will contain a monthly, weekly and daily analysis like the base scenario studied in section 4.1. Scenarios II and III are similar to scenario I, differing only on the increase factors used, so the weekly and daily analysis will not be included for these scenarios.

### 4.2.1 Scenario I - (W=2,S=14)

The first scenario represents the case, where wind generation was doubled and solar generation was increased by a factor of fourteen (14). This scenario represents a realistic increase, according to the LNEG and PNEC30 studies mentioned above.

#### Monthly Analysis

Figure 4.11 shows the monthly energy consumption as well as the monthly increased wind and solar generation. Energy consumption, wind and solar generation, and unsatisfied demand can be verified in table 4.4. In this scenario, there is still less energy generated than consumed in most months,

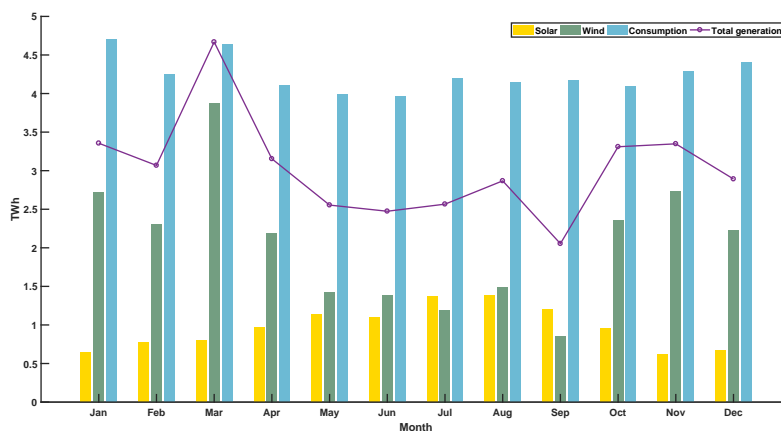


Figure 4.11: Verified Consumption, wind, solar, and total generation in TW h per month, considering scenario I.

however in March the opposite happens. In March, total wind and solar generation surpassed total

energy demand, as table 4.4 shows. If generation would increase as considered there would be an excess of 36 GW h, during this month. The chosen increase has brought the installed capacity values of the two sources closer together, so renewable generation receives a greater contribution from solar generation. In the summer months, solar generation either surpasses the wind generation or is very close to it. Still wind generation represents a large part of renewable generation. The annual unsatisfied demand is approximately 18 TW h, about 35% of the annual consumption (50.9 TW h).

	Consumption (GWh)	Wind Generation (GWh)	Solar Generation (GWh)	Wind + Solar Generation (GWh)	Unsatisfied Demand (GWh)	% Unsatisfied Demand
January	4700	2712	644	3356	1344	29%
February	4246	2298	770	3068	1178	28%
March	4632	3870	798	4668	-36	0%
April	4099	2188	966	3154	945	23%
May	3987	1420	1134	2554	1433	36%
June	3966	1382	1092	2474	1492	38%
July	4199	1194	1372	2566	1633	39%
August	4140	1482	1386	2868	1272	31%
September	4166	850	1204	2054	2112	51%
October	4090	2358	952	3310	780	19%
November	4282	2732	616	3348	934	22%
December	4398	2220	672	2892	1506	34%

Table 4.4: Electricity consumption, increased wind and solar generation, and unsatisfied demand in GW h per month for the year 2018.

Figures 4.12 and 4.13 show the daily breakdown of the months with higher (March and January) and lower (June and September) wind and solar generation. In regards to solar generation one can conclude that on a daily time frame this resource is as variable as wind, since there can be days when there is little sunlight and days when there is plenty. During March, figure 4.12 (a), there were several days when total wind and solar generation was sufficient to satisfy daily consumption. However it is important to note that although the total energy generated on that day was sufficient to satisfy total daily consumption, this does not mean that all hours of the day were satisfied, as renewable generation depends on resources that are neither certain nor constant over time, it varies greatly over an hourly time frame. In January, figure 4.12(b), it can be seen that there are also several days when wind and solar generation surpasses electricity consumption. During the months when there was less wind and solar generation, June and September, none of the days registered enough generation to satisfy consumption, as figure 4.13 shows.

Figure 4.14 (a) shows the hourly consumption and generation during March 1<sup>st</sup>, a day where total

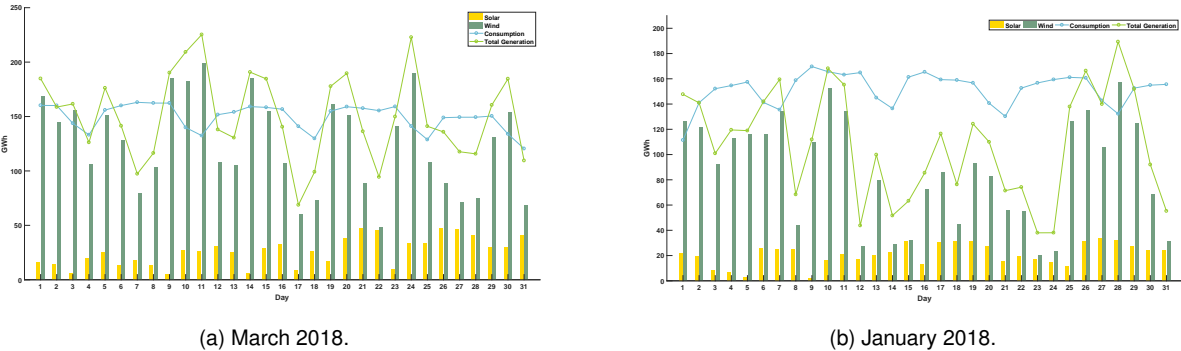
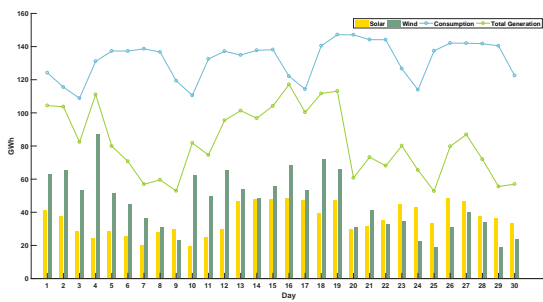
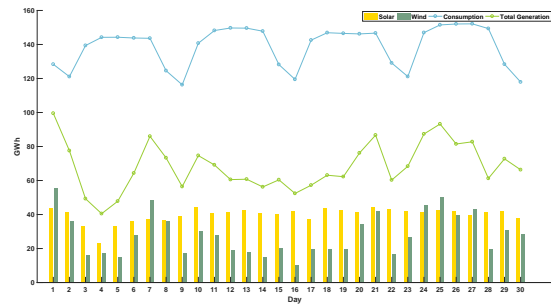


Figure 4.12: Daily breakdown of the months with higher wind and solar generation considering an increase in generation.





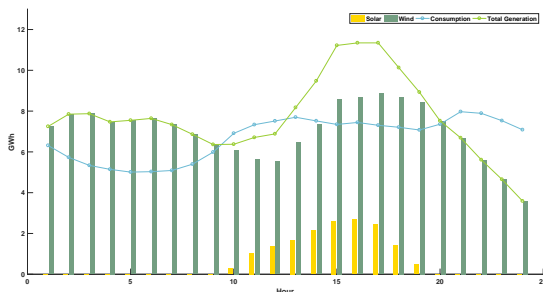
(a) June 2018



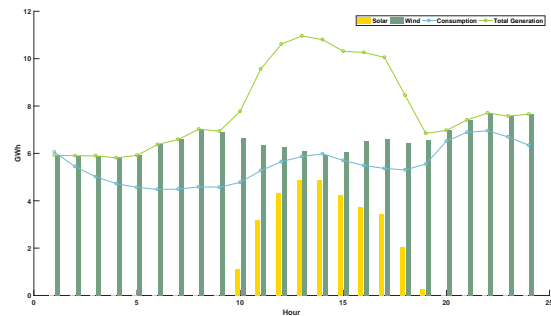
(b) September 2018

Figure 4.13: Daily breakdown of the months with lower wind and solar generation considering an increase in generation.

(increased) generation was higher than total consumption. By analysing figure 4.14 (a) it is possible to notice that there are hours when generation is actually higher than consumption and therefore there is an excess of energy generated, for example between 5 and 8 am. However, between 10 and 12 hours, the total of generation per hour was not sufficient to satisfy that period's hourly demand. This problem could be solved by using ESS, such as pumped storage, which could store excess energy generated during March 1<sup>st</sup>'s early morning, in order to be able to cover the period from 10 am to noon, for example. On January 28, represented in figure 4.14 (b), solar and wind generation would be sufficient to satisfy



(a) March 1<sup>st</sup> 2018.



(b) January 28 2018.

Figure 4.14: Hourly breakdown of electricity consumption and wind and solar generation during March 1<sup>st</sup> and January 28.

demand of almost all hours of the day with the exception of the first hour. A day like this reinforces the need for ESS to keep up with the increase in solar and wind generation, since in almost every hour of the day there was excess energy.

## Weekly

Figure 4.15 shows the demand and increased wind and solar generation in  $GWh$ , using a weekly time frame, during the year. Analysing figure 4.15, it can be verified that during three weeks of the year, generation is higher than demand. These weeks occurred in months where there was more renewable generation, March and November. Even though a considerable increase in solar energy has been

imposed, the weeks of spring and summer are the weeks with the lowest total generation values.

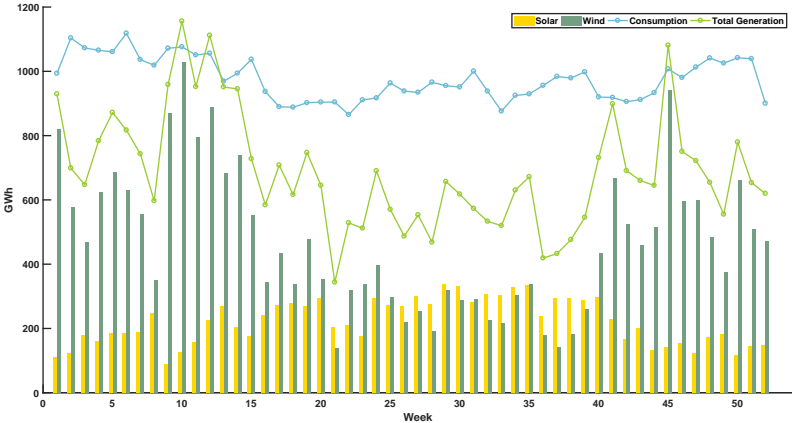


Figure 4.15: Weekly breakdown of energy consumption, increased wind and solar generation and total generation in *GWh*, during 2018.

Table 4.5 shows the consumption, wind and solar generation and unsatisfied demand values correspondent to the highest consumption and generation weeks and to the lowest generation weeks. Both weeks with higher combined wind and solar generation have more wind generation, and both weeks with lower combined wind and solar generation have more solar generation contributing to its total.

	Week	Consumption (GWh)	Wind Generation (GWh)	Solar Generation (GWh)	Wind+Solar Generation (GWh)	Unsatisfied Demand (GWh)	% Unsatisfied Demand
Highest Consumption Week	6 (February 5 to 11)	1118.4	631	185.9	816.8	301.6	27%
	10 (March 5 to 11)	1076.1	1029.1	127	1156.1	-80 (Excess Energy)	0%
Highest Generation Weeks	12 (March 19 to 25)	1056	887.6	224.2	1111.9	-55.9 (Excess Energy)	0%
	21 (May 21 to 27)	904.3	139.2	204.7	343.9	560.4	62%
Lowest Generation Weeks	36 (September 3 to 9)	956	180	239.1	419.1	536.9	56%

Table 4.5: Consumption, wind and solar generation, and unsatisfied demand values in *GWh*, of the highest consumption, highest generation and lowest generation weeks of 2018.

Figure 4.16, 4.17, and 4.18 show, in a hourly time frame, the energy consumption, and wind and solar generation values in *GWh*, of the highest consumption week (week 6), highest generation weeks (weeks 10 and 12) and lowest generation weeks (weeks 21 and 36), respectively.

During week six, even though total generation was not enough to satisfy total demand, it can be seen in figure 4.16 that there were times when generation was higher than demand. Although not nearly enough, the excess energy could have been reallocated to hours with lower generation with energy storage. During one of the highest generation weeks of the year (week 10), from March 5 to 11, there was an excess of 80 *GWh*. However as can be seen in the figure 4.17(a), the energy excess did not occur in a way to satisfy the hourly consumption. There were some days when demand was completely satisfied by the increased wind and solar generation, and there was even excess energy. However that was not always the case, since in that week occurred consecutive hours when there was no excess of energy nor was there enough generation to satisfy the consumption. The 80 *GWh* excess could have been used to satisfy demand in those hours. The same occurs for week 12, represented in figure 4.17(b).

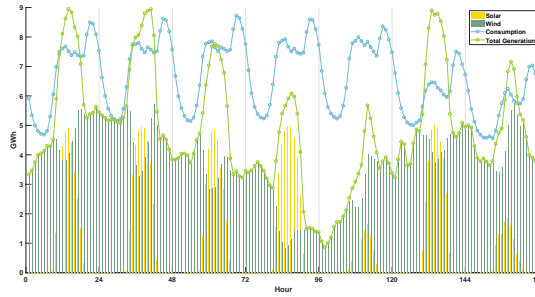
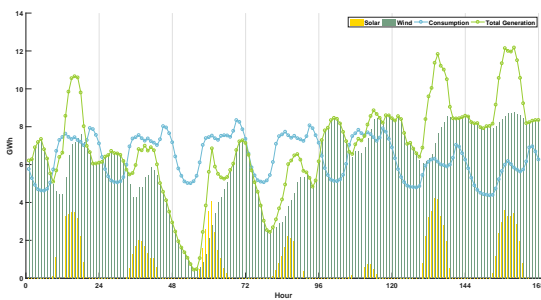
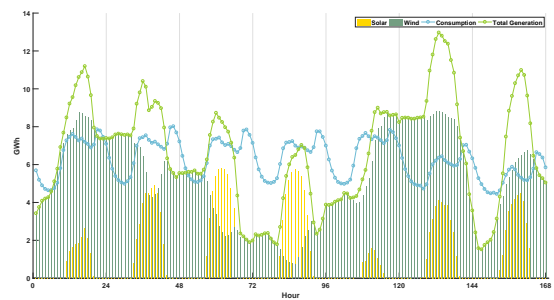


Figure 4.16: Hourly breakdown of consumption, wind and solar generation, and total generation in  $GWh$  during the highest consumption week (Week 6).



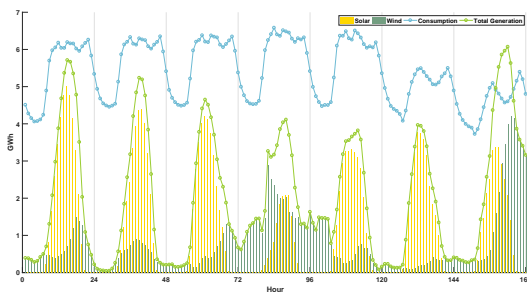
(a) Week 10



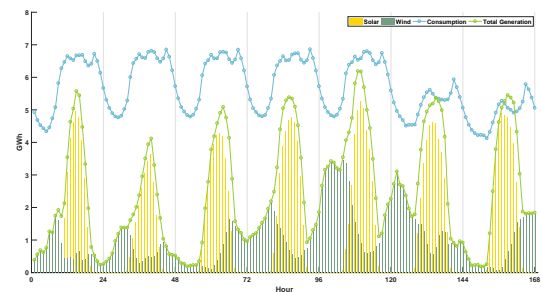
(b) Week 12

Figure 4.17: Hourly breakdown of consumption, wind and solar generation, and total generation in  $GWh$  during the highest generation weeks.

The lowest generation weeks represented in figures 4.18 (a) and (b) are characterized by having more solar than wind generation, however generation was only higher than consumption during a few hours of the weekend, period in which the energy consumption is lower. To satisfy weeks with these characteristics, energy storage would be required, as during a high number of consecutive hours it would be necessary to generate energy to help compensate demand.



(a) Week 21



(b) Week 36

Figure 4.18: Hourly breakdown of consumption, wind and solar generation, and total generation in  $GWh$  during the lowest generation weeks .

## Daily

Table 4.6 shows the consumption, increased generation, and unsatisfied demand values regarding the days with highest and lowest wind and solar generation. Analysing the four days mentioned in

	Day	Consumption (GWh)	Wind Generation (GWh)	Solar Generation (GWh)	Wind + Solar Generation (GWh)	Unsatisfied Demand (GWh)	% Unsatisfied Demand
Highest value of wind generation	March 11	132.4	199.4	25.2	224.6	-92.2 (Excess Energy)	0%
Lowest value of wind generation	May 26	119.1	5.6	29.4	35	84.1	71%
Highest value of solar generation	July 29	113.8	55.5	51.8	107.3	6.5	6%
Lowest value of solar generation	January 9	169.7	109.8	2.1	111.9	57.8	34%

Table 4.6: Values and correspondent days of highest and lowest wind and solar generation in 2018.

table 4.6, it can be seen that wind generation plays a bigger role in total generation than solar. The increase generation scenario defined makes solar installed capacity almost equal to wind capacity, but wind generation is still far superior than solar generation. It can be verified that days with higher wind generation than solar satisfy more demand than days where the opposite happens.

Figures 4.19 and 4.20, show in an hourly time frame, the consumption, and wind and solar generation correspondent to the days with the highest and lowest wind and solar generation, respectively. The 11<sup>th</sup> of March (highest wind generation day), presented in figure 4.19 (a), gathered the sufficient conditions of wind and solar generation to satisfy the electricity consumption during all hours of the day. The generation went beyond the consumption, thus there was excess energy (92.2 GW h) during the 24 hours of the day. During May 26 (lowest wind generation day), in figure 4.19 (b), solar generation was higher

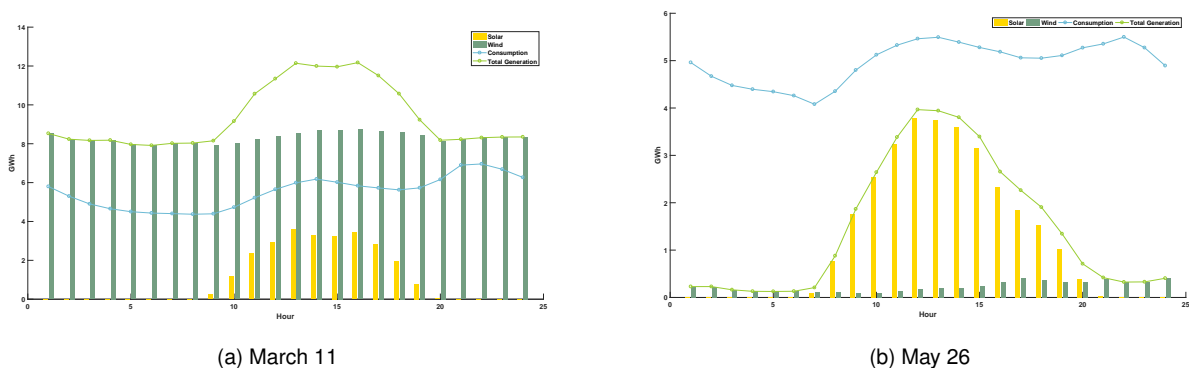


Figure 4.19: Electricity consumption and wind and solar generation during every hour of highest (March 11) and lowest (May 26) daily wind generation.

than wind generation, which registered its lowest value. Generation never surpassed demand during this day.

During July 29 (highest solar generation day), represented in figure 4.20(a), there were hours when consumption was fully satisfied by renewable generation, between 11 am and 9 pm. Although there is excess energy, it was not enough to fully satisfy the remaining hours of the day if that energy could be stored, as can be verified in table 4.6, where unsatisfied demand for July 29 is equal to 6.5 GW h. January 9<sup>th</sup>, depicted in figure 4.20(b), registers low solar generation but high wind generation so it is able to satisfy 66% of demand, as table 4.6 shows.

As can be seen in the figures 4.19 (a), and 4.20 wind generation occurred during all hours of the day,

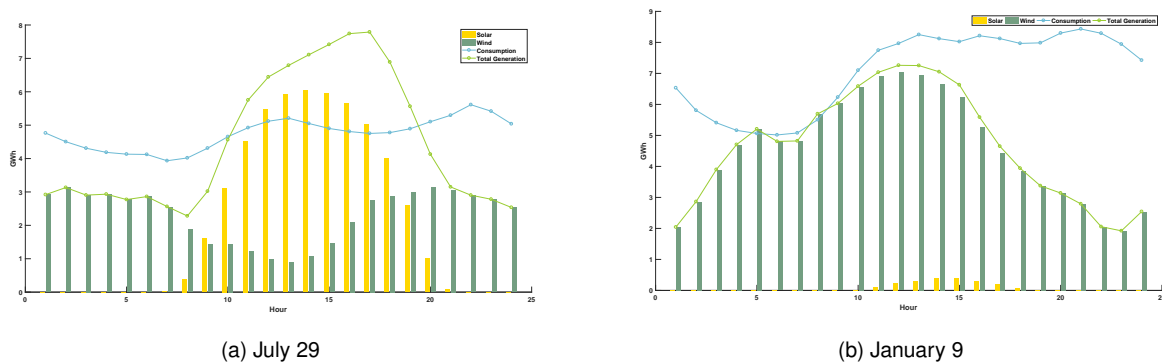


Figure 4.20: Electricity consumption and increased wind and solar generation during every hour of highest (July 29) and lowest (January 9) daily solar generation.

unlike solar generation, that only occurs during daytime.

### Residual Profile

Figure 4.21 shows the residual profile using increase scenario I. The blue bars correspond to excess energy verified in certain hours of the year, while the red bars correspond to unsatisfied demand. This scenario, produced a total of 24.41 TW h wind generation, of 11.56 TW h solar generation, which add up to 35.97 TW h. From figure 4.21 it is also possible to verify that total unsatisfied demand is 18.11 TW h

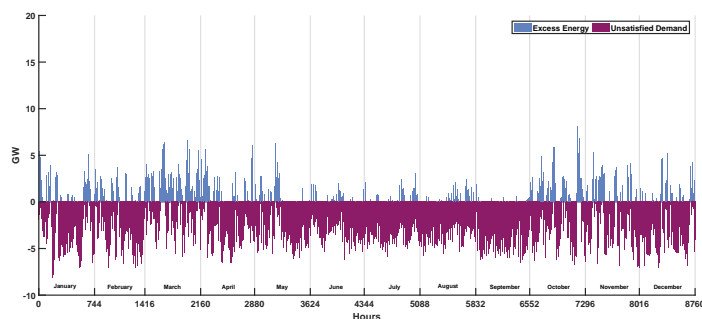


Figure 4.21: Residual profile, in an hourly time frame during 2018, considering scenario I.

and total excess energy is equal to 3.18 TW h. In this scenario, total unsatisfied demand is greater than total excess energy. Surplus energy would not be enough to satisfy the remaining demand if it could be stored by PHS. This increase scenario proves to be insufficient to justify the use of PHS to complement wind and solar generation.

### 4.2.2 Scenario II - (W=3,S=18)

In the present scenario, the increase generation factors considered are  $W = 3$  and  $S = 18$ , meaning wind generation is increased by the factor  $W$ , and solar by the factor  $S$ . This increase in generation goes beyond the results of studies used to define scenario I factors. The depicted generation results may or may not be achieved in reality, and more studies on Portugal's renewable potential would have to be

carried out.

## Monthly Analysis

Figure 4.22 shows for each month of the year, the total consumption, wind and solar generation, and total generation values. 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, although December also registers lower combined generation in comparison with the other winter and autumn months. During months when there is more solar generation, like July, August and September, wind generation tends to be lower and closer to solar generation values. Even increasing solar capacity and generation by a factor of 18, solar capacity is still lower than the considered wind capacity in this scenario, which can explain the almost equal generation values during those months. A simple takeaway from figure 4.22 is that wind generation tends to be greater during the beginning and ending of the year, and solar generation tends to be greater in the middle of the year.

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.

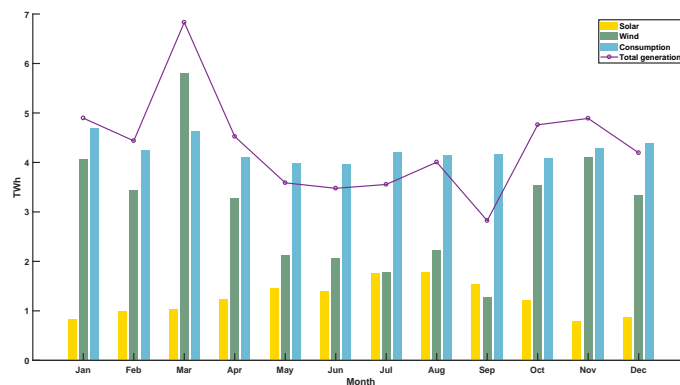


Figure 4.22: Verified Consumption, wind, solar, and total generation in TW h per month, considering scenario II.

## Residual Profile

The residual profile for scenario II is shown in figure 4.23. At a first glance, it is possible to verify that the blue bars tend to be higher than the red ones. In fact, considering this scenario, the total excess energy is equal to 11.96 TW h, and total unsatisfied demand is equal to 11.38 TW h, which means that there is more excess energy than needed energy. If 100% of this surplus energy was stored by PHS, it could mitigate the remaining demand that was not satisfied by wind and solar generation, as it will be studied in chapter 5.

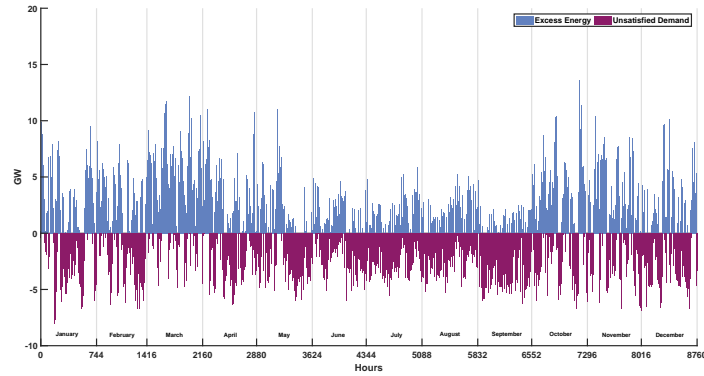


Figure 4.23: Residual profile, in an hourly time frame during 2018, considering scenario II.

### 4.2.3 Scenario III - (W=3,S=25)

In this scenario wind generation is increased by a factor of three (3) and solar generation by a factor of twenty five (25). This is the most extreme scenario in terms of increase capacity and generation. Considering the mentioned factors, wind and solar installed capacity are equal to 15 GW.

#### Monthly Analysis

Figure 4.24 shows, for every month of the year, the total consumption, wind, solar, and combined generation values. In this scenario, 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 generation is higher than wind generation. The 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. Scenario III considers that the installed solar capacity is equal to wind capacity, which does not mean that the generation values are the same, it only shows that solar generation could have a more similar role to wind generation, in the generation landscape, if its installed capacity increases.

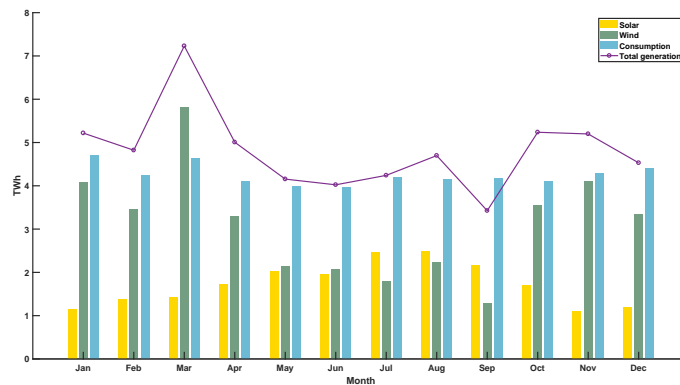


Figure 4.24: Verified Consumption, wind, solar, and total generation in TW h per month, considering scenario III.

## Residual Profile

Figure 4.25 shows the residual profile for scenario III. Analysing figure 4.25, it can be verified that there is much more excess energy than unsatisfied demand, since the blue part of the figure is larger than the red part. In this scenario, excess energy reaches a total of 16.71 TW h, and total unmet demand is equal to 10.35 TW h. Total excess energy is greater than total unmet demand, if surplus energy could be stored, in theory it would be possible to complement completely wind and solar generation in order to satisfy the year's demand. This situation will be analysed in chapter 5.

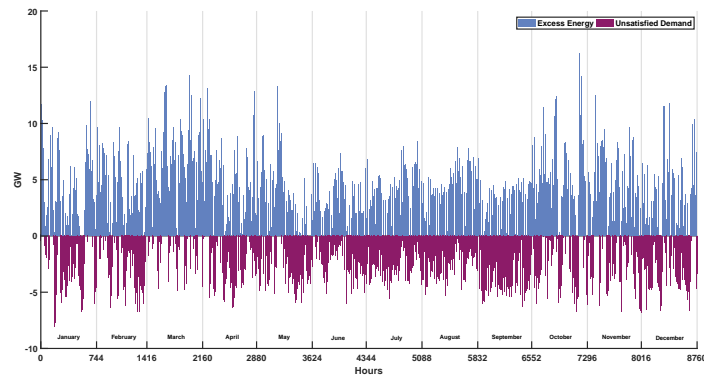


Figure 4.25: Residual profile, in an hourly time frame during 2018, considering scenario III.

## 4.3 Results

The present section compares the results analysed in sections 4.1 and 4.2. Figure 4.26 was created from the figures 4.1, 4.11, 4.22 and 4.24, and shows the total monthly electricity consumption (black line), as well as the total monthly combined generation for each of the four scenarios studied in the current chapter. The base scenario is represented in yellow, scenario I in blue, scenario II in pink, and finally scenario III in green. It is important to mention that, if a certain month has more combined generation

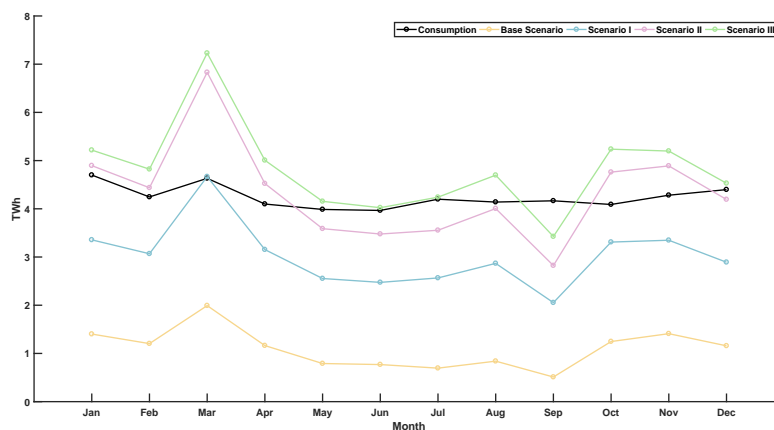


Figure 4.26: Monthly electricity consumption and combined generation considering the base scenario, and scenarios I, II, and III, during the year.



than electricity consumption, it does not mean that all demand was satisfied during said month, it means that overall generation was higher than consumption. To satisfy all demand, every hour of the month must generate more or the same energy as consumption for that hour.

Analysing figure 4.26, the base scenario (yellow) provides the worst results, since in none of the twelve months generation meets consumption needs. In fact, generation is so low that it does not even satisfy 50% of consumption. If there is no increase in wind and solar capacity, it is impossible to satisfy demand, and to justify the use of pumped storage. Increasing installed capacity and consequently generation is crucial, and different increase scenarios provide different results. 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 the  $S$  multiplier (going from  $(W = 3, S = 18)$  to  $(W = 3, S = 25)$ ), only September is left with an energy deficit.

An interesting metric that can be retrieved from the residual profiles is the number of consecutive unsatisfied hours. This is can be seen in figure 4.27, that shows the histograms with bins of 20 hours, for the increase scenarios. The base scenario is not considered since only one hour was satisfied. For the three scenarios, most occurrences are of 20 or less consecutive hours. Analysing the figure, it is possible to see that the  $(W = 3, S = 25)$  scenario has more occurrences in the  $[1 - 20]$  range, than the others. This can be justified by considering that where another scenario might have a streak of 30 hours, due to the increase in generation, in the third scenario the streak might be divided into smaller streaks separated by satisfied hours. Consequently, it is possible to see that as generation increases, the number of sets with more consecutive hours decreases. This is also translated in the value of the highest streak for each scenario. For scenario I the highest streak occurs during 263 hours, for scenario II this value is reduced to 115, and for scenario III is 63. In all three the streaks occur during the second half of May. This metric is relevant since the PHSP operating time is a characteristic that defines the pumped storage facility.

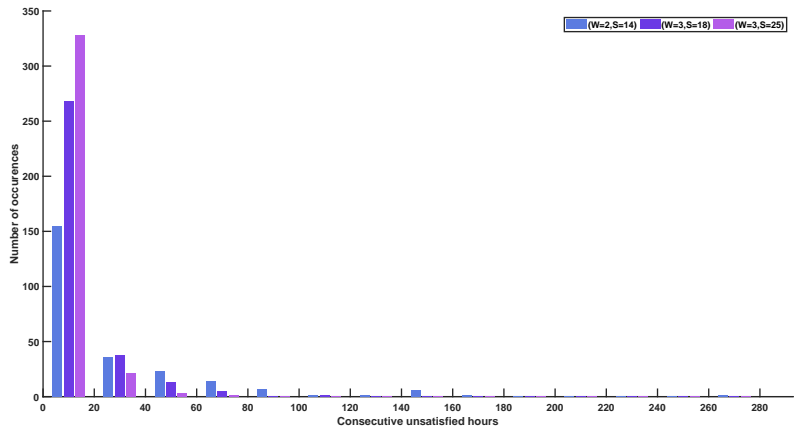


Figure 4.27: Histogram of the number of consecutive occurrences of unsatisfied hours, considering the increased scenarios.

Table 4.7 synthesizes the results from the current chapter by presenting the multiplying factors, wind and solar installed capacity for each of the four scenarios studied, and it also shows total energy consumption, total generation, total excess energy, total unsatisfied demand values for each scenario, and the number of hours on the longest streak of unsatisfied demand. From table 4.7, it is possible to con-

Scenario	Multiplying Factors		Installed Capacity (GW)		Total Energy Consumption (TWh)	Total Generation (TWh)	Total Excess Energy (TWh)	Total Unsatisfied Demand (TWh)	Longest streak of consecutive unsatisfied hours
	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	3.18	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 4.7: Annual consumption, generation, excess energy and unsatisfied demand values of base scenario and scenarios I, II, and III.

clude that the base scenario does not justify the use of PHS, because the total excess energy is several orders of magnitude smaller than the total unsatisfied demand, with only one hour of excess registered in the whole year (8760 hours).

As stated in the analysis of figure 4.26, scenario I is the most conservative of the three studied scenarios, so it provides the worst results. Since the multiplying factors are lower in this scenario, it is natural that generation is also lower. Even so, this scenario is able to generate a total of 3.18 TWh of excess energy. However this result is not nearly enough to satisfy a total unmet demand of 18.11 TWh, if stored and relocated throughout the year. As the multiplying factors increase, the more generation there is, and better results are obtained. In both scenarios II and III, the total combined generation is higher than the total consumption, but these results can be misleading. In theory if this energy could be relocated during the year, all consumption would be satisfied by wind and solar generation. But in practice, due to the fact that there is a large disparity between the months generation (figure 4.26), the pumped storage installations would need massive reservoirs to store the excess energy from March, and redistribute it from May to September. However, for scenario III, most months have more total generation than total consumption, and the pumped storage installations would be used to mitigate hourly/daily/weekly fluctuations allowing for much smaller reservoirs. On the other hand, while scenario III provides the best results, it may not be possible to implement, as the increase factor ( $S = 25$ ) is an ambitious value, far from the PNEC30 plan. To summarize, scenarios II and III have enough excess energy to justify the need for pumped storage, as this energy storage system can relocate surplus energy to hours when generation is not enough to satisfy demand.

# Chapter 5

## PHS to complement wind and solar generation in Portugal

In this chapter the operation of pumped storage is simulated, so that its influence on the electric energy landscape can be analysed. The chapter is divided into two parts. The first focuses on analysing the PHS operation considering the base scenario, scenario II, and scenario III, of chapter 4. The second focuses on analysing how storage capacity and installed capacity influence the PHS contribution.

### 5.1 Simulation of PHS operation

This section aims to demonstrate that there is a need to install PHS and how this energy storage system can complement wind and solar generation.

Using energy consumption and wind and solar generation data from the year 2018, the following four scenarios are considered:

- The values of wind and solar generation correspond to the base scenario described in section 4.1:
  - without pumped storage;
  - with pumped storage.
  
- The wind and solar generation values are increased according to the factors that proved sufficient to satisfy demand in section 4.3:
  - without pumped storage;
  - with pumped storage.

## Considerations

The considerations taken to simulate the operation of PHS using the wind and solar power generation data for the year 2018 are:

- The installed capacity of Pumped Storage is considered to be equal to the maximum value of power verified in the residual profile, so that there was sufficient power of PHS to complement any lack of generation by wind and solar sources. The value was found by observing the maximum value of energy not satisfied by wind and solar resources for one hour, being approximately equal to 8 GW. The value considered will be 8.2 GW to offer some leeway.
- The storage capacity chosen is 1.2 TWh and the initial storage state is equal to the maximum capacity, i.e. the upper reservoir is initially full.
- The simulation of the PHS operation is made considering only one installation with the required installed power and storage capacity, instead of considering several separate installations.
- Wind generation is increased by a factor of 3 (leaving the installed capacity equal to 15 GW), and solar generation is increased by the factors 18 and 25 (leaving the installed capacity equal to 10.8 GW and 15 GW, respectively).
- In regard to the power that PHS can supply, it is considered that any power up to the maximum installed capacity can be supplied (turbine capacity). Pumping capacity is considered to be equal to turbine capacity.
- The minimum storage level of the reservoirs is zero, although this does not represent reality, as reservoirs have a minimum which should be respected, so that they are not empty.
- The simulations start at the first hour of the first day of the year.
- The PHS installation can generate energy as long as it has stored energy in its reservoir (no limit in consecutive generation hours).
- There is no limit in the lower reservoir storage capacity.

### 5.1.1 Case I - Current Generation without PHS

The present analysis is a follow-up of the one executed in section 4.1 of chapter 4.

Figure 5.1 is the annual residual profile obtained from only considering 2018's wind and solar generation to satisfy demand, throughout the 8760 hours of the year. The red bars of figure 5.1 are the unsatisfied demand values for each hour, and the blue bar represents the only occurrence of excess energy during the year.

It is possible to see that it would be impossible to satisfy demand with wind and solar generation alone. Besides that, implementing a ESS, such as pumped storage would not be viable, because the only surplus energy occurrence is 58.5 MWh, (represented by the blue bar), which is a low value.

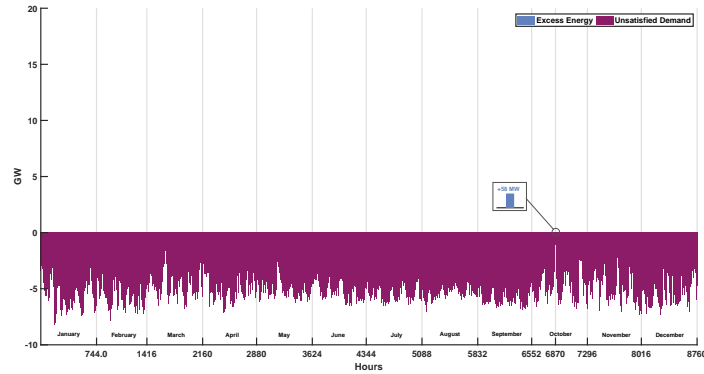


Figure 5.1: Annual residual profile in an hourly time frame, considering 2018's generation data.

In this generation scenario only one hour of the year is satisfied by wind and solar generation, which means that demand was satisfied during 0.01% of the year. In the remaining 99.99% demand is not met. Adding all the red bars, the total unsatisfied demand value is found, and is equal to 37.87 TW h.

Under these circumstances the implementation of pumped storage is not justified, wind and solar generation is insufficient to satisfy demand or to generate surplus energy to be stored.

### 5.1.2 Case II - Current Generation with PHS

Figure 5.2 shows for close-up of the first 300 hours of the year, the dynamics of the upper reservoir used in the simulation. It can be verified that the upper reservoir starts with the maximum storage capacity (1.2 TW h), and as the simulation progresses it begins to empty and consequently will reach a storage level equal to zero at about hour 300. Throughout the remaining hours of the year, the reservoir is empty since there is no surplus energy.

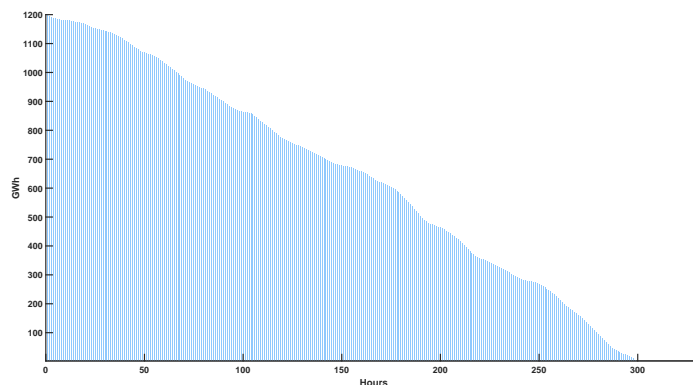


Figure 5.2: Close-up of the annual upper reservoir dynamics in an hourly time frame, considering 2018's generation.

Figure 5.3 (a) and (b) represent the pumped storage operation and its close-up, during the year in an hourly time frame. The light blue bars represent turbine operation, whilst the dark blue represent pump operation. As stated, the energy stored by the fictitious PHS installation only satisfies the first 300 hours of the year, which can be seen in figure 5.3 (b). The  $[0, 300]$  interval corresponds to approximately half

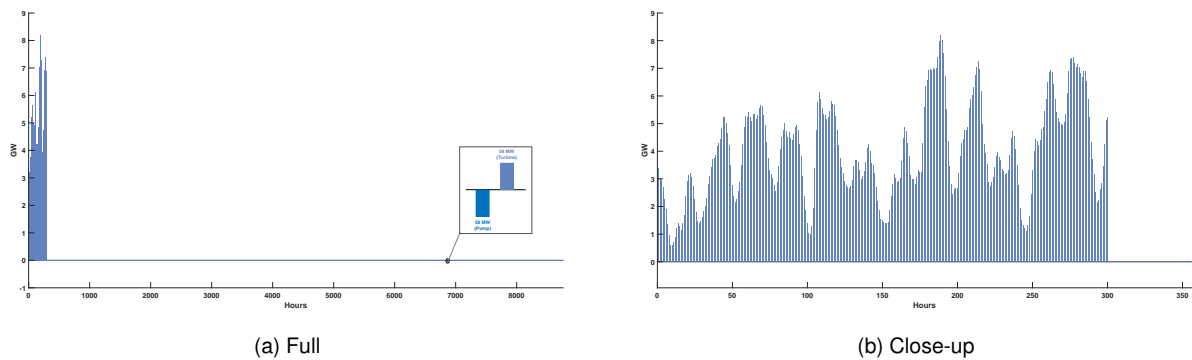


Figure 5.3: Annual pumped storage operation, in an hourly time frame, considering 2018's generation data.

of January. Figure 5.3 (b) also shows that pumped storage's operation is not constant, as it changes significantly from hour to hour, since different hours have different required demand and wind and solar generation. During the rest of the year, as there is no more stored energy, and no energy to store the operation of PHS is null, as depicted in figure 5.3 (a).

However, at hour 6870 on October 14, there is an occurrence of excess energy. The order of magnitude of energy generated is much higher than the excess energy verified, 58.5 MW h, which can be checked in figure 5.3 (a). The dark blue bar represents the pumping of water to the upper reservoir in order to store 58 MW h. In the following hour (6871), as the reservoir stored water in the previous hour, the PHS can generate back 58 MW h, this operation is represented by the light blue bar.

Figure 5.4 (a) and (b), shows the PHS operation (blue) and the residual profile before (red), and after (green) that operation, and its close-up, respectively. The original residual profile (red) represents the amount of energy in an hourly scale not satisfied by wind and solar generation. It can be seen that in the first hours of the year pumped storage operation is symmetrical to the original residual profile, and the new residual profile is null, this means that it was possible to generate the necessary energy during those hours to mitigate the lack of generation. Once no energy is available in storage, the PHS operation equals zero and the resulting residual profile equals the original residual profile, since there is no more energy in the reservoir to compensate demand. Figure 5.4 (b) shows the time when there was excess wind and solar generation, and its effect on PHS operation and the residual profile. At hour 6870, there is an excess energy in the original residual profile (red) of approximately 58 MW h, this excess is then pumped and consequently stored. The pumping operation (storage) performed by the PHS system has a negative signal, and the turbine operation (generation) has a positive signal. As there is excess energy, all consumption was satisfied by wind and solar sources, therefore the new residual profile is equal to zero. In the following hour (6871), the excess stored in the previous hour is used to satisfy part of the energy required in that hour. The original residual profile (red) requires about 256 MW h, however there is only 58.5 MW h stored. This energy is used and according to the new residual profile the value of unsatisfied demand is now equal to about 198 MW h (256- 58.5 MW h).

The simulation results show that it would be impossible to satisfy the missing demand with the amount

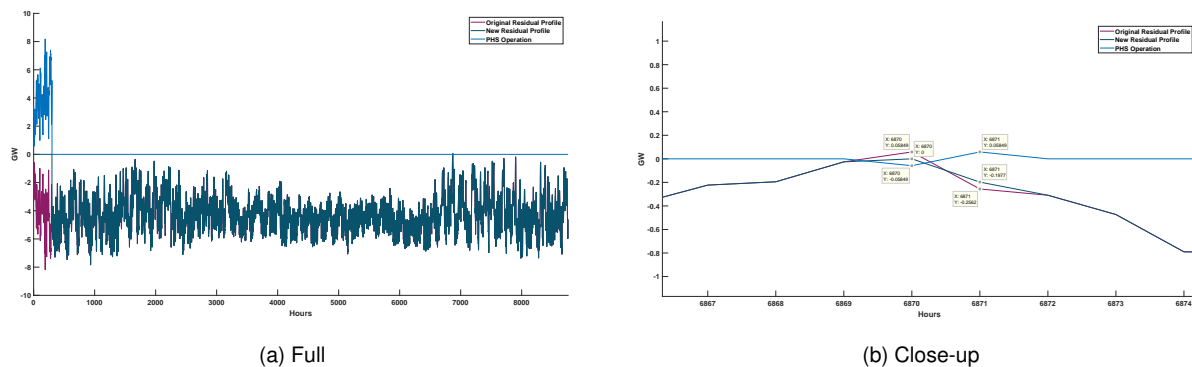


Figure 5.4: Annual pumped storage operation, original and new residual profiles in an hourly time frame, considering 2018's generation.

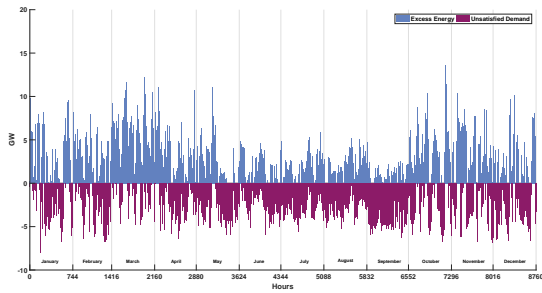
of generation, and PHS considered. On one hand, the initial quantity of storage capacity considered is not sufficient to satisfy all the hours of the year when consumption is not met by the combined wind and solar generation, even considering that the simulation starts with the maximum amount of energy stored. On the other hand because there is no excess energy during the year to be stored by the PHS facilities, as figure 5.1 shows. Therefore the energy spent is never replenished in the storage system, making it useless for the rest of the year.

This example illustrates that having a lot of energy stored is not enough to justify the use of pumped storage (or any similar energy storage system), there must be enough excess and it must happen consistently for the storage system to be replenished. The next cases to be studied will take this into account.

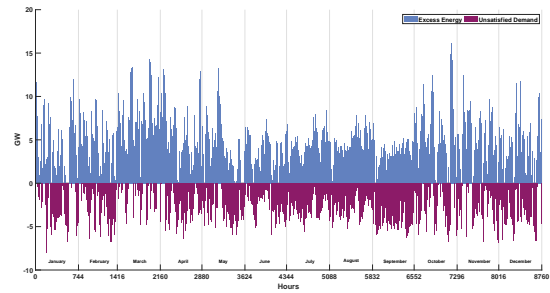
### 5.1.3 Case III - Increased Generation without PHS

If there is no pumped storage the profiles obtained are equal to the ones studied in section 4.2 of chapter 4. Figures 5.5 (a) and (b) represent the residual profile of generation of scenarios II (3, 18) and III (3, 25), in an hourly time frame during the year. The blue bars correspond to surplus generation, and the red bars correspond to unmet demand, during an hour. If all blue bars were added one would get the total excess energy generated in the year, and if the same was done to the red bars, one would get the total unsatisfied demand. For scenario II, the total excess energy is 11.96 TW h, and total unsatisfied demand is 11.38 TW h. For scenario III, the total excess energy is 16.71 TW h, and total unsatisfied demand is 10.35 TW h. In both scenarios, total surplus energy is higher than total unmet demand, but without using pumped storage, all excess energy is useless, since this energy is wasted. Considering the increase inherent to scenario II and III, it was possible to meet energy consumption of 4078 and 4599 hours, respectively, which in percentage corresponds to 46.55% and 52.5%.

Increasing generation proves to be beneficial in improving the percentage of satisfied hours to an extent (about 50% of demand is met), but in order to utilise this increase in an efficient manner, pumped storage should be implemented. If there are no energy storage systems to store surplus energy in order to relocate it to hours in need, increasing generation is a wasteful practice.



(a) (3, 18)



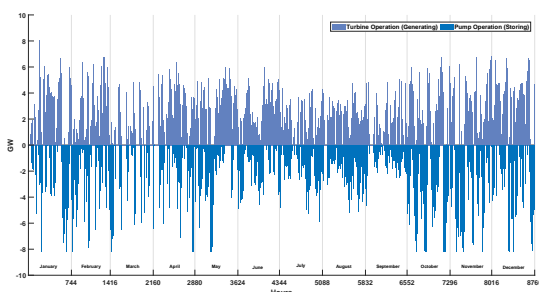
(b) (3, 25)

Figure 5.5: Annual residual profiles in an hourly time frame, considering an increase in generation.

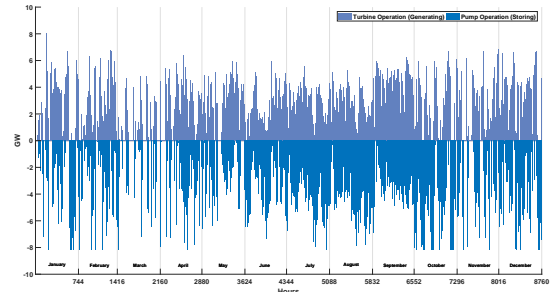
### 5.1.4 Case IV - Increased Generation with PHS

In an ideal situation the PHS operation profile should be opposite of the residual profile, so that all excess energy is stored and at the same time all demand is satisfied. In reality, the entire load must be satisfied, however, not all of the excess energy can be stored, either because there is no storage space or not enough power to pump the excess. Both restrictions exist due to the high investment that is attached to a PHS project. It is not feasible to limit the installed capacity of the PHS installation considering the peak of excess energy but rather considering the peak of consumption, because the purpose, both economically and operationally, is to satisfy the load and not to store energy. Similarly, it is neither economically feasible nor sometimes possible to build reservoirs capable of storing the expected excess energy.

Figures 5.6 (a) and (b) show the pumped storage installation operation profiles, for both increase scenarios considered. The figures are of great relevance since they show how the pumped storage installation would operate. In the PHS operating profiles shown in figure 5.6, the dark blue areas represent the moments when energy storage occurs (pumping mode), while the light blue areas represent the moments when energy is generated (turbine mode).



(a) (3, 18)



(b) (3, 25)

Figure 5.6: Annual pumped storage operation profiles in an hourly time frame, considering an increase in generation.

Figures 5.7 (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, and sometimes reach maximum capacity so they are unable to store more excess energy. These periods can last for months ( March and April). However during periods of low excess energy, the reservoir stores surplus energy 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 (figure 5.5) with the PHS operating profiles (figure 5.6), it is possible

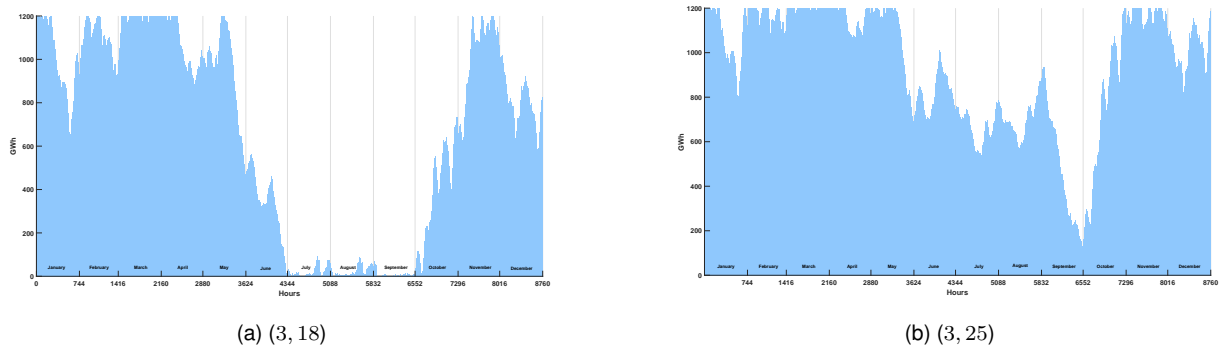


Figure 5.7: Annual upper reservoir dynamics in an hourly time frame, considering an increase in generation.

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, is that at a certain time instant the reservoir might already be at full capacity, so it is unable to store more energy. Figure 5.8 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 5.8 (a)), it is also possible to see a red area from the

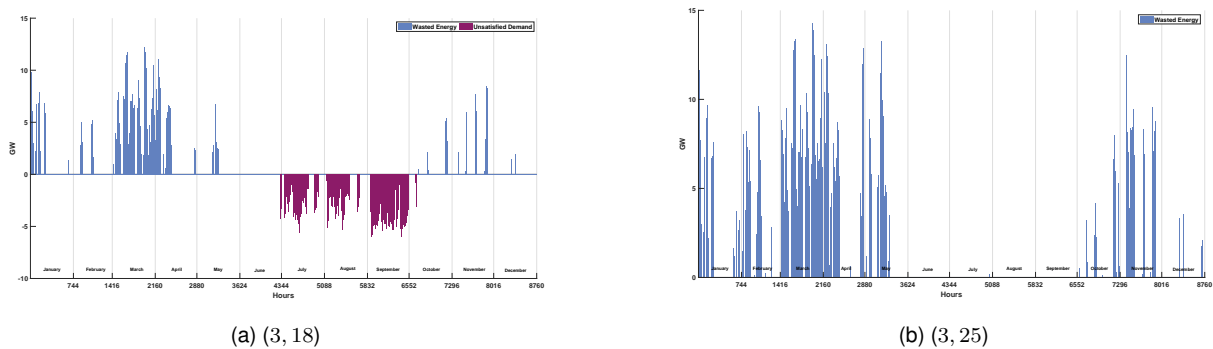


Figure 5.8: Annual residual profiles after PHS operation in an hourly time frame, considering an increase in generation.

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. It is important to notice that this happens because the considered reservoir does

not have enough storage capacity to store the surplus energy of the months prior. This can also be confirmed through figure 5.7 (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 (5.8 (b)), since all demand is satisfied by generation plus PHS. Figure 5.7 (b) also confirms this, since throughout the year the reservoir is never empty. Figure 5.7 also helps visualize what was said about not being able to store all excess energy, since it is possible to see at several instants that the reservoir is full.

By zooming in on a time interval where demand was not satisfied in scenario II, it is possible to further compare the increase scenarios considered. This is shown in figure 5.9 where a close-up of the original and new residual profiles, as well as the PHS operation profile are presented. To assist the analysis, a close-up of the reservoirs is also presented in figure 5.10. At first glance, it is possible to see that the reservoir for scenario III (5.10 (b)) has more stored energy, but is important to notice the scale of the plot, which shows that there is much more stored energy in this scenario, when compared to scenario II. Analysing figure 5.9, it can be seen that when the original residual and PHS operation profile

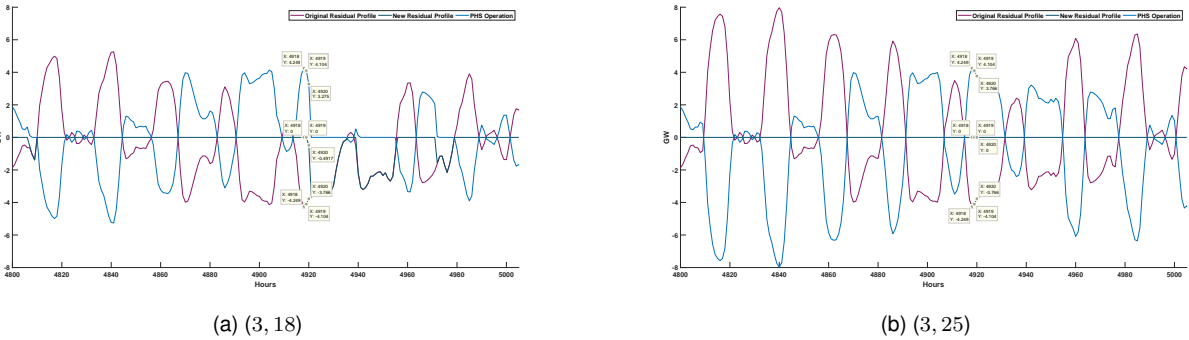
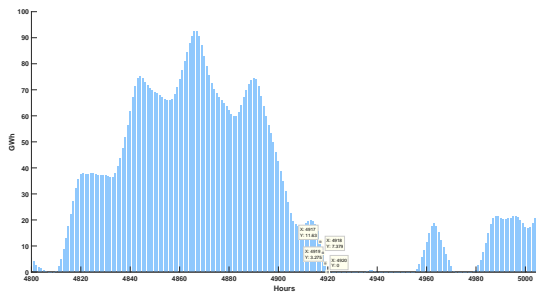


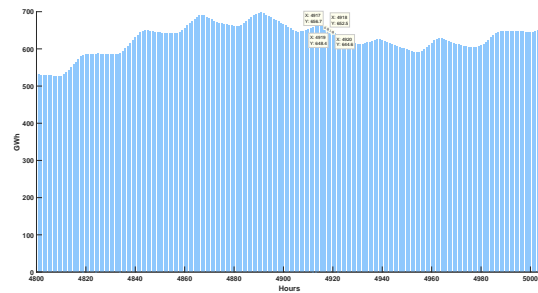
Figure 5.9: Close-up of the annual pumped storage operation, original and new residual profiles in an hourly time frame, considering an increase in generation.

plots are symmetrical, the new residual profile is equal to zero. This means that all excess energy has been stored or that the PHS operation has been able to meet the energy requirements imposed by the residual profile for a given hour, which is an ideal situation. When the profiles are no longer symmetrical it means that there is energy that could not be stored (positive sign) or satisfied (negative sign).

To make a more detailed analysis of the results the hours 4917, 4918, 4919 and 4920 are selected. At hour 4918, in both scenarios, there is the need to supply 4.249 GW h. This operation is only possible if there is enough energy in the upper tank of the system, in the previous hour. Analysing figure 5.10 it is possible to see that in both scenarios, the reservoirs have enough energy to meet demand. Since it was possible to fully counter the residual profile, the new profile is zero for hour 4918, and the stored energy decreased by the same value for both scenarios. In the following hour (4919) the demand can once again be satisfied, and the analysis is the same as the previous hour. However, at hour 4920 it is necessary to generate 3.766 GW h. In the scenario II the reservoir (figure 5.10(a)), at hour 4919 only contains 3.275 GW h, therefore this is the value of energy that the PHS installation can generate. Since this value is not enough, the new residual profile shows the unsatisfied value of 0.4917 GW h. For



(a) (3, 18)



(b) (3, 25)

Figure 5.10: Close-up of the annual upper reservoir dynamics in an hourly time frame, considering and increase in generation.

scenario III this does not happen since the reservoir (figure 5.10(b)) during hour 4919 has 648.4 GW h of stored energy. For scenario II, the upper reservoir is now totally discharged, presenting a zero stored energy value. The state of the reservoir remains at zero as long as there is no excess energy to store and the PHS system is unable to provide energy.

## 5.1.5 Results

In the current subsection a summary of the cases analysed is presented, and table 5.1 synthesizes the results obtained. The metrics present in the table are:

- **Total Energy Consumption:** Total value of energy consumption during 2018;
- **Total Combined Generation:** Total value of energy generated by wind plus solar sources;
- **Total Combined Contribution:** Total value of wind and solar generation that is effectively used to satisfy demand;
- **Total PHS Contribution:** Total value of energy generated by the PHS system used to satisfy demand;
- **Total Unsatisfied Demand:** Total value of energy not satisfied;
- **Percentage of satisfied hours:** percentage of hours during the year in which electricity consumption was mitigated.

Analysing table 5.1 a few things can be noticed immediately. First, when generation is increased, it is possible to see that combined contribution is not equal to combined generation, which happens because in an hour of energy surplus, only part of that energy was effectively used to meet demand. Secondly, on the total PHS contribution the added value of 1.2 TW h was made explicit since this value comes from the fact that the reservoir starts at full capacity, and so this contribution is constant for all simulated cases with PHS. Finally, as already mentioned in this thesis, even though combined generation is greater than total consumption, if no PHS is used to redistribute surplus energy, some demand will not be met.

	No Increase No PHS	No Increase With PHS	With Increase No PHS		With Increase With PHS	
			(3,18)	(3,25)	(3,18)	(3,25)
<b>Total Energy Consumption (TWh)</b>	50.9					
<b>Total Combined Generation (TWh)</b>	13.03		51.48	57.62	51.48	57.62
<b>Total Combined Contribution (TWh)</b>	13.03		39.52	40.55	39.52	40.55
<b>Total PHS Contribution (TWh)</b>	—	1.2+0.00005849	—	—	1.2+7.43	1.2+9.15
<b>Total Unsatisfied Demand (TWh)</b>	37.87	36.67	11.38	10.35	2.64	0
<b>Satisfied Hours (%)</b>	0.01	3.42	46.54	52.50	88.29	100

Table 5.1: Annual simulation results of the four cases studied, in an hourly time frame.

A more in depth analysis shows that if there is no generation increase, demand can not be satisfied relying only on the combined wind and solar generation, even when aided by ESS, such as PHS. This is validated by the values in table 5.1 where for the first case, the wind and solar generation recorded in 2018 can only satisfy electricity consumption during 0.01% of the 8760 hours of the year. In the remaining 99.99%, it would have been necessary to rely on other sources of electricity to satisfy demand. Still considering that there is no generation increase, but using PHS to complement generation, the percentage of satisfied hours, increased from 0.01% to 3.42%. However, this only happened because the reservoir was considered to be full at the beginning of the simulation. Considering a system that did not have stored energy would yield the same results as case I. These results coincide with the results from chapter 4, where the conclusion was that without increasing generation it is impossible to satisfy demand using only wind and solar generation.

When generation is increased by the factors considered it is possible to see that total combined generation is greater than total energy consumption. However, if no pumped storage is used, and since the sources considered are variable output sources, there is no way to transfer excess energy from excess hours to the ones that registered unmet demand. Consequently, according to table 5.1, only around 50% of the 8760 hours of a year would be satisfied. On the other side, 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 remains as is, then there is no practical advantage in implementing PHS in Portugal. On the other hand, if generation is increased, a technology like pumped storage must be used to take full advantage of the said increase. Only with an ESS like PHS it is possible to reach 100% (or close to 100%) of satisfied hours for 2018 using only solar and wind sources.

## 5.2 Implementation constraints

This section presents the study of the different metrics that characterize a PHS installation, in this case, storage capacity (energy) and installed capacity (power) that should be implemented so that wind and solar resources are better complemented.

### 5.2.1 Storage Capacity

In section 5.1 the storage capacity of the pumped storage installation considered was a fixed value of 1.2 TW h. In the current section the storage capacity value will no longer be fixed, it will be the variable under study, in order to identify the minimum storage capacity value that provides the highest percentage of satisfied hours, for each of the generation scenarios previously studied in chapter 4 and section 5.1. The term satisfied hour is defined as an hour in which energy consumption was fully realized by wind, solar and pumped storage generation, as mentioned in section 5.1. The storage capacity of the PHS installation refers to the size of the upper reservoir, and in this case the size is expressed in terms of energy. The study covered all hours of the year 2018, and considered a PHS storage system without stored energy in its initial state (dashed line), and also considered it to start with the maximum stored capacity (solid line). Figure 5.11 represents the variation in the percentage of satisfied hours in relation to the storage capacity of the simulated PHS installation, for the base scenario and scenarios I, II and III, previously studied in chapter 4. Firstly, it can be seen that without storage (upper reservoir storage

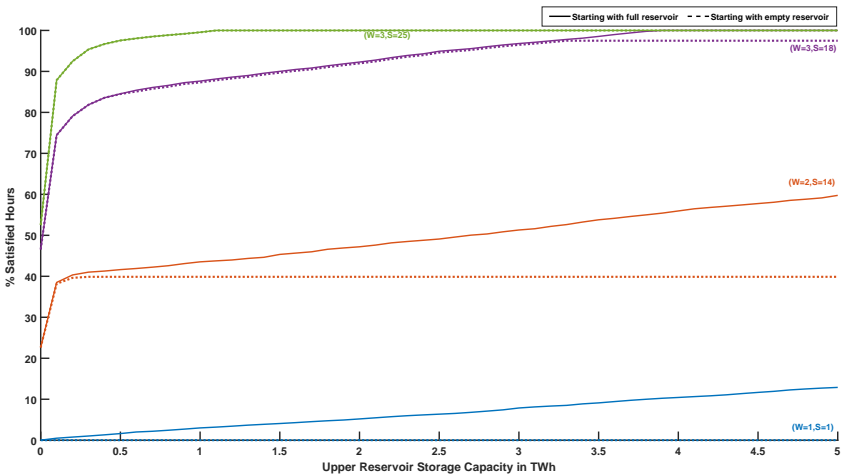


Figure 5.11: Percentage of satisfied hours in relation to the upper reservoir storage capacity, for the base scenario, and scenarios I, II, and III.

capacity = 0) the percentage of satisfied hours is between 0% and 55%, depending on the considered generation scenario. The 0% value corresponds to the scenario with no increase generation. For the augmented scenarios, the initial percentage of satisfied hours are 23%, 47%, and 53%, respectively to scenario I, II and III. As the storage capacity increases, the percentage of satisfied hours also increases. For all scenarios, the curves can be divided into two segments. The first is characterized by a steep slope line, meaning that a small increase in storage capacity causes a significant increase in the number

of hours satisfied. Additionally, for each scenario there is a capacity threshold from which the second segment starts. In this segment the curves continue to preserve the linear relationship between the two variables, but with a less steep slope, so 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. If storage capacity increases from 0 to 0.1 TW h (100 GW h), the percentage of satisfied hours increases by 20%, and about 75% of the year is satisfied by combined generation and pumped storage. To see a new 20% increase in the percentage of satisfied hours, storage capacity would have to increase from 0.1 TW h to 2.6 TW h. With this capacity about 95% of the year is satisfied. When considering higher capacity values, the variation of the percentage of satisfied hours is even slower. The maximum percentage of satisfied hours, considering that the reservoir starts full is 100% (5% increase) for a storage capacity of 3.9 TW h. If the reservoir is empty in the beginning of the simulation, then the maximum percentage of satisfied hours is 97.5%, registered for any storage capacity value above 3.3 TW h, since there are hours in the beginning of the year that require energy that is not available.

For the base scenario (blue curves), any percentage of satisfied hours comes from the initial stored energy and never from actual pumped storage operation. This example reiterates that without increasing the installed capacity of wind and solar sources it is impossible to satisfy consumption just by considering the referred sources of generation, nor is it justifiable to use energy storage systems as PHS because there is no excess energy that can be stored.

Figure 5.11 also shows that for scenario I, there is no point in increasing storage capacity above 0.1 TW h. In fact, with a generation increase by factors (2, 14), the surplus energy for each hour is very low, and if the reservoir starts empty the amount of surplus energy is never enough to justify a larger reservoir, as seen in the orange dashed curve of figure 5.11. Looking at the orange solid curve, one can mistakenly conclude that a larger reservoir is needed, but in fact the increase in satisfied hours only happens because, as the reservoir capacity is increased there is more energy in the beginning that can be used to satisfy demand.

The purple and green curves, corresponding to ( $W = 3, S = 18$ ) and ( $W = 3, S = 25$ ) scenarios, show that for a greater generation increase, considering larger reservoirs is viable, since there is a lot more energy to be stored and consequently replenish the reservoir. This means that even when the reservoir starts empty the variation of the percentage of satisfied hours does not stagnate. Considering these two 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 the purple 3.9 TW h, and the green 1.1 TW h. The higher the increase factors, the smaller the reservoir has to be to satisfy all the hours of consumption. The green graph shows the particularity of reaching 99.99% of satisfied hours even if the tank starts empty. This is because there is a lot of generation so almost every hour is satisfied by wind and solar generation and there is also plenty of excess to recharge the reservoir. The maximum value is not 100% because the first hour of the year is not fully satisfied by wind and solar generation and as there is no stored energy it is not mitigated by the complementarity of the PHS system.

Considering the two scenarios that proved viable, the storage capacity required for each percentage

of satisfied hours can be obtained by zooming in on figure 5.11 and placing cursors in the desired percentages. This can be seen in figure 5.12. The storage capacity limit considered is 5 TW h, and the minimum percentage of satisfied hours considered is 80%. In this figure, it is possible to see cursors in the various percentages considered, ranging from 80% to 100%, in 5% increments.

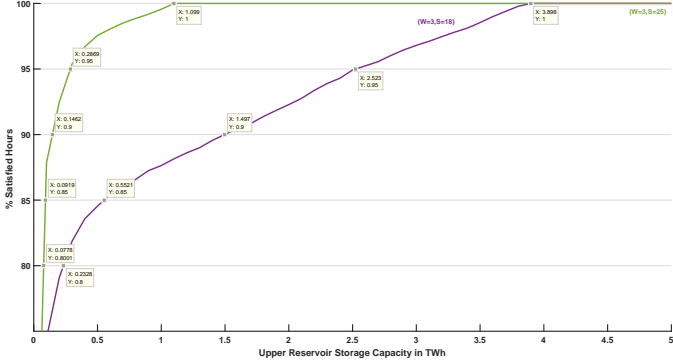


Figure 5.12: Percentage of satisfied hours, between 80% and 100%, in relation to the upper reservoir storage capacity, for scenarios II, and III.

### 5.2.2 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 greater or equal to 8.04 GW, as this is the power needed to cover the worst hour (the hour that requires the biggest PHS contribution so its consumption is fully met). 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. To find the capacity for a certain percentage, the threshold starts at 8.04 GW (100%) and is pulled upwards. As the threshold is being pulled the worst hours registered in the year are left unsatisfied. This process stops when the desired percentage of satisfied hours is reached, and consequently the installed capacity needed is obtained.

Figures 5.13 and 5.14 show the profiles, and display the installed capacity thresholds that allow the considered percentages to be covered, for the cases where energy generation was increased by the factors (3, 18) and (3, 25), respectively. Figure 5.15 shows the same information contained in figures 5.13 and 5.14, but obtained in a different way. 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 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. As can be seen in figure 5.15, the power values for the 438<sup>th</sup> worst hour are 4.55 GW and 4.49 GW, which are the same as the ones obtained with the first approach, and are represented in figures 5.13 and 5.14, respectively. The same calculation can be done for the remaining percentages to obtain all power values. In figure 5.15 it can be seen that the curves for each scenario are almost

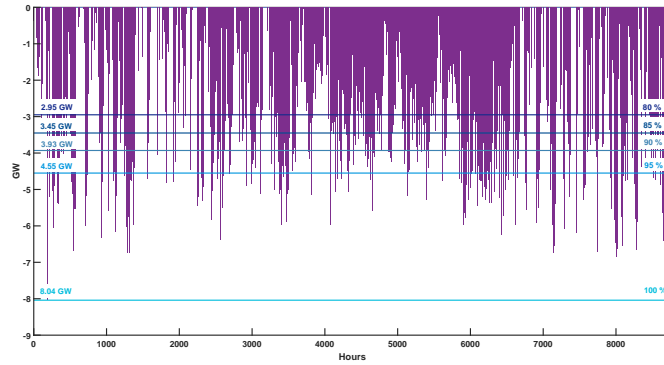


Figure 5.13: Residual profile of scenario II with the installed capacity thresholds.

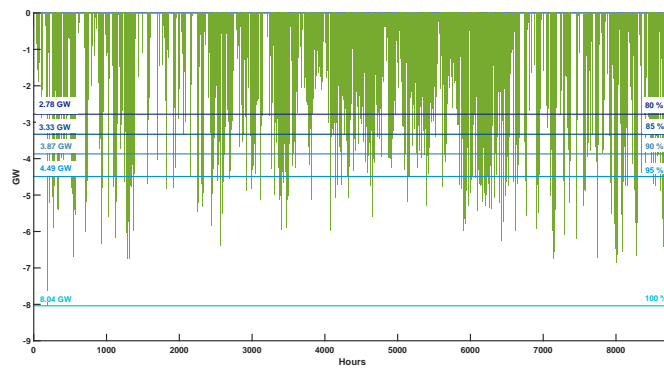


Figure 5.14: Residual profile of scenario III with the installed capacity thresholds.

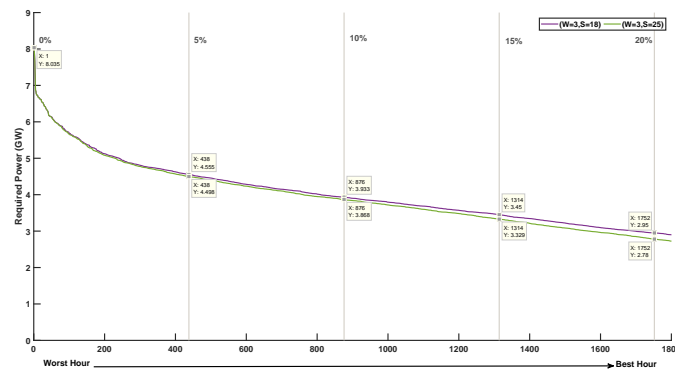


Figure 5.15: Required installed capacity according to the desired percentage of satisfied hours.

overlapping, especially in the beginning of the plot, which confirms that the power results of the two scenarios are nearly the same.

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. 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.



# Chapter 6

## Locations

Portugal has a topography that allows the implementation of pumped hydro storage systems. In addition to the numerous terrain elevations and water courses, it also has a vast coastal area that can be exploited for PHS projects. This chapter will use the study *A global atlas of pumped hydro energy storage* [9], presented by the Australian National University, to gather possible locations to implement PHS in Portugal. The possible locations will be analysed with the goal of identifying a set of viable locations that could be used to complement renewable sources in the country.

### 6.1 Possible locations for PHS installations

The mentioned study aimed to identify on a global scale, potentially viable locations for implementation of PHS, and managed to find 616000 projects with around 23 million GW h of storage potential using a geographical information analysis system (GIS). It is important to note that none of the potential PHS locations discussed in this study have been the subject of geological, hydrological, environmental, heritage and other studies, and it is not known whether any particular site would be suitable, and that the accuracy of the sites depends on the accuracy of the source data. There may also be locations that are in protected areas or urban areas not identified by the source data [9]. According to the study the potential locations found for the installation of PHS have 2 GW h, 5 GW h, 15 GW h, 50 GW h or 150 GW h of storage capacity in the upper reservoir. In addition to the storage capacity, other essential characteristics for the study of a potential location for a PHS facility were identified such as: area of the reservoir (in hectares), water volume of the reservoir (in gigalitres), minimum altitude difference between potential upper and lower reservoirs (Head) (in meters), minimum horizontal distance between potential upper and lower reservoirs (separation) (in kilometres), etc [9]. This text will only focus on the locations of 150 GW h. In Portugal about thirty nine possible locations with 150 GW h of storage capacity have been found. Figure 6.1 shows the 38 possible locations. Some of the locations have reservoirs that are beyond the Portuguese border. These locations are disregarded. The upper reservoirs are represented in

light blue and the lower ones in dark blue. Each container pair is assigned a class A (dark red), B (red), C (orange), D (dark yellow), or E (light yellow) according to an approximate cost model. The cost of a class A structure is approximately half of class E. It should be noted that the possible locations are all in the north of the country, where there are more terrain elevations.

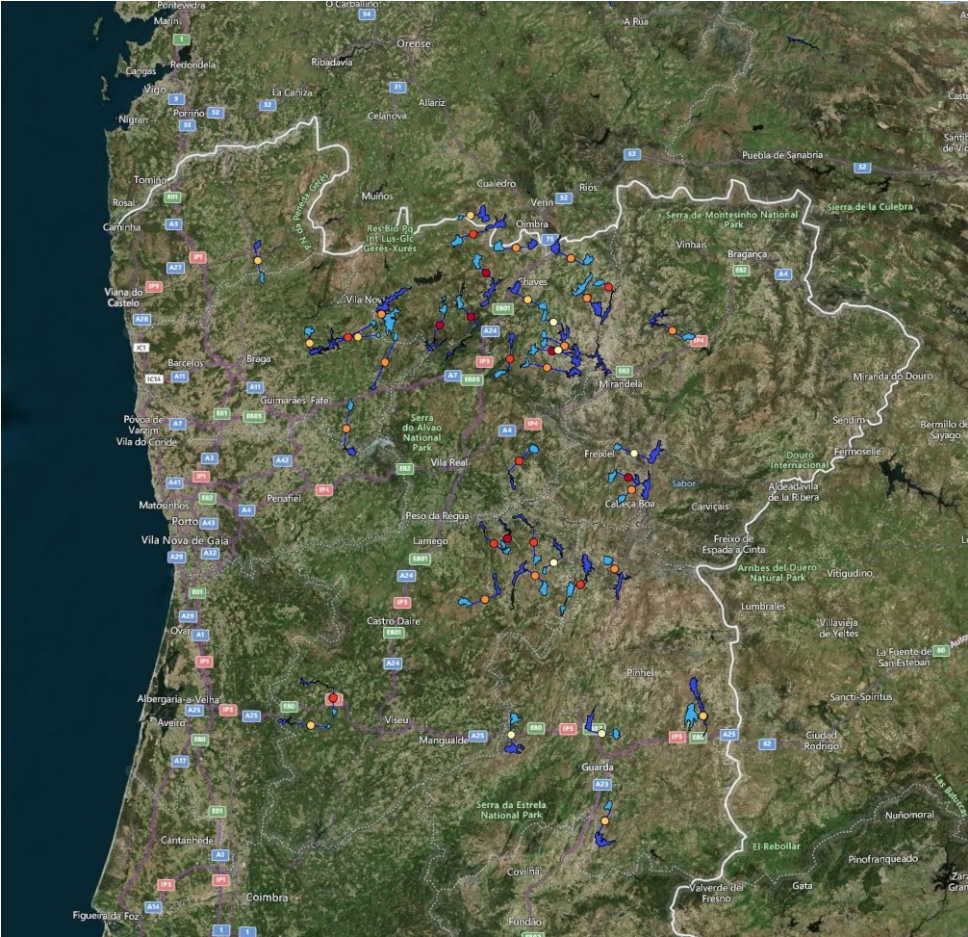


Figure 6.1: Possible locations found in Portugal according to AREMI's Global Pumped Hydro Atlas project.

## 6.2 Number of Locations

Section 5.2 studied how storage, and installed capacity influenced the percentage of satisfied hours. In the present section, these results will be used to identify the number of PHS installations needed.

### 6.2.1 Storage Capacity Restriction

The first restriction is in relation to storage capacity. One of the conclusions reached was that, for greater storage capacities, the percentage of satisfied hours is higher. Figure 5.12 shows the storage capacity values needed for each desired percentage. Table 6.1 summarizes the values presented in figure 5.12, and includes the number of PHS installations required to obtain the storage capacity for each considered percentage, taking into account that the locations under study have a possible storage

capacity of (150 GW h). The number of PHS installations ( $N$ ) required is calculate using equation 6.1.

$$N = \text{ceil}\left(\frac{\text{RequiredStorageCapacity} \cdot 1000}{150}\right) \quad (6.1)$$

This value is found by dividing the required storage capacity in GW h, hence the multiplication by 1000, by 150 GW h which is the maximum storage capacity of each of the possible locations. It is then rounded up to the next integer value because the number of PHS installations cannot be decimal, and there cannot be less storage capacity than the required. 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. As a final remark, it is possible to verify that for scenario ( $W = 3, S = 25$ ) one installation is enough to satisfy 90%, so the values of 80% and 85% can be disregarded.

% Satisfied Hours	[W=3,S=18]		[W=3, S=25]	
	Storage Capacity (TWh)	Number of PHS installations	Storage Capacity (TWh)	Number of PHS installations
80%	0.2328	2	0.0778	1
85%	0.5521	4	0.0919	1
90%	1.497	10	0.1462	1
95%	2.523	17	0.2869	2
100%	3.898	26	1.099	8

Table 6.1: Storage capacity, and number of PHS installations required according to the percentage of satisfied hours for the increased generation scenarios considered.

## 6.2.2 Installed Capacity Restriction

It is important to mention that the installed capacity of a certain PHS installation mainly depends on the head and water flow, whereas these two factors depend on the location and on the turbines to be used, respectively.

In relation to the installed capacity restriction, figures 5.13 and 5.14, from section 5.2, 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. While, for example, the Frades II dam has 736 MW of installed capacity, new hydro projects in Portugal are expected to have 1.15 GW, so the chosen value of 1.1 GW installed capacity per facility seems feasible.

Table 6.2 shows the number of facilities needed for each of the considered percentages, taking into account the installed capacity thresholds. The number of installations is obtained through equation 6.2.

$$N = \text{ceil}\left(\frac{\text{InstalledPowerNeeded}}{1.1}\right) \quad (6.2)$$

To understand the relevance of this study, one can look at the highest installed capacity value, which

% Satisfied Hours	[W=3,S=18]		[W=3, S=25]	
	Installed Power needed (GW)	Number of PHS installations	Installed Power needed (GW)	Number of PHS installations
80%	2.95	3	2.78	3
85%	3.45	4	3.33	4
90%	3.93	4	3.87	4
95%	4.55	5	4.49	5
100%	8.04	8	8.04	8

Table 6.2: Installed capacity, and number of PHS installations required according to the percentage of satisfied hours for the increased generation scenarios considered.

corresponds to satisfying 100%, and is equal 8.04 GW. Today, the Bath County Pumped Storage Station is the largest in the world with 3 GW of installed power, supplied by six Francis reversible turbines. This clearly shows that, with current technology, installing 8.04 GW in a single facility is not viable.

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%.

### 6.2.3 Results

While the two restrictions were studied separately, in reality both have to be considered at the same time. Since for each case the minimum required number of PHS facilities was found, the results must now be combined. In general, for the (3, 25) scenario, the number of installations is higher considering the installed power restriction (table 6.2) rather than the storage capacity one (table 6.1). The opposite happens for the (3, 18) scenario, where the storage capacity restriction will be the one to dictate the number of installations. For scenario (3, 25) when the percentage of hours to satisfy is 100%, the number of installations required (8) is equal for both restrictions (storage and installed capacity). The joined results are summarized in table 6.3.

% Satisfied Hours	[W=3,S=18]	[W=3,S=25]
	Number of PHS installations	Number of PHS installations
80%	3	3
85%	4	4
90%	10	4
95%	17	5
100%	26	8

Table 6.3: Number of PHS installations required according to the percentage of satisfied hours, and storage and installed capacity restrictions, for the two increase scenarios.

Analysing table 6.3 it is possible to verify that to satisfy at least 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%, when considering 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 PHSP.

## 6.3 Location Selection

The location selection will consist in choosing possible sites presented by the AREMI study [9], as previously mentioned. The aim is to evaluate said locations following the criteria that should be taken into account when installing PHS in order to find viable locations and eliminate non-viable ones. The criteria taken into account is the following:

- The reservoirs can not overlap with major populated areas (e.g small town) or roads (e.g. 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 wind farms (solar parks were not considered since the locations were mostly in the north of the country, while solar parks are mostly in the south, meaning that the distance to solar parks can be discarded);

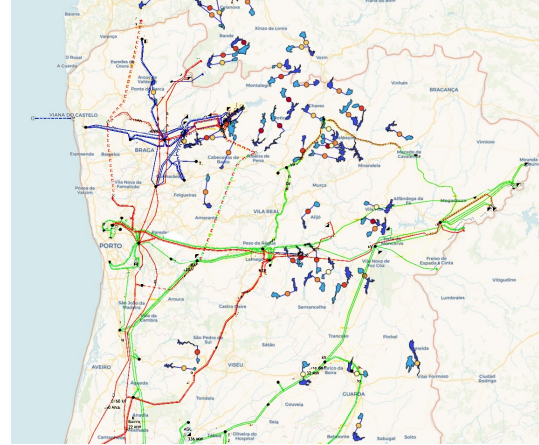
It is important to note that there are other criteria to consider when implementing a PHS facility but that for this study were not used due to lack of available information. Some other important criteria include [46]:

- Availability of right of way;
- Permitting;
- Environmental issues;
- Need to update existing lines and substations due to injection of new capacity;
- Available transmission line capacity;

To apply the criteria chosen for the selection of locations, images such as those in figure 6.2 were analysed. Additionally, the possible locations were analysed on the map of Portugal using the locations' coordinates, to verify if they were situated over populated areas and roads. Figure 6.2 (a) shows a clipping of the northern part of the national very high voltage electricity transmission network in the year 2018. The red lines correspond to the 400 kV transmission lines, the green ones to 220 kV and the blue ones to 150 kV. By analysis of figure 6.2 (a) it is possible to check how dams with pumping are connected to the network, as well as the location of several wind farms. Table 6.4 shows for each dam with pumping analysed, its installed capacity, and its connection to the national electricity transmission network. It is possible to verify that the dams with pumping can be connected to the network either through power transformer substations or, switching and transition stations. Figure 6.2 (b) shows the overlap of the national electricity transmission network with possible sites for implementing PHS, thus making it possible to check which sites are closest to transmission lines and connection points.



(a) National Electricity Transmission Grid (Source REN)



(b) National Electricity Transmission Grid plus possible locations

Figure 6.2: Clipping of the northern part of the national very high voltage electricity transmission network (a) and merge of same clipping with the possible locations of figure 6.1 (b).

Dams with Pumping	Installed Capacity (MW)	Connection		Voltage Level		
		Power Transformer Substation	Switching and Transition Stations	400 kV	220 kV	150 kV
<b>Alqueva</b> (not shown in figure 4.6(a))	<b>256 and 254</b>	X		X		
<b>Frades II /Vila Nova III</b>	<b>736</b>		X	X		
<b>Salamonde II</b>	<b>220</b>		X	X		
<b>Foz Tua</b>	<b>251</b>	X		X		
<b>Baixo Sabor</b>	<b>148</b>	X			X	
<b>Aguieira</b>	<b>336</b>		X		X	
<b>Torrão</b>	<b>140</b>	X			X	
<b>Alto Rabagão</b>	<b>68</b>	X				X
<b>Frades I / Venda Nova II</b>	<b>191</b>	X				X
<b>Vilarinho das Furnas</b> (Group 2)	<b>125</b> (Total)		X			X

Table 6.4: Dams with pumping and respective installed capacity, and their connection to the national very high voltage transmission network.

Following the mentioned criteria, from thirty nine possible locations remained nine. Figure 6.3 shows the nine locations selected (numerical labelled yellow square), and an example of one location that proved to be unfeasible (red square). Like this location example, all the other discarded locations did not respect the first criteria. Each viable location has been assigned a number so that it can be more easily referred to. Figure 6.4 shows the location to which label 1 was assigned. This location is close to the Bodiosa substation (400 kV) and its lower reservoir would use part of the Vouga river. Thus it would only be necessary to build the upper reservoir from square one. Regarding the other locations, these are some of their geographical characteristics:

• **Location 2:**

- Proximity to Chafariz substation (220 kV);
- Proximity to wind farms (ex: Vale de Estrela (25 MW)).

• **Location 3:**

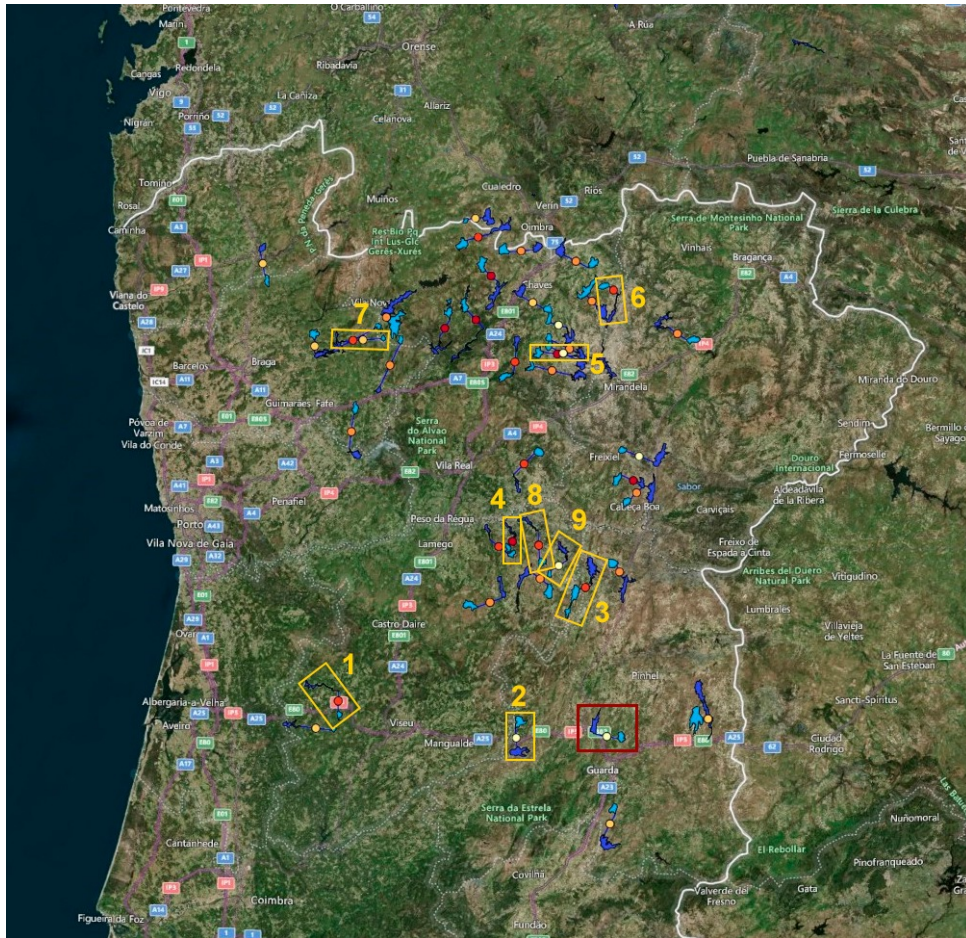


Figure 6.3: Selected locations, and an example of a non viable location in Portugal.

- Proximity to Pocinho substation (220 kV);
- Proximity to wind farms (ex: Trancoso (28 MW)).
- **Location 4:**
  - Lower reservoir would be a section of the Távora river;
  - Proximity to Armamar substation (400 kV / 220 kV);
  - Proximity to wind farms (ex: Douro Sul (140 MW)).
- **Location 5:**
  - Proximity to Valpaços substation (220 kV).
- **Location 6:**
  - Lower reservoir would be a section of the Rabaçal river;
  - Proximity to Valpaços substation (220 kV).
- **Location 7:**
  - Lower reservoir could be a use of the reservoir of the Ermal Dam;

- Proximity to Vieira do Minho switching station (400 kV);
- Proximity to wind farms (ex: Lomba do Vale (21 MW));

• **Location 8:**

- Lower reservoir would be a section of the Torto river;
- Proximity to Armamar substation (400 kV / 220 kV);
- Proximity to Valeira switching station (220 kV).

• **Location 9:**

- Lower reservoir would be a section of the Torto river;
- Proximity to Pocinho substation (220 kV);
- Proximity to wind farms (ex: Alto Douro (250 MW)).

The images of the remaining selected locations can be found in the appendix A.1. Figure 6.5 shows the

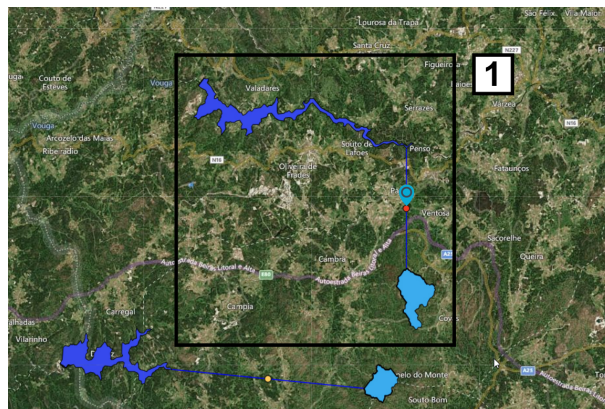


Figure 6.4: Aerial view of location number 1.

close-up of the location that proved to be an unfeasible option. As seen in the figure, the upper reservoir overlaps a village, depicted by the yellow square, and the lower reservoir overlaps a motorway, depicted by the red square. Table 6.5 shows for each chosen location some main features such as:

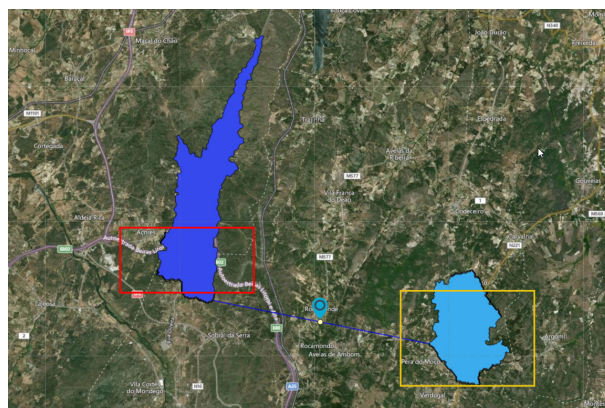


Figure 6.5: Aerial view of a non viable location.



Location	Head (m)	Separation (km)	Average Slope (%)	Volume (GL)	Class
1	699	5.3	13	102.9	B
2	269	5.1	5	265.5	E
3	290	2.8	10	247.3	B
4	722	2.3	35	99.5	C
5	520	7.7	7	137.5	A
6	429	3	14	166.4	B
7	722	10.1	7	100.1	D
8	540	7.1	8	132.1	B
9	496	5	10	145.2	E

Table 6.5: Characteristics of the possible 9 locations.

- **Head** (m): minimum altitude difference between potential upper and lower reservoirs;
- **Separation** (km): minimum horizontal distance between potential upper and lower reservoirs
- **Average Slope**: ratio between the head and the separation;
- **Water volume** (Gl): water capacity of the upper reservoir;
- **Class**: cost of a site according to an approximate cost model.

## 6.4 Results

This section will bring together the results of sections 6.2 and 6.3 in order to achieve the objective of determining how many and which locations are the most suitable for the installation of PHS in Portugal. Recalling table 6.3, depending on the desired percentage of satisfied hours studied the required number of PHS installations should be equal to 3, 4, 5, 8, 10, 17 or 26. However, in section 6.3 it was concluded that there are only 9 viable locations to implement PHS. Thus the situations where 10, 17 or 26 PHS schemes would have to be installed will be discarded as there are not enough locations. In short, the possibilities that remain are as follows:

- Install three PHSP and be able to satisfy 80% of the unmet demand hours for any of the generation increase scenarios;
- Install four PHSP and satisfy 85% of the unmet demand hours considering the increase pair ( $W = 3, S = 18$ ), or 90% considering the pair ( $W = 3, S = 25$ );
- Install five PHSP and satisfy 95% of the unmet demand hours considering the increase pair ( $W = 3, S = 25$ );
- Install eight PHSP and satisfy 100% of the unmet demand hours considering the increase pair ( $W = 3, S = 25$ ).

Therefore, eight of the nine possible locations should be chosen, as eight is the maximum number of installations that it is required. The selection of the eight locations was made according to the following criteria:

- Head;
- Class;
- Separation;
- If the lower reservoir is part of a river.

Taking into account the criteria, the best locations are those with higher heads, lower cost class, smaller separation and if its lower reservoir uses part of a river (lower construction costs). Each location will be awarded a score, and the locations with higher scores will be the selected ones. The score for each location comes from the equation 6.3, which acts as a cost function.

$$C = C_{Head} \cdot W_h + C_{Class} + C_{Separation} + C_{LowerRes} \quad (6.3)$$

where:

- $C$  is the total cost;
- $C_{Head}$  is the cost associated with the head of the location;
- $W_h$  is the weight attributed to the head;
- $C_{Class}$  is the cost associated with the class of the location;
- $C_{Separation}$  is the cost associated with the separation of the location;
- $C_{LowerRes}$  is the cost associated with using part of a river as a lower reservoir;

It is important to note that since the values of each location characteristic (see 6.5) are of different orders of magnitude it is necessary to map the value range of each characteristic to a range in which the values are normalized. For this purpose, a mapping function was created which performs a linear interpolation of the characteristic values of the locations, as shown in the equation 6.4. The mapping function is only used for mapping the head, class and separation costs. This equation can be obtained through the linear equation  $y = m \cdot x + b$  knowing two points in advance,  $(x_{min}, new_{min})$  and  $(x_{max}, new_{max})$ . Other equations could have been used, for example a quadratic equation, but the linear equation yielded satisfactory results. Additionally it was considered that having a higher head was more important than the other criteria, and for that a weight of 1.1 (+10%) is multiplied to the cost of the head.

$$C_y = (x - x_{min}) \cdot \frac{(new_{max} - new_{min})}{(x_{max} - x_{min})} + new_{min}; \quad (6.4)$$

where:

- $C_y$  is the new value of the criteria;
- $x$  is the value to be mapped;
- $x_{min}$  is the lower limit of the interval containing  $x$ ;

- $x_{max}$  is the upper limit of the interval containing  $x$ ;
- $new_{max}$  is the upper limit of the interval where  $x$  is going to be mapped;
- $new_{min}$  is the lower limit of the interval where  $x$  is going to be mapped;

An example that explains the effect of the mapping function is the mapping of the head interval from [699; 269; 290; 722; 520; 429; 722; 540; 496] to [9.57; 3.49; 3.79; 9.90; 7.04; 5.75; 9.90; 7.32; 6.70].

For the head and separation the output range of mapped values is [1, 10] and for the class is [5, 10]. For using a river as lower reservoir the cost is binary, and equal to 0 or 3. Figure 6.6 shows the score of each location after applying the cost function. By analysing figure 6.6 it is possible to conclude that location 4 is the location with the highest score, and that 2 is the location with the lowest score. As mentioned above, in order to satisfy the cases considered, it is necessary to choose the three, four, five and eight locations best groups. Thus the location selection resulted in the following groups:

- **Best 3 Locations Group:**
  - 4, 1, and 6;
- **Best 4 Locations Group:**
  - 4, 1, 6, and 8;
- **Best 5 Locations Group:**
  - 4, 1, 6, 8, and 5;
- **Best 8 Locations Group:**
  - 4, 1, 6, 8, 5, 7, 3, and 9;

Analysing figure 6.6 it is possible to verify that the locations with the highest head have, in principle, the highest scores, which reflects its importance when choosing a PHS installation site. The relevance of

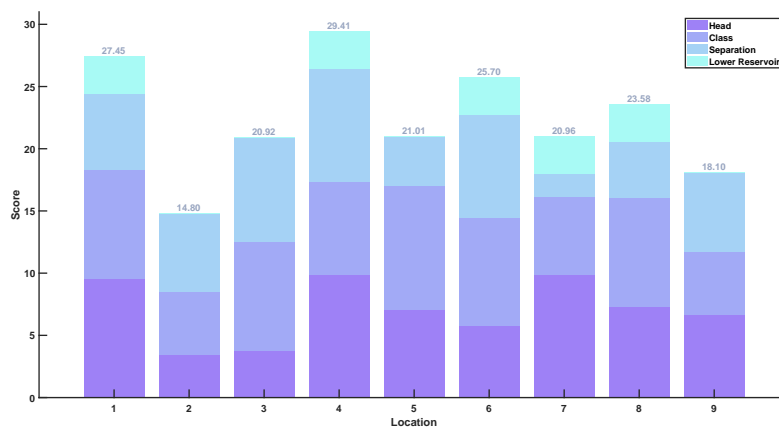


Figure 6.6: Total score for each of the nine locations analysed.

having a high head lies on the fact that it reduces the cost associated with the turbine, because a higher

head allows a lower flow for a given power. Having the lower reservoir be a part of a river, although advantageous, was not considered a decisive criteria when classifying a location. Overall, the 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. Since location 2 had the worst score (lowest head of the possible location group) it was the one eliminated from the selection. As there were only nine viable locations to select, only one location was discarded. 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. And the best locations are, in order of their score according to the chosen criteria: location 4, 1, 6, 8, 5, 7, 3 and 9.

# Chapter 7

## Conclusions

This dissertation aimed to verify the possibility of implementing pumped hydro storage in Portugal in order to complement wind and solar energy, so that electricity consumption would only be satisfied by these resources. Besides, possible locations were studied to determine which ones were suited for the required purpose.

Pumped hydro storage was traditionally used to smooth load variations on the power grid. Nowadays, there is an interest in implementing PHS to complement variable output sources, such as wind and solar. Pumped hydro storage can reduce the fluctuations introduced in the grid by intermittent sources by storing surplus energy and providing it when needed. The main disadvantage of PHS is the need for locations with specific geographical features, however due to the Portuguese topology, this is not a decisive factor against implementing PHS in the country. In Portugal, pumped hydro storage is not present in off-stream PHS form, as it only exists in dams with a reversible turbine/pump configuration, although the Gouvães PHSP (Alto Tâmega project) is being built and is scheduled to begin operations in 2021.

Analysing the Portuguese consumption and generation landscape during 2018, it was possible to see that wind and solar generation suffers a lot of variations. Wind generation tends to be higher in the first and last three months of the year, and lower during the summer. Whereas, 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. Considering these results, it is not viable to install PHS if there is no increase in installed capacity. Three scenarios where wind and solar generation was increased were considered, but only two proved to be sufficient to meet demand, and justify the use of PHS. In both, wind generation was increased by a factor of 3, but the first increased solar by a factor of 18, and the second by a factor of 25. Both scenarios have advantages and caveats.

The ( $W = 3, S = 18$ ) scenario is more realistic, but the majority of its excess energy is generated during 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 pumped storage operation for the different scenarios considered, it was possible to validate that implementing PHS is only viable when there is considerable surplus energy that can be relocated to meet demand. Out of the scenarios considered, only ( $W = 3, S = 18$ ) and ( $W = 3, S = 25$ ) justify the use of PHS. Depending on the required percentage of satisfied hours, the needed storage capacity of the reservoirs is different, with larger reservoirs allowing higher percentages of satisfied hours. For scenario ( $W = 3, S = 18$ ), it is possible to reach 95% of satisfied hours using a reservoir of 2.6 TW h, and 100% with a reservoir of 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. Another factor that must be considered is the installed capacity. To guarantee that all hours are satisfied, the 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, meaning that if there is an installed capacity limit, the same can be respected while satisfying a high percentage of hours. In this case by installing 4.55 GW instead of 8.04 GW, it is still possible to satisfy 95% of the hours.

The study used to analyse PHS locations, presented 38 possible locations in Portugal with 150 GW h of storage capacity, all located in the northern part of the country. The possible locations were analysed, and in only 9 of them, the correspondent reservoirs do not overlap with small towns and 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. Considering scenario ( $W = 3, S = 18$ ), it is only possible to satisfy 85% of hours if 4 installations of PHS with 1.1 GW installed capacity are implemented, because the number of needed installations surpasses the number of possible locations. For scenario ( $W = 3, S = 25$ ), it is possible to satisfy 100% if 8 similar installations are implemented. 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.

## 7.1 Future work

This thesis allows for two main roads of future work. The first is related to the consumption and generation data used, and the second is related to the locations of the PHSP.

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.

The locations studied were obtained from the Global Pumped Hydro Atlas project [9], which means that there are possibly other locations, not included in this study, that can prove to be viable or even better options than some of the selected ones. Still regarding the chosen locations, a network including the PHS facilities and wind and solar parks could be created, and its respective power flow could be studied.





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# Appendix A

## Locations

### A.1 Locations Selected

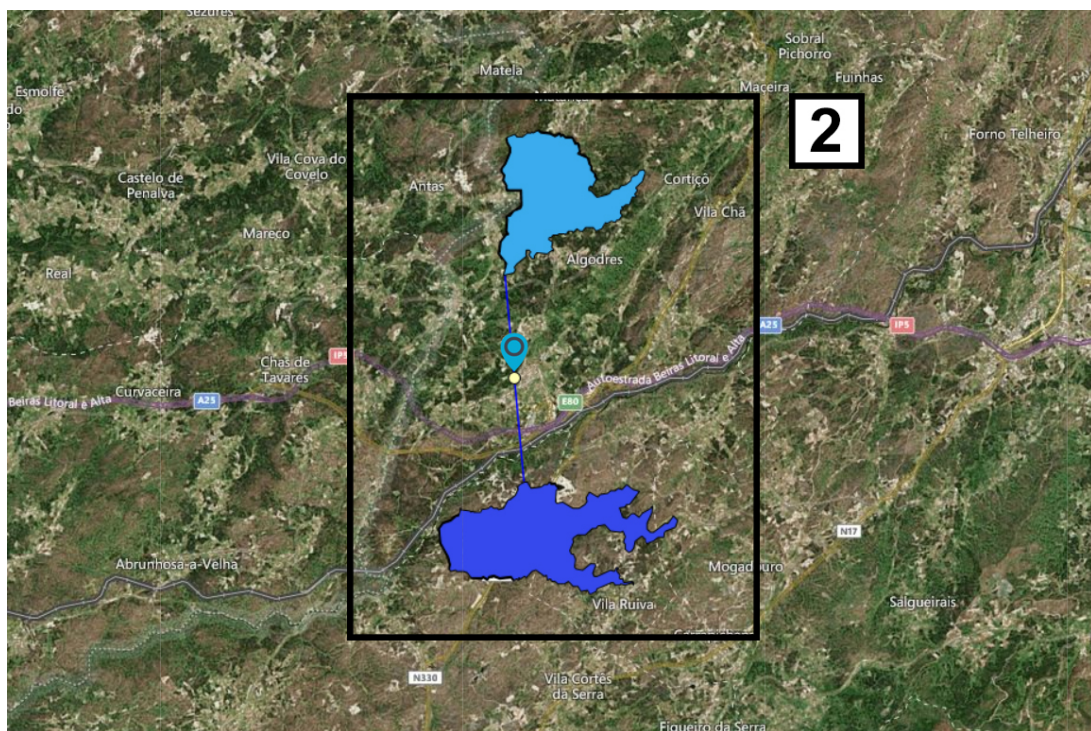


Figure A.1: Aerial view of location number 2.

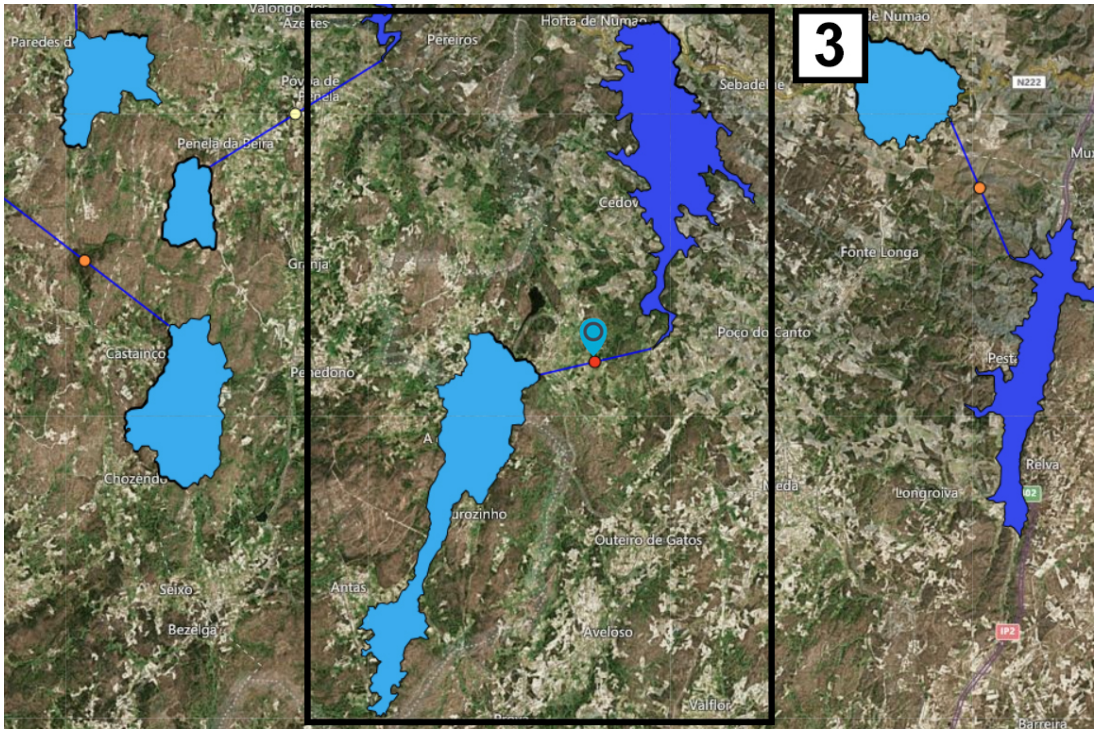


Figure A.2: Aerial view of location number 3.

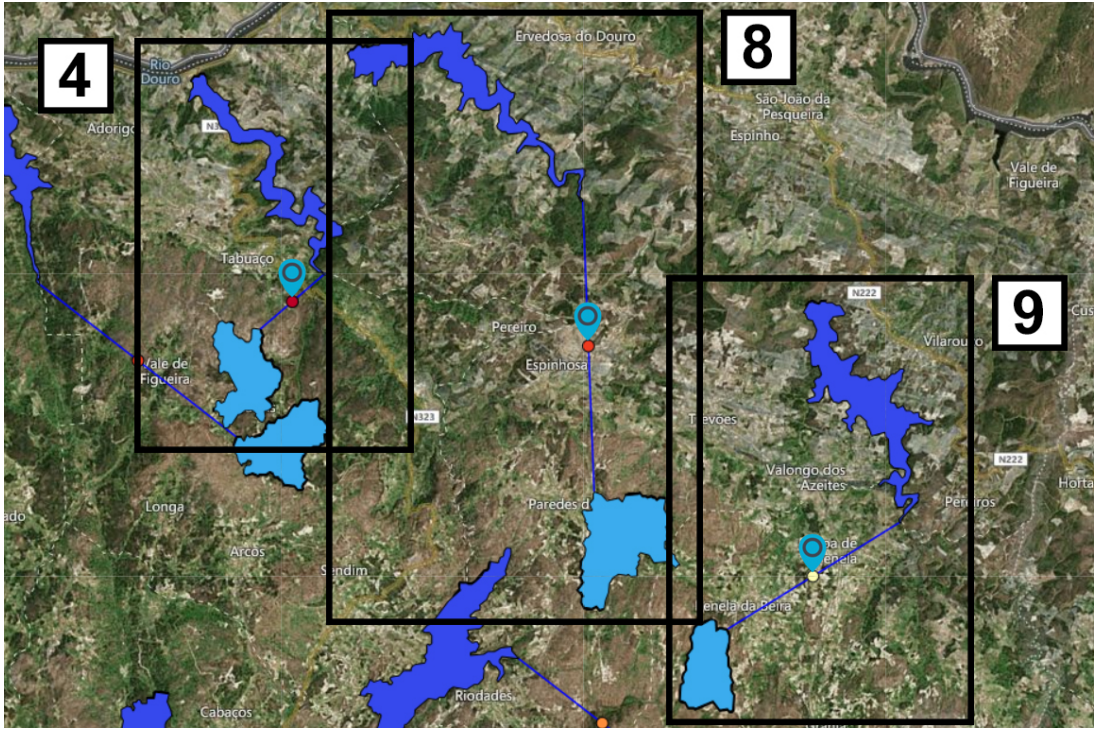


Figure A.3: Aerial view of locations number 4, 8 and 9.

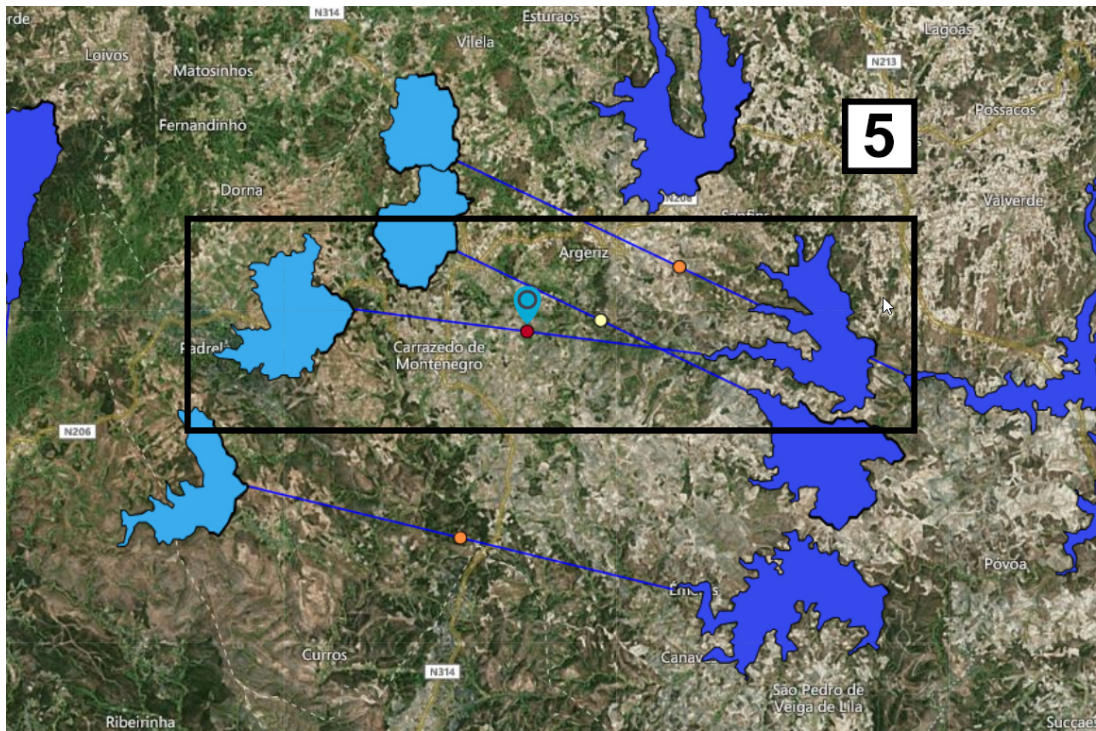


Figure A.4: Aerial view of location number 5.

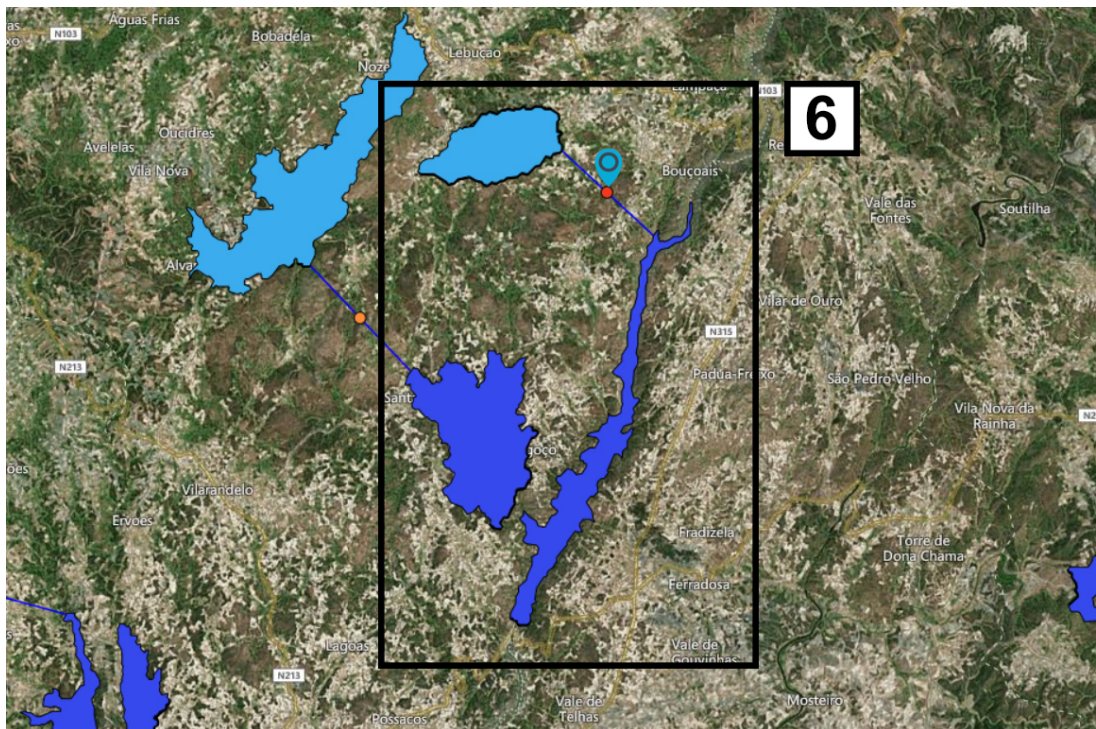


Figure A.5: Aerial view of location number 6.

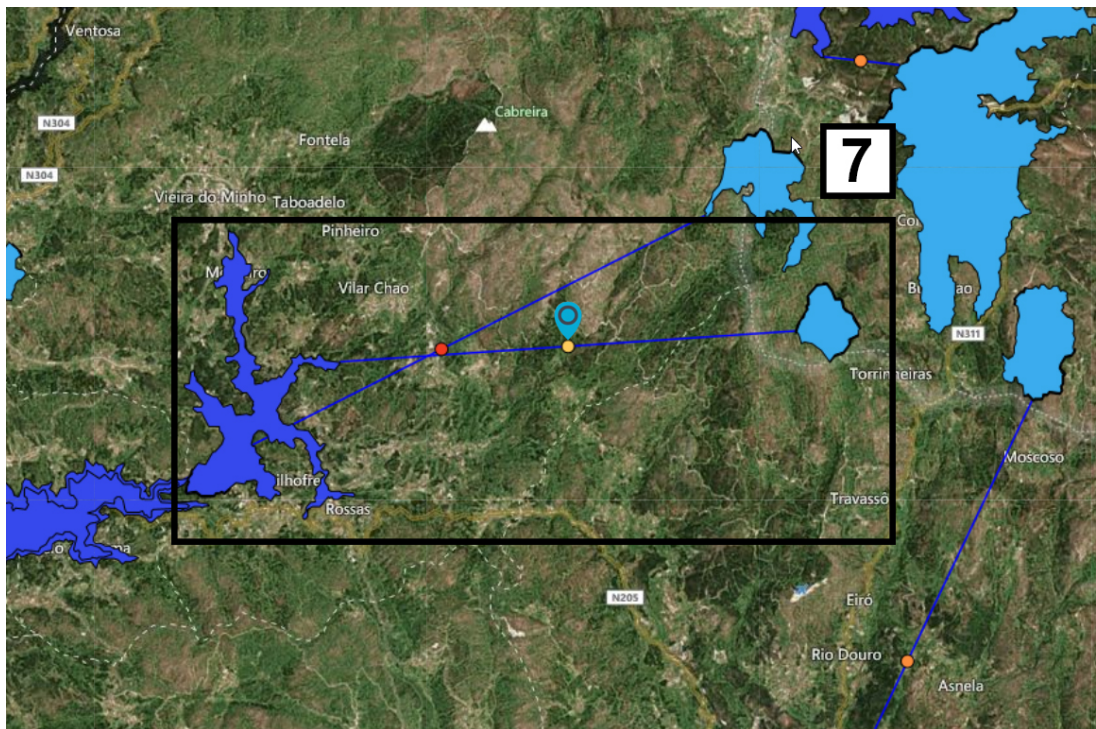


Figure A.6: Aerial view of location number 7.