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Master of Science in Energy Engineering

Pumped Hydroelectric Storage Systems: Technical Review and Economic Assessment

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Abstract

Pumped Hydroelectric Storage systems are the most mature and commercially developed technology for storing large quantities of energy. The technology may bring great added value for the upcoming era, due to its capability of managing the surplus of energy generated on the electrical grid, to promote the penetration of renewable energy sources and so the reduction of fossil fuels use. The new energy policies and possible benefits from the Pumped Hydroelectric Storage have led to the construction of new facilities in Europe, such 880 MW (Gouvães) in Portugal, 360 MW (Obervermuntwerk II) in Austria, 1000MW (Kaniv) in Ukraine, 200 MW (Soria-Chira) in Spain.

Many studies have been carried out discussing its benefits from several perspectives. The present work aims at investigating the economic profile of a Pumped Hydroelectric Storage system, to understand the variables that affect the profit and the way they interconnect with each other in order to maximize it. The study focuses on the Italian and Portuguese energy markets and studies different operational strategies to investigate the possible economic outcome in both countries. The operational strategies use price thresholds to define the moments in which the PHSs should generate or pump energy. In addition, several hypotheses are considered with respect to the PHS working capacity: either the system works under the current PHSs' use trends (OS 1), or as an ideal system working with an on/off function at full installed capacity (OS 2), or lastly as a system whose power increases gradually, depending on the price variation (OS 3), until reaching the installed capacity.

The assessment results show that the same operational strategy presents a different optimal exploitation strategy for the Italian and Portuguese cases and, more importantly, that there are significant possibilities for current facilities to have a larger participation in the respective energy market, leading to both increased renewable sources exploitation and higher revenues for the storage systems. More specifically, OS 2 is the operational strategy that better performs in terms of maximized profit, for both countries. Indeed, the yearly maximized profit under OS 2 is 290 million € and 118 million € for Italy and Portugal respectively, compared to 58 and 57 million € for the same countries in OS 1 (worst performing strategy).

Keywords: Pumped Hydroelectric Storage; Energy market; electricity price.

Sommario

I sistemi idroelettrici a pompaggio sono la tecnologia più matura e sviluppata a livello commerciale per stoccare grandi quantità di energia. Data la loro capacità di gestire i surplus di energia generata e immessa nella rete elettrica, questa tecnologia potrà dare un forte contributo nel futuro alla penetrazione delle fonti energetiche rinnovabili nel mercato energetico e alla conseguente riduzione dell'uso dei combustibili fossili. Le nuove politiche energetiche e i possibili benefici derivanti dall'uso dei sistemi PHS hanno portato e porteranno alla costruzione di nuovi impianti in Europa, con dimensioni pari a 880 MW (Gouvães) in Portogallo, 360 MW (Obervermuntwerk II) in Austria, 1000MW (Kaniv) in Ucraina e 200 MW (Soria-Chira) in Spagna.

Molti studi sono stati fatti sui benefici di tale tecnologia, affrontando l'argomento da diversi punti di vista. Il presente lavoro punta a analizzare il profilo economico di un sistema PHS, in particolare andando ad analizzare le variabili che influenzano il profitto del sistema e come esse si interconnettono per massimizzarlo. Lo studio si concentra sui mercati energetici italiano e portoghese e applica diverse strategie operative (SO) per massimizzare il profitto in entrambi i paesi. Le SO usano soglie di prezzo per definire i momenti in cui il sistema PHS deve generare o pompare energia. Inoltre, vengono considerate diverse ipotesi sulla capacità di sfruttamento del PHS : si assume che il sistema venga esercitato in accordo con gli attuali trend di funzionamento del PHS, basati sugli esiti del mercato elettrico (SO 1), oppure mediante un funzionamento ideale di tipo on/off disponendo della piena capacità installata (SO 2), o ancora che il sistema lavori con variazioni di potenza graduali e dettate da segnali di prezzo, fino a raggiungere la piena capacità (SO 3).

I risultati dello studio mostrano che la stessa SO presenta una metodologia di sfruttamento differente per i casi italiano e portoghese. Inoltre, evidenzia che gli impianti attualmente in uso possono incrementare la propria partecipazione al mercato energetico, con l'obiettivo di aumentare sia lo sfruttamento di risorse rinnovabili che i profitti del PHS. In particolare, SO 2 è la SO che presenta migliore performance in termini di massimizzazione del profitto, per entrambi i paesi. Infatti, il profitto annuale massimizzato con SO 2 è di 290 milioni di € per l'Italia e di 118 milioni di € per il Portogallo, paragonato a 58 e 57 milioni di € per gli stessi paese in SO 1 (peggiore performance).

Parole chiave : Sistemi idroelettrici di pompaggio, mercato eletrico, prezzo dell'elettricità

Introduction

This thesis aims at investigating the economic profile of a Pumped Hydroelectric Storage system, whose contribution to the energy market, especially in terms of supporting the use of renewable energy sources and improving energy management services, is already widely recognized and studied in literature.

In **Chapter 1** an introduction on the world's future energy demand is given based on studies from the principal energy agencies in world. Moreover, the thesis analyses the present and future energy demand in Italy and Portugal. The objectives of the thesis are explained.

Chapter 2 presents a literature review on the main Energy Storage Systems and new developments on each technology. More into detail, it focusses on the history of Energy Storage Systems, the classification of the Energy Storage System according to the form of energy under which the storage is done and an assessment of the Energy Storage System depending on their main characteristics and functionalities.

Chapter 3 deepens the knowledge of the Pumped Hydroelectric Storage, explain the possible types and main advantages of each system. The chapter also lists the Italian and Portuguese Pumped Hydroelectric Storage, which will be used for the simulation, and the main Pumped Hydroelectric Storage in the world.

Chapter 4 differentiates the regulated and liberalized markets. After a contextualization, an explanation of each type of market (such as day ahead market or future market) is given for Italy, Portugal, Australia and U.S.A.

In **Chapter 5** a graphical analysis from the energy generated and energy pumped, and the electricity price is done for both Italy and Portugal. The chapter reviews the direct correlations between the electricity price and the two types of energies. Other complementary studies consist on understanding how the hours of the day and the different seasons of the year affect the energy generated, energy pumped and price variation.

Chapter 5, with the help of the multiple linear regression and the graphical analysis, uses several variables to describe the energy generated and energy pumped trends into equations for 2017 in Portugal and Italy. The variables modelling the energy equations could be related with price, such as ratio between maximum and minimum daily price or average of the 5th highest prices of the day, or time based, such as seasons or hour periods.

Chapter 6 asses three possible operational strategies to explore the Italian and Portuguese PHS potential, with the purpose of obtaining the maximum highest profit. Each operational strategy, expressing its formulation and main assumptions. Next, an analysis of the results is discussed, in order to choose the operational strategy which, maximize the maximum profit.

Lastly, the main conclusions and possible future developments are defined.

1 Future energy demand

According to the US Energy Information Agency and the International Energy Agency, the world's energy demand will expand by 30% by 2040. The expected growth is a result from an estimated global economic increase of 3,6% yearly and an expansion of the population from today 7,4 billion to approximately 9 billion in 2040.[1]

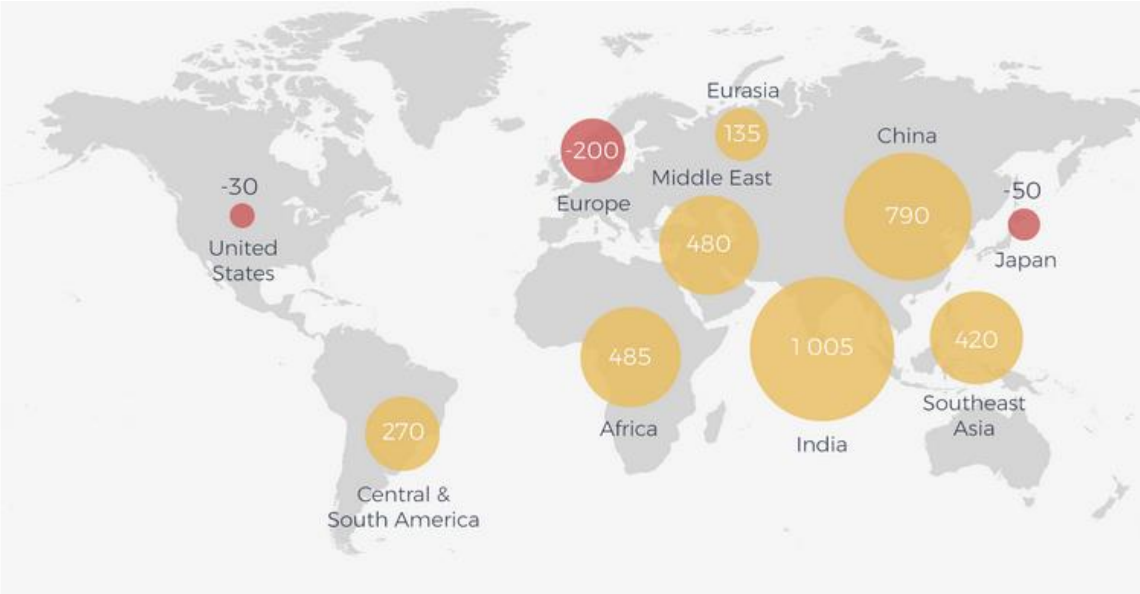


Figure 1 Change in primary energy demand (Mtoe) from 2016 to 2040[1]

The World Energy Outlook 2017's New Policies Scenario expects a considerable decrease of energy demand in Europe, around 200 Mtoe, due to European Council environmental policies and 2030 Framework for climate and energy. The 2030 Framework for climate and energy aims to obtain a more secure and sustainable energy system in the EU to promote the long-term greenhouse gas reduction targets by 2050. The strategy of reduction passes by the increase of renewable energies and energy efficiency and encouraging private investors in using low-carbon technology, restoring pipelines and net electrical grids.

The New Policies Scenario assumes an expansion close to 2200 Mtoe in India, China and Southeast Asia, which is the equivalent as adding China or India's current consumption to 2016 world consumption. According to US Energy Information Agency's International Energy Outlook 2018, the energy consumption growth is related to development of the economy in this region. India's energy production growth is explained by being the world's largest population in 2040 and the fastest growing economy, directly related to the increase of exports and industrial development.

On the other hand, China presents a stable demography, but the raise of GDP aligned with China's high energy intensity requirement leads to an increase of the energy demand. This energy consumption growth can be up to 25% or 20% by 2040[2][3], depending on the penetration of renewable energy sources and energy storage, if the Fast Transition Scenario defined by 2040 occurs. The Fast Transitions Scenario assumes a growth of 60% of China's personal consumption share of GDP by 2040, instead of the 50% estimated by the International Energy Outlook 2017. As seen in Figure 2 it is expected to reach a total primary energy demand of nearly 18000 Mtoe yearly.

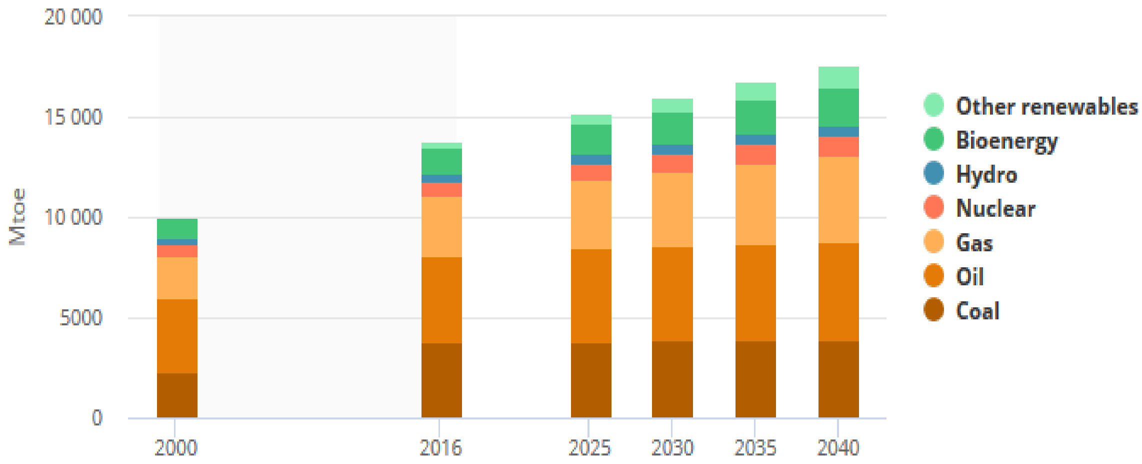


Figure 2 Total Primary Energy Demand, New Policies Scenario (World Energy Outlook 2017)

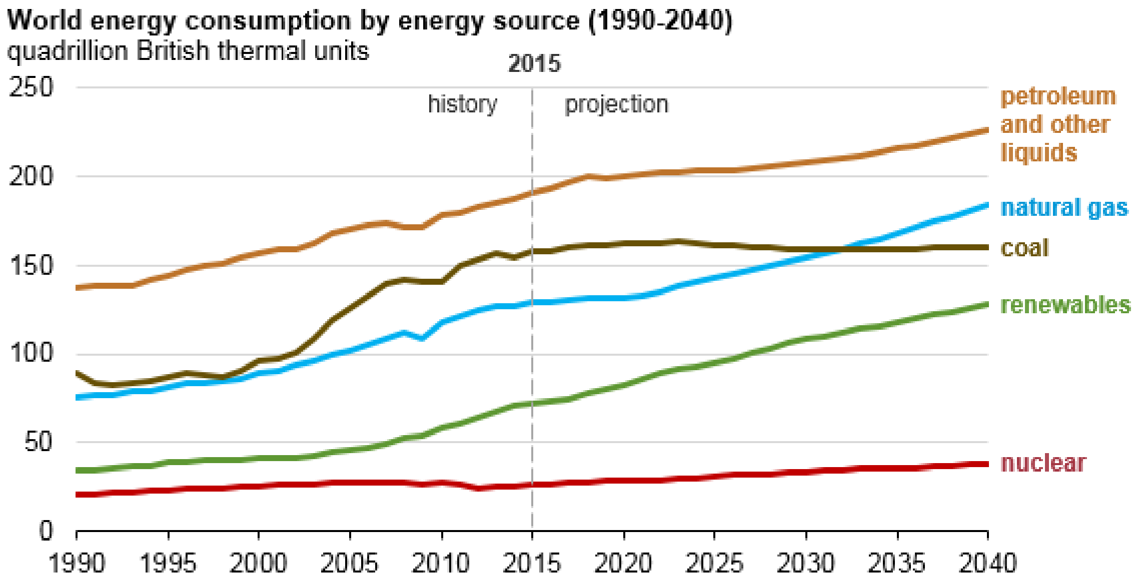


Figure 3 Change in primary energy demand from 1990 to 2040, International Energy Outlook 2017

Before analyzing the two scenarios, in Table 1, it is important to recall the energy unit conversion to the International System of Units: while 1 quadrillion British thermal unit (BTU) is equivalent to $1{,}055 \times 10^{12} MJ$, 1 million tons of oil equivalent (MTOE) equals to $4.187 \times 10^{10} MJ$. Thus, 1 quadrillion BTU corresponds to 25,22 MTOE.

In a quick assessment the two scenarios project that:

- After 2016 the world coal consumption for energy purpose stabilizes;
- Petroleum and other liquids present a considerable raise in the IEO 2017 and a small growth in the new policies scenarios;
- The natural gas presents the highest growth among the fossil fuels for both scenarios;
- The nuclear energy presents a small growth on both scenarios;
- The renewable energy estimated increase is approximately 78%.

Table 1 Comparative assessment between the New Policies Scenario 2017 and International Energy Outlook 2017

	New policies scenario - 2016	New policies scenario - 2040	International Energy Outlook - 2040
Unit	Mtoe	Mtoe	Mtoe
Coal	3755	3929	4057.2
Oil	4388	4830	5152.5
Natural Gas	3007	4356	4586.4
Nuclear	681	1002	957.6
Renewable Energies	1929	3467	3250.8

1.1 Europe's future energy demand

Since the beginning of the century, Europe has acknowledged the energy and climate problems affecting the world. Major and ambitious plans have been designed for the mitigation of negative environmental impacts, since the reduction of primary energy consumption and the increase the energy conversion efficiency. The European Institutions funded thousands of projects through partnerships with private companies, such as the EU-storage (which promotes the pumped hydro storage plants), or by European organizations specialized on the subject to promote the decarbonization. One of the most important milestones is to reach the penetration of renewables by 27% on the energetic gross production.

The European Network of Transmission Systems Operator (ENTSO-E), which represents 43 transmission system operators from Europe, created the Europe Power System 2040. The purpose is to develop an electrical and gas grid that ensures the competitiveness and sustainability of the energy supplied in the regions. The infrastructure will provide the main support for the technological developments, allowing a reduction until 80% of the emissions for European Union in 2050[4].

The Figure 4 presents the possible scenarios for the energetic and power demand for the European Union country:

- Sustainable Transition (ST): Target reached through regulation, emission trading schemes subsidies, maximizing the use of the existing infrastructure;
- Distributed Generation (DG): Prosumers at the center-small scale generation, batteries and fuels switching society engaged and empowered;
- Global Climate Action (GCA): Full speed global decarbonization, large-scale renewables development in both electricity and gas sector;
- EUCO3: is a core policy scenario produced by the European Commission. The scenario models the achievement of the 2030 climate and energy target as agreed by the European Council.

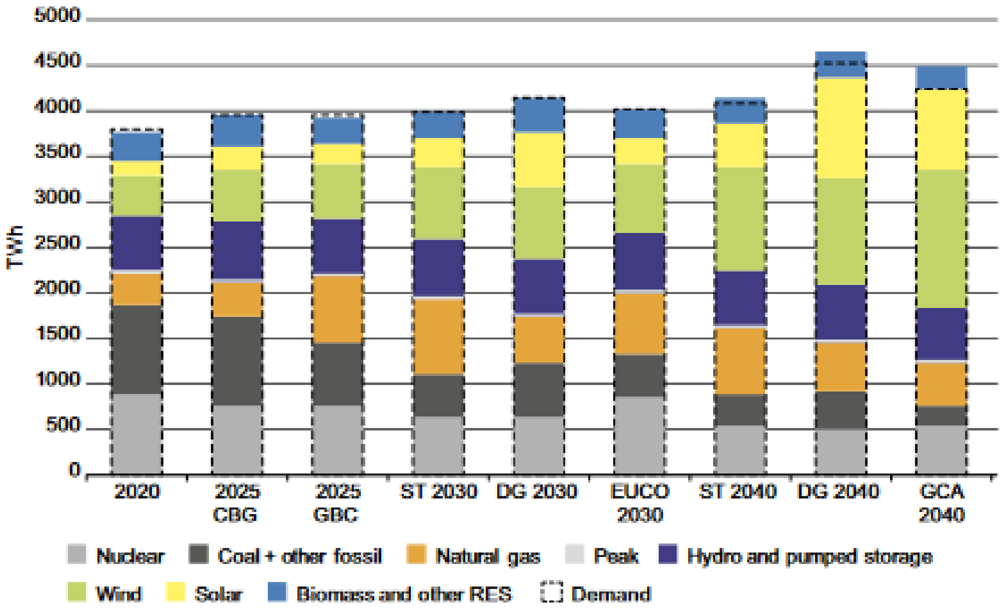


Figure 4 European Energetic Generation and Consumption Scenarios - TYNPD 2018

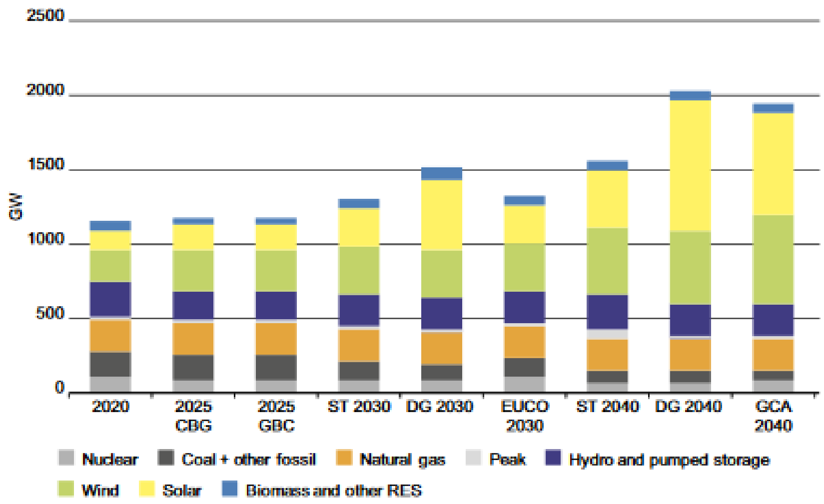


Figure 5 European Installed Production Capacity Scenarios - TYNPD 2018

The main tendencies of the scenarios are a reduction of the Nuclear energy production and a clear reduction of the coal and other fossil fuels. On the other hand, there is an increase on the Natural Gas dependency, Wind and Solar Energy. The levels of hydroelectric and pumped storage and biomass will remain constant.

1.2 Italy's future energy demand

With all Europe moving forward to a better reach the objective of 80% emission reduction, Italy is laying down several actions to achieve this direction. The Italian National Energy Strategy 2017 plan presents 3 main aims:

- Increase Italy's competitiveness in the energy market;
- Attain Europe's environmental and decarbonization targets by 2030 in sustainable ways;
- Improving the security of energy supply and flexibility of the energy systems and Infrastructures.

Table 2 Price of energy in some European Energy Market- GME[5]

Cost of energy in €/MWh	**Area**	**2017**
Ipex	Italy	54,0
Powernext	France	45,0
EEX	Germany	34,2
Ornel	Spain	52,2
NordPool	Scandinavian countries	29,4

As we can see from Table 2, Italy presents the highest cost of energy in the European continental region. According to the “Ministero dello Sviluppo Economico” in 2016 the gap between the natural gas costs from Italy and North European countries was 2 €/MWh. The same Ministry concluded that the average Italian family pays nearly 35 €/MWh above the European Union average. The study also concludes that it is crucial to increase the reliability and security of the grid, to reduce the energy import from the neighbor countries.[6]

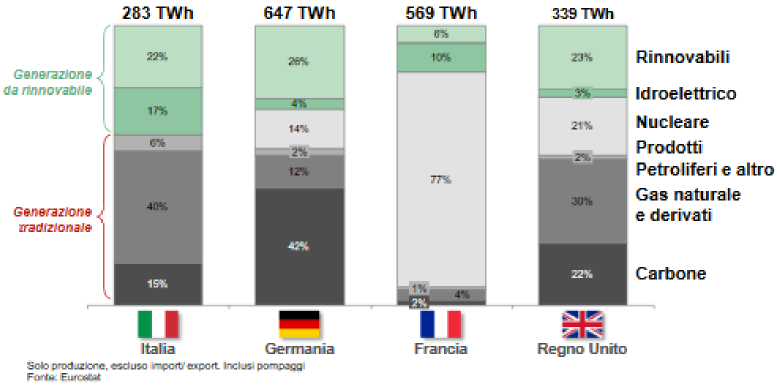


Figure 6 Electricity generation in 2015, source: Eurostat

Although Italy requires importing energy from their neighbor countries, the gross energy generation presents a penetration from renewables energies of 27%. According to “Strategia energetica nazionale 2017”, in 2016 the renewable sources supplied 17,5% of the gross energy consumption with influence in the electricity and heat production. The Italian national energetic policy emphasis the importance of increasing the renewables penetration to reach the European milestone for 2030. It also expects that this growth and energy efficiency developments/improvements will reduce the cost of renewable energy electricity cost.

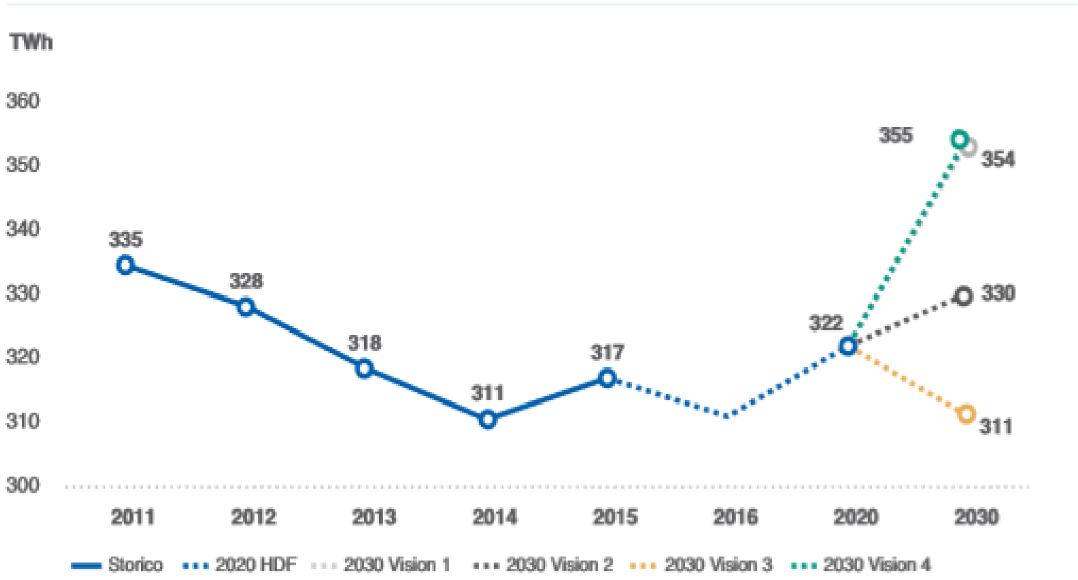


Figure 7 Estimated energy demand evolution in Italy, source: Terna & ENTSO-E TYNDP 2016

ENTSO-E, with the consultation of Terna (Italian transmission network operator) (Figure 7), through the study "Scenari della domanda elettrica in Italia" estimated several scenarios for the future energy development in Italy. The analysis assumed the development of electrical cars and heat pump influence on the electrical demand. Furthermore, the study considers that energy efficiency reaches the objectives (at the desired milestone).[7]

In each scenario different hypothesis are assumed, by changing characteristics such as the diffusion and types of energy storage, expansion of the smart grids, objectives of the decarbonization, cost of fuels and the possibility of stocking CAES with carbon. There are 4 main visions:

- Slowest progress V1;
- Constrained progress V2;
- National green transition V3;
- European green revolution V4.

The Visions 1 and 3 were predicted by Terna and the Visions V2 and V4 were studies developed from ENTSO-E based on the previous. The Table 3 shows the characteristics of each scenario.

Table 3 Characteristics of the vision scenarios on the possible energetic demand in Italy - Terna & ENTSO-E 2016

	Slowest progress (VI)	Constrained progress (V2)	National green transition (V3)	European green revolution (V4)
Economie and financial conditions	Leastfavourable	Less favourable	More favourable	Mostfavolrable
Focus of energy policies	National	European	National	European
Focus of R&D	National	European	National	European
CO_2 and primary fuel prices	low CO_2 price, high fuel price	low CO_2 price, high fuel price	high CO_2 price, low fuel price	high CO_2 price, low fuel price
RES	Low national RES (>= 2020 target)	Between V1 & V3	High national RES	Ontrackto 2050
Electricity demand	Increase (stagnation to small growth)	Decrease compared to 2020 (small growth but higher energy efficiency)	stagnation compared to 2020	Increase (growth demand)
Demand response over Demand (%)	As today (0%)	Partially used (5%)	Partially used (5%)	Fully used (20%)
Electric vehicles over Demand (%)	No commercial break through of electric plug-in vehicles (0%)	Electric plug-in vehicles (flexible charging) (5%)	Electric plug-in vehicles (flexible charging) (5%)	Electric plug-in vehicles (flexible charging and generating) (20%)
Heat pumps over Demand (%)	Minimum level (1%)	Intermediate level (5%)	Intermediate level (5%)	Maximum level (9%)
Adequacy	National - not auto nomo us limited back-up capacity	European - less back-up capacity than V1	National - autonomous high back-up capacity	European - less back-up capacity than V3
Merit order	Coal before gas	Coal before gas	Gas before coal	Gas before coal
Storage	As planned today	As planned today	Decentrall zed	Centrall zed
Demand CAGR 2015-2030 (%)	+0.8%	+0.3%	-0.1%	+0.8%

1.3 Portugal's future energy demand

Similar to Italy, Portugal presents ambitious plans to follow the EU new policies. To promote the EU energy policies the Portuguese government established the "Plano Nacional Integrado Energia e Clima 2021-2030" in December 2018. The plan proposes to reduce by 17% the CO_2 emissions in relation to 2005 levels, the reinforcement of renewable energy sources, the improvement of energy efficiency (by reducing 35% the primary energy consumption) and the improvement of the electrical network within the country.

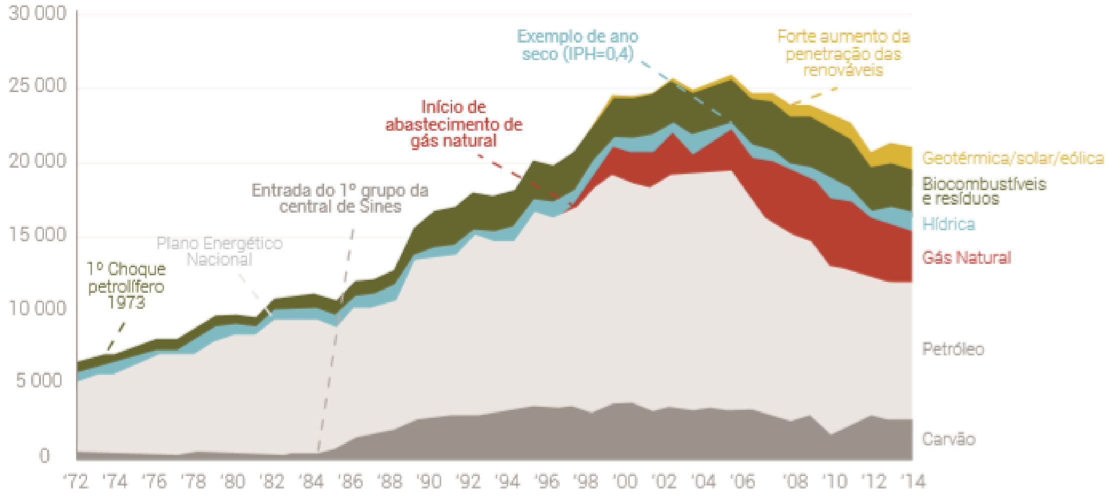


Figure 8 Primary energy consumption in Portugal from 72 to 2014, in ktoe [8]

The Figure 8 shows that the primary energy consumption in 2014 presents great dependence on fossil fuels, especially on oil. The combination of fossil fuels is slightly above 15 Mtoe (74%), while the mix of renewable energy sources totals between 5 and 6 Mtoe (26%). The introduction of renewable energy sources permitted to reduce the dependence on oil from 80% in 1972 to 50% in 2014.

Nonetheless, Portugal needs to import fossil fuels to satisfy the energy domestic demand. To reduce the energy import in the past decades the Portuguese government has made strong investments in solar, wind and geothermal technologies. Due to this strategy, Portugal managed to decrease their energy dependency to the exterior from 85% to 75% in the past 20 years.

Table 4 Projection of the renewable energies installed capacity (GW) by 2040, Portugal

	2015	2020	2025	2030	2035	2040
Hydroelectric	6,0	7,0	8,2	9,0	9,0	9,0
Wind	0,4	1,8	2,8	2,9	2,9	2,9
Solar	5,0	5,4	5,6	5,6	5,6	5,6
Others	0,3	0,5	0,5	0,5	0,5	0,5
Total	11,7	14,7	17,1	18,0	18,0	18,1

The Table 4 shows the projections of renewable energies installed capacity based on the current policy.

The Energias de Portugal (EDP) (privet company with main operations in production, distribution and commercialization) analyzed the energetic market based on the Portuguese national plan 2021-2030, through the Energy Outlook 2017. They identified 2 different scenarios:

- a thermal scenario, which presents low investments in renewable energies and in the network grid during the period and so focuses in the present technologies;
- a green scenario, where renewable energy sources and energy efficiency in the country are promoted, increasing the independence from fossil fuels.[8]

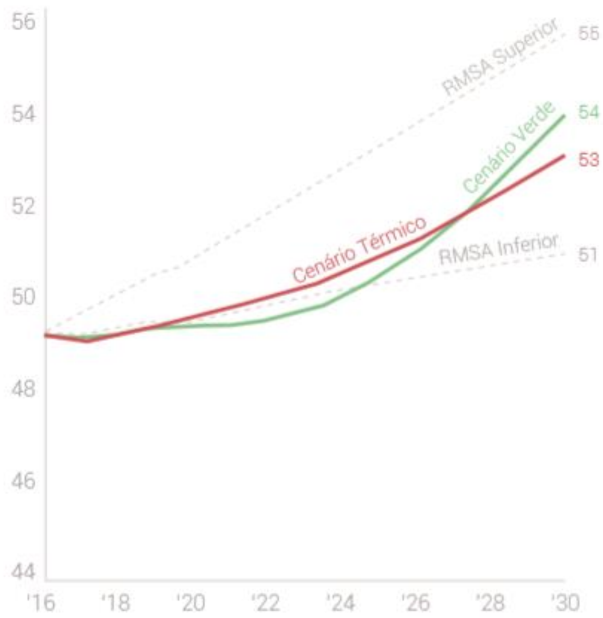


Figure 9 Energy demand (TWh) for continental Portugal, 2030; red curve- thermal scenario; green curve- green scenario

The Energy outlook 2007 from EDP (Figure 9) predicts that the green scenario's energy demand is slightly higher than the thermal scenario's, due to the increase in electrical cars (1,6 TWh) and Heating and Cooling (2,2 TWh). The thermal scenario assumes no increase Heating and Cooling between 2016 and 2030 and a growth of electric car energy demand of 0,2 GWh until 2030.

The Figure 10 shows Portugal's installed capacity and energy generation in 2016 and in the two scenarios in 2030. The thermal scenario's installed capacity presents a total 23 GW, with a participation of renewable mix of 71%. Observing the green scenario there is an increase in the installed capacity (30GW) and in the renewable mix 77%. This difference occurs mainly because of the contribution of solar PV, since in the green scenario it has a share of 19%. When analyzing the energy generation for both scenarios, the difference in the thermal plants' contribution is evident. While the thermal scenario has a share of 30% in the energy generated, the green scenario only uses 9% of thermal plants. Observing more carefully, we see an expected increase of 12% coming from the solar PV and 9% from the wind turbines.

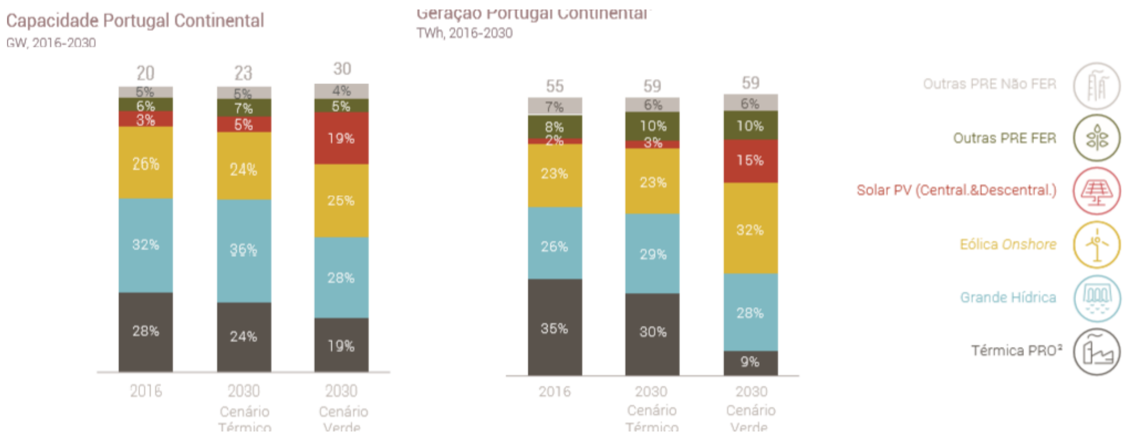


Figure 10 (left) Portugal installed capacity (right) Portugal Energy generation from 2016 until 2030

1.4 How can the Energy Storage systems contribute to satisfy the increase in Energy Demand

As referenced in the present chapter, the energy demand is increasing in most countries and a fast adaptation is required to mitigate negative impacts such as stresses in the world's resources, greenhouse gases emission and environmental damages. The necessity of reducing the energy generated from fossil fuels led many countries to prepare plans to promote the use of renewable energies and energy storage systems, with a view to increase energy efficiency.

In particular, the use of Energy Storage Systems, such as Pumped Hydroelectric Storage, is of increasing importance to the countries' future energy plans. These systems can manage the surplus of energy generated by the electrical network and promote the de-coupling from fossil fuels. Many studies have already been carried out on the benefits of these technologies, from several perspectives. This thesis aims at investigating the economic profile of a Pumped Hydroelectric Storage system, in particular to understand the variables affecting the profit and the way they interconnect with each other in order to maximize it.

The study focuses on data on the Italian and Portuguese energy markets, with a view to compare the results of the analysis. Italy and Portugal were chosen because both countries present ambitious energy policies for the European Commission (EC) energy and CO_2 emission reduction objectives. Moreover, the similarity of their region and their energy market make them interesting cases.

2 State of the Art of Energy Storage

2.1 History of Energy Storage

The first proof of an energy storage system is from 245 B.C. near Baghdad, Iraq, and it is based on the principle of fuel cells. “It consists in a small container with very thick walls, covered by a material like asphalt, and inside a copper foil-wrapped tube, which was connected to the upper part of a copper disc. A very thin ramrod was clamped to the down lid and passed through the center of the tube, without touching the walls.

In the flask vinegar or grapefruit juice was fermented. The acids allowed a migration flow of electrons from the copper tube of iron ramrod when the metals were connected at one end, generating a sum current. Experiments have shown that this battery generated between 1 and 2 volts.”[2]

Historians believe that the electrical current from the “fuel cell” was used as medical tool to reduce pain in Greece and it was a product of the alchemists’ studies.

At the end of XVIII century Luigi Galvini experimented to connect a frog leg to two different types of materials. He observed that the frog leg moved, and he assumed it was thanks to an “animal electricity”. Alessandro Volta understood that the frog leg behaved like an electricity conductor (electrolyte). Alessandro Volta also studied the performance of different metals in certain salt solutions. Based on Galvani’s “animal electricity”, Volta designed the first battery, the Voltaic pile, which consisted in a pile of zinc and copper plates using salt water as an electrolyte. At that moment it was not possible to use the batteries for industrial applications.

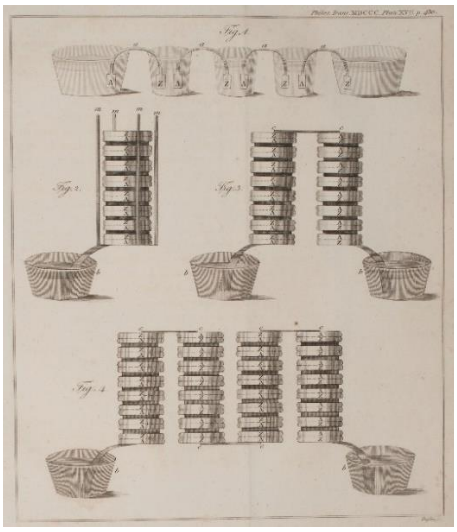


Figure 11 Voltaic pile

The first commercial application of batteries started around the 1880s, after Emile Alphonse Faure invented and patented a device called the sticky plates, which consisted in coating lead plates with a mixture of lead powder and sulfuric acid. The next steps were towards enlarging the storage capacity and the electric power.

The Pumped Hydroelectric Energy Storage (PHS) systems are responsible for the storage of energy through the potential energy of the elevated water. Comparing with the other types of energy storage systems the PHS systems were developed very late.

2.2 Energy Storage Systems

Nowadays most of the energy generation comes from fossil fuels. With current industrial development, population growth and their increase in life's expectancy, the world struggles to satisfy their needs, leading to the stress world's resources.

Another problematic proven by several studies is the climate change, which was a direct result from the careless technological development since the Industrial Revolution. The accumulation of greenhouse gases (methane, carbon dioxide and nitrous-oxide) on the atmosphere created an increase in global temperature and aggravated many natural phenomena such as hurricanes, tempests, floods, droughts or heat waves.

These problematics and others allowed to, through the Kyoto treaty and other conventions, establish new objectives such these negative effects can be mitigated. These objectives pass by reduction of CO_2 emissions, electricity generation with less dependence from fossil fuels, growing use of renewable energy sources. Unfortunately, the renewable energy sources present a great problem which is their dependency on the nature. This difficulty limits the renewable energies' full dependency, because contrarily to a fossil fuel plant, their energy generated cannot be programmable to satisfy their networks demand.[9]

The development of Energy Storage Systems provides a great complementary solution to the network stability and reliability problems.

The Energy Storage Systems that act on the power grid have electrical energy as both input and output. Through a conversion process, the input energy is stored in another form and then converted back into electricity when technically needed or economically convenient. Therefore, it is typical to talk about 'Electrical Energy Storage'. Such systems have many applications:

- Use of the surplus electricity available on the electrical grid to store energy and then to convert it back to electrical energy in peak hours;
- Facilitation of the energy management services and increase of their reliability;
- Promotion of de-coupling from energy production by conventional fuels;
- Regulation and control of the electricity transmission and distribution networks;
- Electrical cars motion, having an inverse benefit on their battery's evolution as well as the possibility to use car batteries as storage elements for the electrical grid;
- Support of smart grids management.

The Energy Storage Systems may be even more influential in an off-grid situation. Certain regions, like some countries in Africa or South America, do not have a national electrical grid making them extremely dependent of the power generated locally. In these cases, an off-grid network is a convenient solution, which is built upon the use of locally available renewable energy sources and fuel generators. The introduction of an Energy Storage System in such off-grid applications allows to mitigate the renewable sources fluctuation, to increase the grid reliability and the voltage regulation, and to preserve energy for moments of high demand.

In developed regions, where the energy consumption is higher, the benefits of using energy storage systems are focused on the grid optimization and on the minimization of the waste of energy. Here, the usage of Renewable Energy Sources helps to achieve a stable constant production of energy in the non-peak hours, which is normally supplied by coal fired technologies or even nuclear power plants, allowing the Energy Storage Systems to release their stored energy at the peak hours.

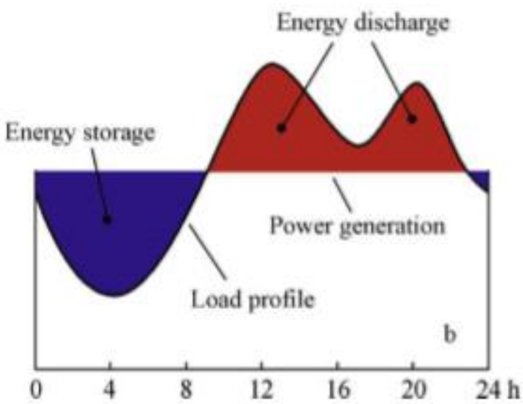


Figure 12 Energetic Storage Systems in load leveling

Furthermore, the Energy Storage Systems can compensate the momentarily shortage of energy supplied by the renewable sources intermittency. As it will be explained in section 2.2.1 certain types of Energy Storage systems are used on industries to supply high demands of energy for short periods.

2.2.1 Classification of Energy Storage Systems

Energy Storage Systems can be classified based on several categories, such as stored energy capacity, power-to-energy ratio, duration of storage, power time response. The different categories allow a proper assessment of which technology should be used for a specific application. Here, a characterization of the Energy Storage Systems is provided according to the form of energy under which the storage is done, i.e., electrical, chemical, thermal, mechanical. Table 5 shows the several categories and subcategories of Energy Storage according to the form of storage.

Table 5 Classification of energy storage according to the form under which energy is stored.

Energy Storage			
Eletromagnética	**Chemical**	**Thermal**	**Mechanical**
Capacitors and Supercapacitors	Batteries: Lead, Nickel, Sodium Sulphur, Lithium ion	Low Temperature Thermal Energy Storage	Flywheel Energy Storage
Superconducting Magnetic Energy Storage	Flow cell batteries: Vanadium Redox	High Temperature Thermal Energy Storage	Compressed Air Energy System
	Fuel cell		Pumped Storage Hydropower plant
	Thermochemical Energy storage		

Each form of energy presents different characteristics:

- **Electromagnetic Energy Storage**: the system accumulates energy under the form of electricity; thus it does not require any form energy conversion. The electrostatic systems accumulate charges in a metal plate thanks to the presence of dielectric materials (capacitors and supercapacitors). While in an electromagnetic system the creation of a strong magnetic fields allows to store energy (super conducting magnetic field);

- **Chemical Energy Storage:** the energy storage is related with the behavior of atoms and molecules. The different potential of an electrochemical system represents the maximum available power between a “higher level state” and a lower energetic state. The system can be subdivided in: (i) electrochemical static, if the structure is composed by an anode, a cathode and an electrolyte, and (ii) electrochemical flowing, where the electrolyte flows through a reaction chamber. The Chemical Energy Storages present 3 phases: power-to-fuel, storing fuel and fuel-to-power. The system **power-to-fuel** process chemical compounds to produce reactants i.e. fuels. Normally the fuel produced is H_2 but can also be a product from fossil fuels conversion. The conversion from **fuel-to-power** is the reverse process. The stage of **storing fuel** requires the deposit of fuel in reservoirs (which can be high pressure storages in tanks or in natural impermeable caves; also, alternative storage systems exist that require extremely low temperatures (around 30 K) to achieve liquefaction) [10];
- **Thermal Energy Storage (TES):** this type of energy is based on the temperature difference between a material and the surrounding environment. Both cold storage (where the material temperature is below the environment one) and hot storage (where or the material temperature is above the environment temperature) exist. If the material temperature is higher than the environment, the system can accumulate energy by exploiting the sensible heat (the material does not change phase) or the latent heat (the material changes phase). In case of a material that presents a lower temperature than the environment, the system requires the use of a refrigerant circuit;
- **Mechanical Energy Storage**: this type of energy storage can be divided into potential energy and kinetic energy. In the first case, potential energy is stored in a reservoir so that particles are kept and later used to generate energy through their release. The Compressed Air Energy Systems (CAES) and the Pumped Hydropower Storage Systems belong to this subcategory. On the contrary, the flywheels are moving systems where the storage of energy is related to the kinetic energy of the bodies.

Another classification looks at the main purpose that is achieved by the operation of the energy storage system. Here, two categories can be identified:

- **Power regulation:** the system’s main objective is to ensure the electric network reliability, regulation of the network (e.g., frequency or voltage) and energy quality. The main characteristics of these systems are the high power and the low storage capacity, corresponding to short discharge periods ranging from second to few minutes. Ideally, they present a low specific cost, high reliability and availability. Main systems that belongs to this category are: capacitors, supercapacitors, flywheels, superconducting magnetic energy storage and certain types of batteries;

- **Energy Storage:** the system's purpose is to store large amounts of energy and release it to the electrical grid at a different time. They can be focused on profit (consuming energy at cheap price and selling during peak hours), on supporting the penetration of renewable energy technologies, on peak shaving, or on power leveling. Main systems that belong to this category are: pumped hydroelectric storage plants, CAES, flow batteries, certain types of batteries, Hydrogen storage system and low temperature TES.

2.2.1.1 Electromagnetic Energy Storage Systems

Capacitors and Supercapacitors

The capacitor is composed by a layer of insulator that involves several electrical conductors. The insulator layer normally is made of certain types of ceramic, glass or plastic films, while the electrical conductors consists of metal foils.[9]. The layer of insulator is known as the dielectric and it allows the electrical conductors to behave like islands, i.e., when applied an electrical current the conductors will be charged positively and negatively.

The capacitors can charge and discharge very rapidly, presenting a great advantage towards the use of batteries. Also, the low degradation after a several thousands of cycles presents a good gain. On the other side, the low energy density of the capacitors (only a few kw) would require the production of capacitors with a large storage capacity. The production of such system would be highly costly. Thus, the capacitors cannot be used as storage system to supply the peak hours.

The Supercapacitor differs from the capacitor, since it uses an electrolyte solution to surround and connect the conductors, instead of using the dielectric to separate the charge plates. The energy is stored at the surface electrode, but thanks to the surface areas' increase, the energy density decreases. This technology is applied to start engines, actuators and motors. For instance, it is used in the motors start-and-go. The recuperative breaking system allows to charge the Supercapacitors, resulting in the reduction of fuel to start the car.

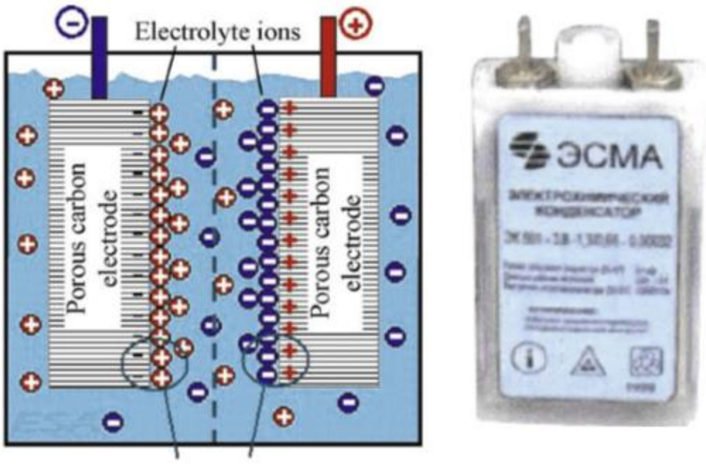


Figure 13 Capacitor/ Supercapacitor

Superconducting Magnetic Energy Storage

SMES (Superconducting Magnetic Energy Storage) utilizes an electrical current to create a magnetic field and store electrical energy. The system is composed by coil of a superconductive material, a cryogenic system and a power conversion system. The main property of the superconductive material is: if the temperature is below the critical temperature the resistance of the material tends to 0. Under these conditions it is possible to disconnect the power source and let the current circulate between the coil. The magnetic field created by the circulation of the current stores the energy. The SMES energy can be estimated by $E = 0{,}5LI^2$, where L is the inductance of the coil and I is the current passing through it.

Currently there are 2 types of SMES: Low Temperatures and High Temperatures, where the cryogenic liquid is at 5K and at 70K, respectively. Nowadays the Low temperatures SMES are well matured while the High Temperature SMES are still under development.

The main advantages of SMES are the high density, the high response time (in order of milliseconds), high energy storage efficiency. This device is appropriate for regulation the voltage of the grid. The main disadvantages are the high production cost and the cryogenic field’s energetic cost. Furthermore, there are the environmental problems associated to the magnetic electrical field.

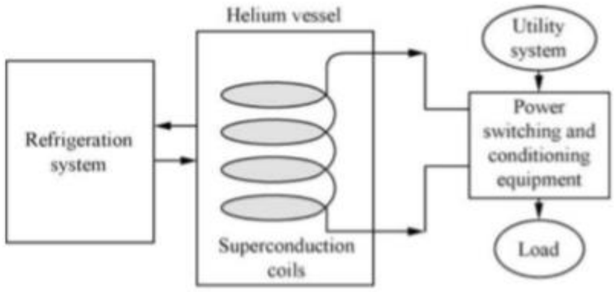


Figure 14 SMEG scheme; SMEG installed at Kameyama Plant 2 (China) Nominal power 10 MW

2.2.1.2 Chemical Energy Storage Systems

Electrochemical Energy Storage (batteries)

The rechargeable battery is one of the main technologies used to preserve energy. The Battery Energy Storage (BES) can be applied for industrial applications, household, energy management or power quality. Through a chemical reaction it stores an amount of energy. The BES is composed by electrochemical cells, under a liquid or paste form, or a solid electrolyte connecting a positive electrode (anode) and negative electrode (cathode). When discharging, the anode releases a flux of electrons to an external circuit until reaches the cathode. On the other hand, when charging the BES, it is required to apply an external current to the cathode to "pump" electrons to the anode.

"*Batteries are in some ways ideally suited for electrical energy storage applications. They not only provide fuel flexibility and environmental benefits, but also offer several important operating benefits to the electricity utility. They can respond very rapidly to load changes and accept co-generated and third-party power, thus enhancing the system liability*."[11]. Even though is a maturated technology, it presents disadvantages that do not advise its use for large scale storage such as low energy density, degradation after thousands of cycles, high maintenance costs and incomplete discharge. Furthermore, the chemical compounds are toxic for the environment, requiring a controlled disposable of their waste.

There are two type of BES: Conventional batteries (lead acid, Nickel, Sodium Sulphur and Lithium ion) and flow cell batteries (Vanadium redox).

Lead acid batteries are the most maturated of the BES. Their cathode is composed by PbO_2 and the anode by Pb and the electrolyte is sulfuric acid (H_2S0_4). They present low costs of production, good discharge efficiency, high reliability, fast response and simple manufacture. The cons are the low energy density, which would require big volumes/surface areas for the creation of large energy storage systems, the low life cycle and the environment hazard due to the usage of a heavy metal such as lead. The lead batteries are good option to control the load leveling and peak shaving. Moreover, they can be coupled to solar panels and windfarms to regulate their instability in an off-grid situation. Now it is underdevelopment an ultra-battery that works at a continuous partial state of charge with reduced maintenance cycle.

Figure 15 Lead-Acid Battery Storage system; left: Xtreme Power 1 MW - 1 MWh; right: Electric Power Research Institute of California 10 MW – 40 MWh

Rechargeable nickel cadmium batteries have also a good maturity. Their cathode is composed by Nickel hydroxide, the anode Cadmium hydroxide and the electrodes are separated by an alkaline electrolyte. Normally they require a metal case with a self-sealing safety valve. This battery system presents a high energy density, a good reliability and low maintenance costs. On the other hand, it has low life cycle (1000 cycles), high costs of production and the toxicity of cadmium. The nickel cadmium batteries have an additional limitation: They suffer from "memory loss". They only charge completely for several full discharge cycles.

Sodium Sulfur batteries use molten sodium and molten sulfur as electrodes and beta aluminum as solid electrolyte. The chemical reactions require a high temperature around 300 to 350 ºC, to keep the liquid state of the electrodes. This reaction has a high reactivity under ideal operational conditions. These batteries present a good life cycle (2500 times), high energy density, high charge/discharge efficiency, barely no maintenance and high recyclability. The drawbacks are the heat requirement to keep the high temperatures, the risk of explosion if sodium interacts with air and the constant corrosion from the insulators due to the corrosive atmosphere surrounding them. The sodium sulfur batteries are mainly used and developed in Japan. There are 30 sites presenting more than 20 MW stored energy for a period of 8 hours allowing a good energy management.

Lithium batteries have Lithium metal oxide as a cathode, graphite carbon as anode and uses lithium salts dissolved in organic carbonates as an electrolyte. When the battery is charged and starts discharging, the lithium atoms ionize and migrate from the carbon graphite, while the flux of electrons pass by an external circuit. The process can be reverted with the help of external current. The advantages are the high cycle life (10000 cycles), high energy density and high efficiency. If produced at large scales the biggest drawbacks should be taken into consideration: the high cost of packing, the internal protection of the cycle and the cycle DoD (depth of Discharge) can affect the battery life time.

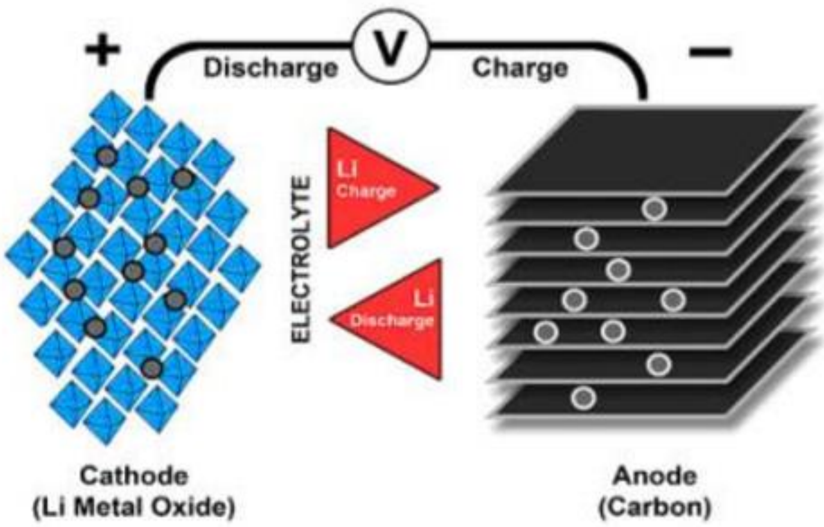


Figure 16 Lithium ion battery scheme

A flow battery uses a chemical reaction to transform the chemical energy into to electrical energy. In this case the electrolyte contains several dissolved electroactive species, which are stored in two different tanks. To charge or discharge the system the electrolyte is pumped through the electrode, producing electricity or storing chemical energy.

A redox flow battery requires that all electro-active materials are dissolved in the electrolyte, while a hybrid flow battery the materials are stored internally.

The Vanadium redox battery stores energy by using vanadium redox couples. The anode variates from V^{2+}/V^{3+} and while the cathode changes from V^{4+}/V^{5+}. The redox couples are stored in mild sulfuric acid solutions, i.e. electrolytes. The H^{+}

exchanged between the electrolytes tanks passes through an hydrogen permeable membrane, allowing to charge or discharge the system.[11]

A good advantage to the traditional batteries is that electrode does not suffer physical or chemical changes during the chemical reaction, improving the life cycle of the system. Furthermore, it presents high electricity conversion efficiency and low maintenance. It is a more complicated system since it requires the use of pumps.

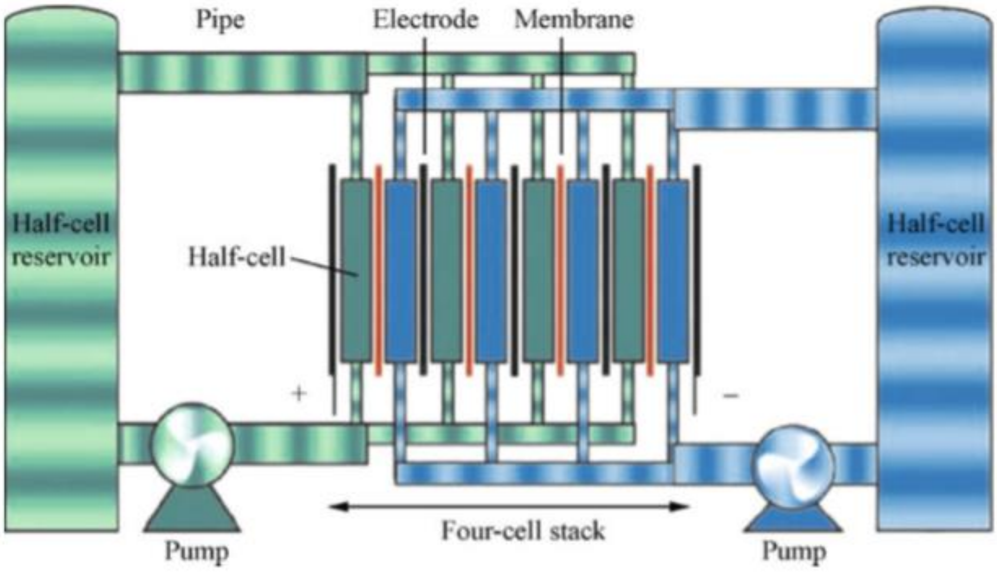


Figure 17 Flow battery schematic

As briefly referenced before the Chemical Energy Storages can explore 3 different phases: an initial phase designated as Power-to-fuel, where the system uses the excess of electricity in the network or electricity at convenient price to produce fuel, a storing fuel phase, which purpose is to store the produce fuel for electricity generation, and fuel-to-power, which consists on the reconversion from the fuel to electricity. Below, we analyze each phase.

Power-to-fuel

The technology consists in the production of stable chemical compounds, such as hydrogen or methanol, through several processes. The most frequent fuel produced is hydrogen and there are several technologies that produce it:

- **Alkaline water electrolysis**: The KOH and NaOH are used as electrolysis solution. This technology is the most mature and popular for the hydrogen production. The migration of the hydroxide ion OH^- through the diaphragm that separates the electrodes allows the production of H_2. The system may work in a batch mode or continuously and normally works until a pressure of 30 bars[12] and temperature of 80 ºC. At the moment, the system is under investigation to understand its behavior at high pressures and temperatures. If the electrical current is reduced there is the possibility of mixing hydrogen and oxygen when crossing the diaphragm;

- **PEM electrolysis**: like Alkaline electrolysis, the PEM technology requires water to produce hydrogen. However, in the PEM cell the hydrogen proton migrates through the polymer membrane. They may have a maximum pressure of 30 bars and temperature between 50 and 80 ºC [13]. Nowadays they are produced at commercial scales with a nominal power of hundreds of kW and efficiencies between 48% and 65%. In this case since the hydrogen ion crosses the membrane there is no mixing between oxygen and hydrogen, which is a good advantage when compared to the alkaline electrolysis;

- **SOE electrolysis**: This technology is called Solid Oxide Electrolyzer (SOE) and requires the use of high temperatures and ceramic electrolytes. The high temperatures present a limitation for the intermittently work of the system. On the other hand, these high temperatures permit to reduce the electricity consumption, as long as the energetic source has a higher temperature that pre heats the reactants. The technology is an endothermic reaction and is not available for commercial appliance.

Storing Fuel

After the production of hydrogen, it is important to ensure that the storing system is appropriate. For a proper sizing of the reservoir, it is required to understand the storage capacity under its limitations due to volumetric density ($kg_{H2}/m^3{}_{stocked}$) and gravitational density ($kg_{H2}/kg_{stocked}$). The main types of storage are:

- Liquid storage: Liquefied hydrogen requires to be lower than the critical temperature (-240 ºC) and to have a high volumetric density (between 30-40 $kg_{H2}/m^3{}_{stocked}$). The biggest disadvantage of this storage type is the energetic cost required to keep hydrogen in the liquid state. Studies computed that it is required approximately 12% of its LHV (14,4 MJ/kg_{H2}) at the atmospheric pressure. A secondary problem are the boil-off losses[1] from the reservoir. Even though the reservoirs are

[1] Boil-off losses occur when the liquid is close to the vaporization temperature, by design choice, and the small heat variances from the environment are responsible for the evaporation of part of the liquid.

thermal insulated, the daily losses from this phenomenon are still 0,1% of the Hydrogen mass in large scale reservoirs and 2 to 5% on small scale reservoirs;

- Gas storage: The gaseous hydrogen requires a reservoir with very high pressures and low volumetric densities. The pressures should between 350-700 bars.

Another possibility to store gaseous fuel, such as hydrogen or natural gas, are the natural caverns. While using natural caverns the requirement of high pressures is dropped thanks to the cavern's large storage capacity (m^3). The caverns can be salt caverns, underground aquifers or gas deposits. Examples of reservoirs that are being used: Teesside, UK (Sabic Petrochemicals, 3 × 70 000 m3), Clemens Dome, Texas, U.S. (ConocoPhillips, 580 000 m3) e Moss Bluff Salt Dome, Texas, U.S. (Praxair, 566 000 m3 max).

- Solid storage: If the hydrogen is compressed at low pressures (>50 bars), a solution passes by the connection of hydrogen with several metallic materials (i.e. Ti, Mg, Va, Li). Under these pressures the hydrogen is forced to occupy the spaces in the metallic matrix. Moreover, the hydrogen may create a covalent bond with certain chemicals. To reverse the bonding process, it is only required to supply heat to the mixture. The dehydrogenation may present very high values of energetic consumption, reducing the useful energy available. Lithium-Aluminum and Sodium-Aluminum alloy are used to store hydrogen.

Fuel-to-power

The last step consists on the production of electricity from fuel. The simplest and more convenient way to convert the fuel to electricity is by using a fuel cell. In a fuel cell, the anode is the fuel side while at the cathode the new species are produced, and an electron flux current is produced. the fuel cell is an open system, while the flow battery is a close system, i.e. in the fuel cells the reactants are consumed and need to be replaced.

There are three types of fuel cells such: low temperature fuel cells, high temperature fuel cells and fuel cell with reversible combustion. Most of the fuel cells work use low temperature and the Proton Exchange Membrane Fuel Cells (PEM FC), the Alkaline Fuel Cells (AFC), the Phosphoric Acid Fuel Cells (PAFC), the Regenerative Fuel Cells (RFC) and the Direct Methanol Fuel Cells (DMFC) belong to this group. The PEMs are the most developed technology.

The Molten Carbonate Fuel Cells (MCFC) and the Solid Oxide Fuel Cells (SOFC) belong to the high temperature fuel cells. These systems are supplied by natural gas or other types of hydrocarbons.

The fuel cell with reversible combustion may produce the electric energy or consume electric energy for the generation of fuel. If the system is united in a single stack is designed as Unitized Regenerative Fuel Cell (URFC), while if the system is separated into two stacks is called Regenerative Fuel Cell System (RFC).[12]

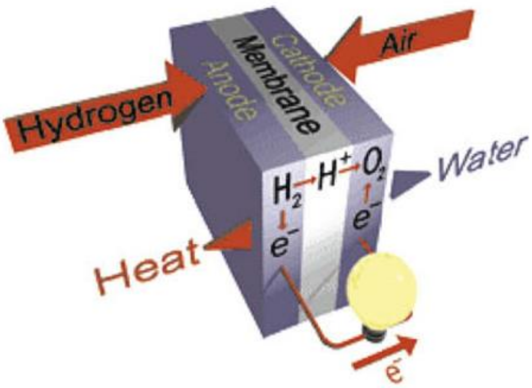


Figure 18 Hydrogen Fuel Cell

The hydrogen fuel cell uses the hydrogen and the oxygen as reactants to produce electricity and water, $2H_2 + O_2 \rightarrow H_2O + energy$. The system may also work reversibly if it has water and an electrical current applied. The main advantages of using fuel cells are the quiet mechanism, the good discharge rates, being less pollutant than conventional fuels and the simplicity of production for large scales systems (for hundred MW). The disposal of fuel cells requires to be controlled and recycled as much as possible since the electrodes and catalysts, like palladium, are a hazard for the environment. The PEM FC are commercialized. The fuel cells are under development, in order to reach better costs of production and to increase improve their work performance.

Thermochemical Energy Storage (solar hydrogen, solar metal)

Solar fuels are a recent technology that is still in an early stage development. The objective is concentrating diluted sunlight into a very small amount of water using parabolic mirrors, so the irradiation concentrates and heats the water, until it reaches high temperatures. Then the water supplies heat to a chemical reactor, which purpose is to produce fuel to be stored and transported. The energy input to a solar fuel could be converted to electricity through a steam Rankine cycle or other type of cycle, but it would be highly inefficient.

The main advantage is that the conversion from solar to electricity presents the same efficiency independent if the technology is producing fuel to store or producing fuel to electricity directly. Summering the efficiency system is independent from the irradiation. Also, the system parabolic mirrors allow downsizing the plant proportionally to a possible higher capacity factor. The main solar fuel used nowadays are:

- Solar hydrogen: The hydrogen can be obtained through 5 thermo chemical process: solar thermolysis, solar thermochemical cycles, solar reforming, solar cracking and solar gasification. Each process requires heat for the chemical reaction, supplied by the concentrated solar energy, and a reactant. H_2O is the source for following processes: solar thermolysis, solar thermochemical cycles, solar reforming and solar gasification. Fossil Fuels supply the reactants for solar reforming, solar cracking and solar gasification;
- Solar metal: Metals are a good possibility to transport and store energy. The chemical processes resulting from the power generation are oxidized metal, that can be recycled through a reduction reaction. The reduction reaction of the metal's oxide is endothermic and pollutant. The process can be mitigated with the use concentrated solar;
- Solar chemical heat pipe: In this technology, the high temperature accumulated by the solar energy supplies the required heat for the endothermic reaction occurring in the chemical reactor. The products are stored and transported to a site where it is converted into electricity. Here the reaction is exothermic, and the heat released is equal to the conversion from the reactants to products, thus the products of the exothermic reaction are the reactions heated by the solar radiation. The reverse reactions frequently used are CH_4 reforming methanation and the NH_3 dissociation synthesis.

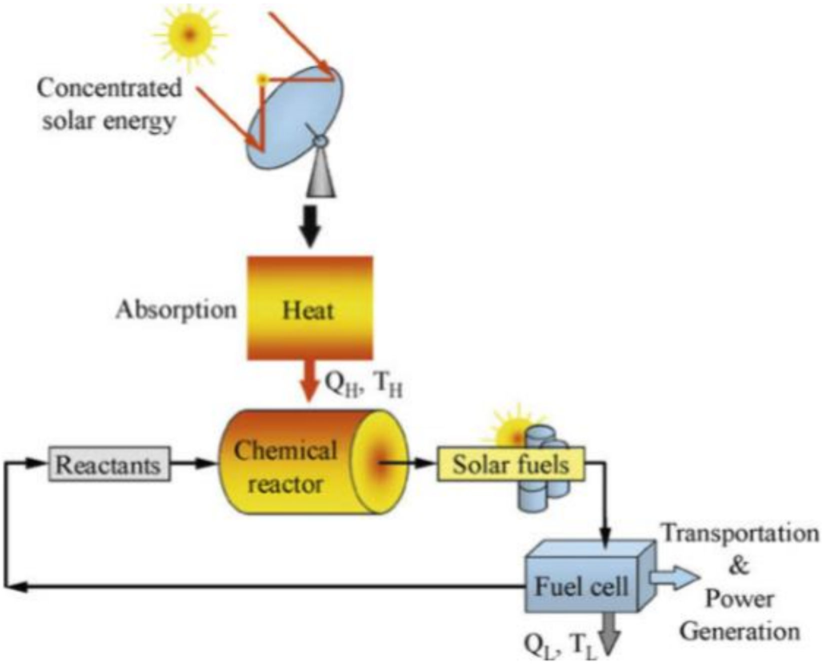


Figure 19 Solar Energy conversion into solar fuel

2.2.1.3 Thermal Energy Storage

The Thermal Energy Storage (TES) consist in the use of materials that can preserve their temperature when properly insulated. This type of storage system can be classified as Low Temperature Thermal Energy Storage (Low T-TES) or High Temperature Thermal Energy Storage (High T-TES) depending on the temperature of the stored fluid. This system presents a low overall efficiency on average (30-60%)[9]. They are environmentally friendly and are a good mechanism when exploiting renewable energy sources in relation to commercial buildings.

Low Temperature Thermal Energy Storage

The most relevant Low T-TES technologies that are under development are:

- Aquifers Low T-TES: this technology has the purpose of reducing the dependence on the energy cost during the peak hour in a large commercial building. Water is cooled down by a refrigerant and stored. During peak hours, the accumulated energy will be used to cool the building. The amount of stored energy depends on the temperature difference and if the water is chilled or frozen;

- Cryogenic Energy Storage (CES): liquid nitrogen or liquid air are cooled down until cryogenic conditions at off-peak hours or by using renewable energy sources. During the peak time a heat engine uses the cryogenic fluid to generate electricity. The CES can have the same application as the Aquifers Low T-TES. They present a high energy density, a low investment cost and the capacity of storage for long periods. However, they have a low average efficiency.

High Temperature Thermal Energy Storage

The HighT-TES technologies that are under development are:

- Molten Salt Storage and Room Temperature Ionic Liquids (RTILs): the RTILs are organic salts that present a low vapor pressure and melting temperature (below 25 ^{0}C). The organic salts mixed with water or organic oil increase the capacity of storing energy. The mixture temperature can increase until several thousands of degrees without degrading, depending on the type of salt. The molten salts may present several advantages when used in a solar plant;
- Concrete Storage: this type of storages uses concrete or castable ceramics to conduct heat and is insulated from the external environment. The technology transfers energy from an external fluid such as molten salts or water, which is warmed from the parabolic through;[11], [14]
- Phase Change Materials (PCMs): These materials exploit their change of phase (usually from solid to liquid) when they reach a given temperature. Comparing PCMs with for instance the molten salt, we conclude that the latent heat of the phase change permits a better exploitation the energy density, i.e., the PCMs require a smaller storage capacity than a material that does not exploit the change of phase.

2.2.1.4 Mechanical Energy Storage

Flywheel Energy Storage (FES)

A flywheel is composed by 5 elements: the flywheel itself, several bearings, a reversible electrical motor/generator, a power unit and a vacuum chamber. The motor powers up the flywheel by increasing its momentum, thus storing kinetic energy in the system. When the flywheel decelerates, the motor behaves as a generator releasing energy. The vacuum chamber reduces the air resistance leading to an increase of the system overall efficiency. Furthermore, the usage of non-contact magnetic bearing reduces the friction of the system, thus reducing its losses. The amount of energy stored in the system depends on the flywheels rotational speed, the friction affecting the system and the system mass. It can be calculated by the following equation:

$$E_k = \frac{1}{2} I \omega^2$$

where I is the angular moment of the FES and ω is the rotation velocity.

The FESs are divided into 2 groups: low-speed FES, (typically operating at 6000 rpm) and high-speed FES (reaching a maximum of 100000 rpm). The low-speed FES presents a high storage capacity for a short time period, while the high-speed FES has a lower storage capacity for a longer time period. This technology is often used in industrial applications or on small electrical distribution grids since it allows a reduction of the consumption during the peak hours. The main problems are the presence of strong magnetic fields near the device, which may result in a reduction of its efficiency. This technology is still considered under development.[15]

Figure 20 left: Flywheel Scheme; right: Flywheel plant at Stephentown (NY, USA), 200 flywheel, Nominated Power 20 MW, discharge period 15 minutes

Compressed Air Energy Storage (CAES)

CAES is a technology that can store large amounts of energy, ideal for bulk power management. The concept is simple: when the cost of electricity is low the air is compressed into the reservoir and when the cost of energy is high, the air is released producing electricity at the exit. As an alternative, the air can be compressed into an underground aquifer.

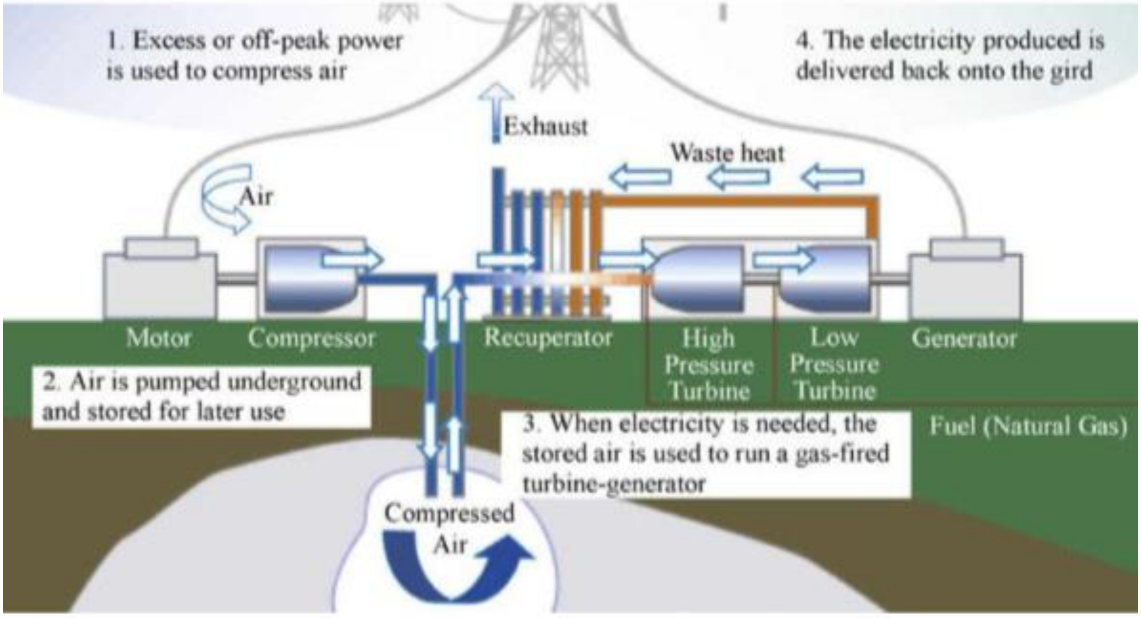


Figure 21 CAES scheme

As it can be observed in the Figure 21, there a charging and a discharging stage. During the charging phase, the excess power from the electric grid supplies energy to a motor, which is coupled to inter-refrigerated axial compressors that compress air into the reservoir at a pressure up to 80-bar. Before entering the reservoir, the air is cooled down for a better control of the relative humidity of the reservoir. During the discharging phase, the reservoir releases the compressed air, which passes through a heating process and, after reaching the desired temperature, it is directed to a turbine (typically large axial machine with high pressure and low-pressure stages), finally transmitting the kinetic energy to the electrical generator. If the system uses an additional fuel to heat the compressed air that will pass by the turbine, it is designated as Non-Adiabatic CAES, while if the system uses a thermal storage unit for that, it is designated Adiabatic CAES. The heating of the compressed air is crucial for its expansion, since it avoids the water particle in the air from freezing against the turbine blades.

In Germany and in the USA, there are a few underground mines or natural caverns that are used for CAES plants. Enel was exploring a 25 MW CAES in Sesta, Italy, but had stop the exploration due to geothermal disturbances [9]. The main criteria for the reservoir are the presence of hard and impermeable rock. The underwater CAES is under development in the Ontario Lake. The purpose is to balance the air pressure and the water pressure.

Another type of CAES is the Advanced Adiabatic CAES (AA-CAES), where instead of using the fossil fuels, a thermal storage unit and sources are used to heat the air before the expansion. The first AA-CAES plant study case in Europe was ADELE, at Saxony-Anhalt in Germany. Adele was a consortium between several German institution and was under development for several years, but it was never successfully built. The projects included a TES and the use of wind energy to power the compression.

The large-scale CAES present moderate response time and are good at partial load performance. They are ideal to increase the penetration of the renewable energy technologies by smoothing their output, load shifting, peak shifting and frequency and voltage control. The main drawback is the requirement to discover sites geologically appropriate for the technology. Furthermore, the lack of maturity increases the cost of the specific energy.

Figure 22 McIntosh CAES Plant, Alabama U.S.A., Nominal power 110 MW, Discharge duration 26 hours

Pumped Hydroelectric Energy Storage

The Pumped Hydroelectric Energy Storage (PHS) is the most mature technology among the Energy Storage systems. A large description of this technology is provided in Chapter 3, with a technological review, a list with the principle main PHS, innovative systems exploring PHS and current trend of the countries constructing PHS.

2.2.2 Assessment of the Energy Storage Systems

This subsection provides a brief analysis of the characteristics of the main Energy Storage Systems. Figure 23 shows the time discharge response and possible nominal power of each technology. The technologies are divided according to their possible applications into 3 groups: reserve and response services, transmission and distribution grid support, and bulk power management. Both the time of discharge and the nominal power are extremely important to define the circumstance under which a technology is used. The PHS and the CAES typically present high nominal power and long discharge times. As for the hydrogen storage systems, they present good conditions for bulk power management, the batteries can only be used as reserve and response services and transmission and distribution grid.

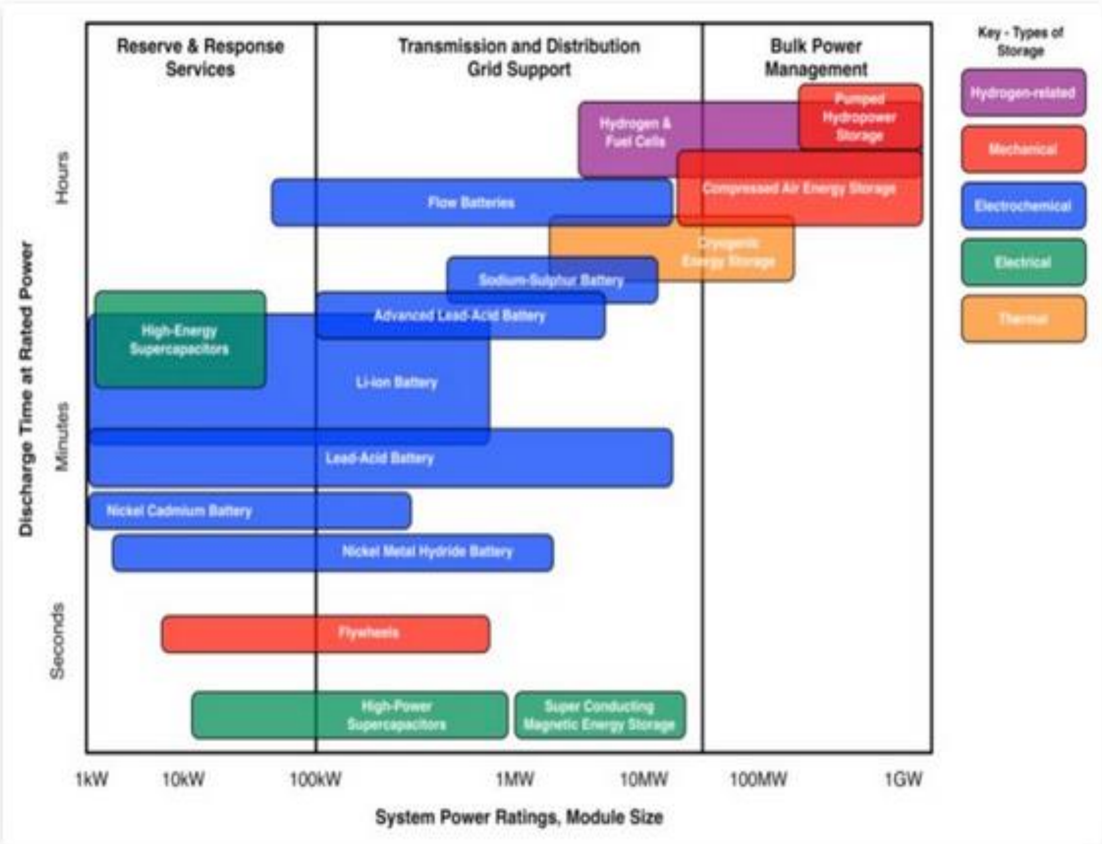


Figure 23 Applicable power ranges and discharge power duration of different energy storage technologies- Energy Storage Sense

The Table 6 shows the main characteristics from the Energy Storage Systems.

Table 6 Main characteristics from Energy Storage Systems [9]

Storage System Classification	Technologies	Accumulated efficiency	Cycle of life	Duration	Nominal Power	Time reponse	Discharged time	Power density	Energetic density	Maturaty
Electrical Energy Storage	High Energy Supercapacitor	>95%	n.a.	40 years	0,2-100 MW	seconds	seconds	100 MW/L	10-30 Wh/L	developing
	SMES	95-98%	n.a.	30 years	0,1-10 MW	miliseconds	minute	2500 W/L	6 Wh/L	developing/ commercialized
Chemical Energy Storage	Pb acid	75-85%	500-3000	5-15 years	~10 MW	miliseconds	minutes- 20 hours	10-400 W/L	50-90 Wh/L	maturated
	Ni-Cd	60-70%	1000-5000	10-20 years	~0,01 MW	miliseconds	minutes -1 hour	80-600 W/L	60-150 Wh/L	commercialized
	Ni-Na-Cl	85-95%	4500	<15 years	~10 MW	miliseconds	2 hours or more	n.a	100-120Wh/kg	commercialized
	Na-S	70-80%	>4500	15-20 years	0,2-50 MW	miliseconds	6 hours	140-180 W/L	150-250 Wh/L	commercialized
	Li-ion	90-98%	2000-10000	15-20 years	0,001-50 MW	miliseconds	minutes-4 hours	1,5-10 MW/L	200-500 Wh/L	commercialized
	Vanadium Redox	85%	~16000	15 years	50.MW	miliseconds	20 hours	2 W/L	16-33 Wh/L	commercialized
	Zn-Br	65-75%	n.a.	10-20 years	3-500 kW	miliseconds	10 hours	25W/L	30-65 Wh/l	developing
	Na-SBr	75-90%	n.a.	n.a	15MW	miliseconds	2 hours or more	n.a	n.a	developing
Thermal Energy Storage	Low TES	20-45%	n.a.	20 years	50 MW	seconds	hours	n.a	n.a	developing
	High TES	20-45%	unlimited	20-40 years	40MW	seconds	hours	n.a	80-120 Wh/L	developing/ commercialized
Mechanical Energy Storage	FES	95%	20000	n.a	200kW	seconds	minutes	1-2 MW/L	20-80 Wh/L	developing/ commercialized
	CAES	70%	n.a.	30 years	100-500 MW	minutes	several hours	2W/L	3-6 Wh/L	developing
	PHS	70-85%	unlimited	>80 years	10 MW-5GW	seconds-minutes	days	0,5W/L	0,5 Wh/L	maturated

As discussed before, the discharge time one of the main characteristics that defines the purpose of the technology, however the cycle of life and the accumulated efficiency determine the viability of the technology.

The cycle of life is a parameter that can be limited by the number of cycles or the number of years. Certain types of batteries may suffer from reactants degradation or memory loss, which as explained before, is the reduction of the State of Charge with the increasing number cycles. Therefore, analyses the loss of storage power "quality" with the increase number of cycles. A good example of a limitation due to the number of cycles are the lead batteries, since they can even endure 15 years, but after 3000 cycles they lose the capacity to charge becoming inconvenient. On the other hand, mechanical energetic storage technologies such as, CAES and PHS, have limitations due to degradation of the storage facilities. For the latter, a periodic maintenance can bring good advantages on their reliability.

Most of the Chemical Energy Storage Systems have a good accumulating efficiency and a discharge time of some hours, making them good candidates to explore the market prices. The cost of production is connected to the number of cycles the system can do, thus technologies with low number of cycles become economically inconvenient.

The accumulated efficiency is the first criteria to be analyzed for a technology. It evaluates the performance of the output energy over the energy fed to the system. In practice, this analysis is the first requirement to fulfil to pass from a developing stage to a commercial application.

Parameters such as power density and energetic density allow a proper sizing and planning of the devices, which can be focused on the creation of mobile devices (requiring high power density) or a stationary device (high storage capacities and low power density). Figure 24 shows the maturity of the technology by 2020. The PHS and the lead batteries are completely maturated and have been in the market for several decades. The devices which have the label "developing" (Table 6) are still in Research and Development with several Pilot projects around the world. For most of the other technologies, their maturity allows their commercialization (example: electrical car), but they are still under development since their performance can be optimized through the change of quantities ratio of reactants, supporting materials or shape change.

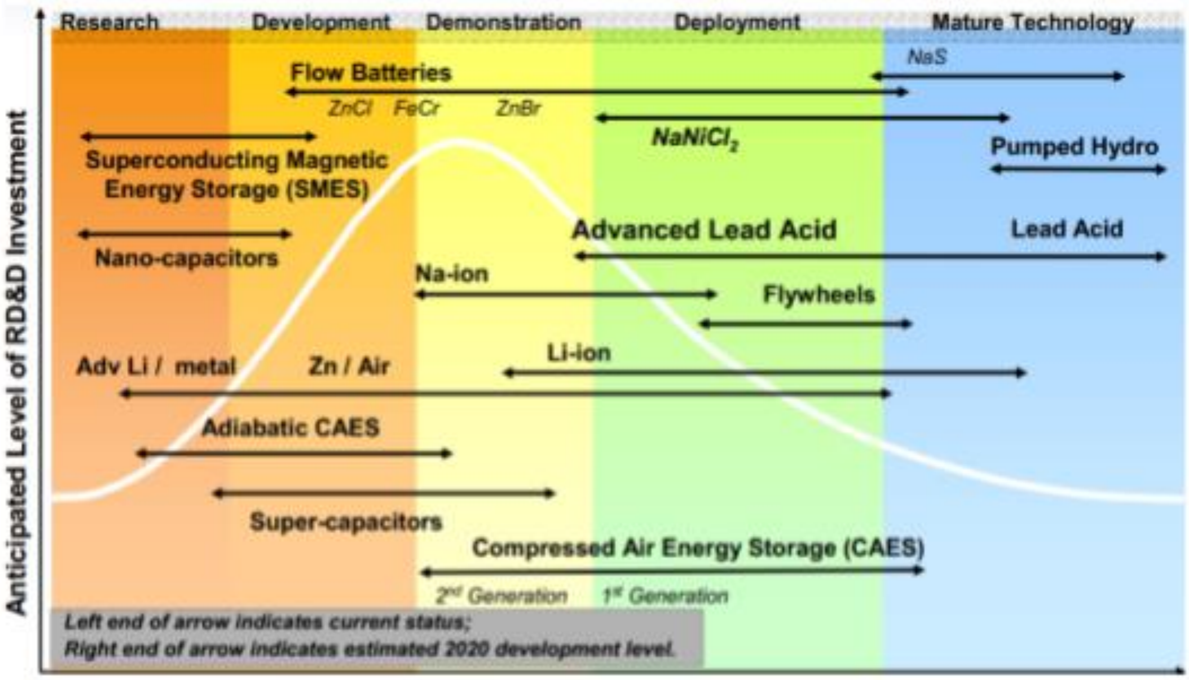


Figure 24 Technological maturity of Energy Storage System (2020)

3 Pumped hydroelectric storage systems

3.1 Main characteristics of Pumped hydroelectrical storage systems

As briefly discussed in chapter 2, the Pumped Hydroelectric Storage (PHS) is one of the oldest and most mature technologies for energy storage. The first documentation of PHS construction comes from the end of the XIX century in the Alps region, in Italy and Switzerland. In 1929 the first pumped hydroelectric facility was implemented in Connecticut, USA. Currently, the capacity of PHS systems is near 90 GW around the world and it is used for 3% of the global electricity generation. The system's overall efficiency may vary from 70 to 80%.[15]

The PHS, just like most of the storage systems, uses an economic principle to work. As explained before, the electricity price in the electrical market varies between a downhill peak and an uphill peak, like Figure 12, favoring the operation of a PHS system in the two modes: a pumping phase when it is economically convenient to buy energy and a generation phase, when it is economically convenient to sell energy.

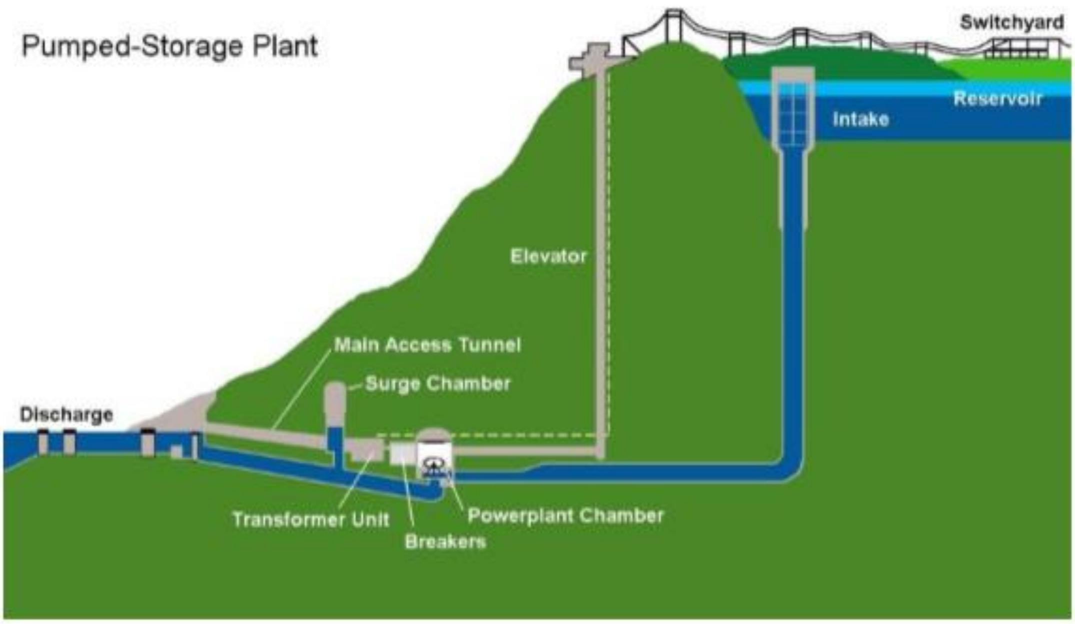


Figure 25 Scheme of a Pumped Hydroelectric plant

During the pumping phase, water is moved from a lower to a higher altitude and stored in the upper reservoir. On the opposite, during the generation phase the water is released from the upper reservoir and directed to the turbine to produce energy with help of the generator. The processes require a pump and a turbine (which can be part of a turbo-pump group or two dedicated machines), an electrical motor/generator, and a duct that leads the water to and from the reservoir. Usually, for each phase there is a dedicated duct.

The nominal power and the energy storage capacity from the PHS are dependent on the mass flow rate released and the net head drop from the reservoir to the power station and the storing capacity of the reservoir, respectively.

Figure 26 Alqueva Pumped Hydroelectric Storage Plant, Portugal

3.2 Types of Pumped Hydroelectric Storage Plants

3.2.1 River Pumped Hydroelectric Storage Plants

The traditional PHS is situated along a river, blocking its natural flow. The PHS system presents some disadvantages which can be economic, since it requires a high capital costs leading to a high payback time (most of the time related to the civil works that are influenced by the topography and geography of the surroundings), or environmental, such as the direct impact of the water flow created by the structure, the visual impact and the flooding of the surroundings (which can lead to loss of biodiversity, reallocation of people), the noise pollution from the turbines and the impacts on the fish which can be mitigated with the construction of a fish ladder. The advantages of creating PHS are the long-life cycle of the structure, which can last from 80 to 100 years, the availability and reliability of the water course and the possibility of water management for other purposes, like irrigation or domestic use. Moreover, the PHS does not add pollutant emissions. The availability of water resource in the river can be affected by periods of floods or droughts.

Another positive aspect of the PHS is its capacity for bulk management storage. The possibility of bulk management may explore 2 different strategies:

1. Exploring the price variation through the day, increasing the economic profit of the plant;
2. Controlling, storing and production from the renewable energy intermittency. Wind energy is highly fluctuating due to meteorological parameters. A reduction in the curtailment of renewable energy generation will increase their penetration and ensure a faster payback time for the investors.

The bulk management capacity is a common advantage in all types of PHS.

3.2.2 Pumped Hydroelectric Storage Plants in mountain regions

The first PHS plants were created in the Alpine region, in Italy and Austria, at the end of the 1800s. They represented a period of innovation of the electrical grid in the region and a revolution in the Energy Storage Systems, which than led to the exploitation of PHS around the world form the 1930s on, after the development of reversible turbine-pump systems. Nowadays their efficiency has been greatly optimized.

In the Alpine region (Germany, Austria, Switzerland and Italy) the energy demand can be largely satisfied by the hydroelectric plants of the regions during the peak hours, when the energy prices are high. Independently from the behavior of hydroelectric plants, the PHS also participate on the energy market. The PHS generates energy when the electricity prices are high and pump energy when there is a surplus from electrical grid coming from other renewable energy sources (prices are lower). [16]

As exemplified by the picture in Figure 27, a PHS plant in the Alpine region has 2 reservoirs: one reservoir at higher height and another at a lower altitude. Each one of them presents a storage capacity and a turbo-generator group, like the traditional PHS. When the storage capacity of lower reservoir reaches the maximum, the water is released to ensure the safety of the surroundings.

Figure 27 Nant de Drance PHS, Switzerland 900 MW nominal power

According to the report "*Rethink pumped storage hydroelectric in the European Alps"*, with the new climate changes Austria and Switzerland are rethinking and moving their policies towards the creation of new PHS system while Italy is reducing its utilization.

One of the difficulties of the PHS companies from this region is the profitability. The current policies of carbon taxes and subsidies for renewable energy sources changed the influence of the hydroelectric companies on the electrical market. As a result, the PHS systems have been obliged to reduce their offering price, due to subsequent increase of renewable energy sources technologies. Moreover, the penetration of wind and solar energy changed the price of energy per hour diagram, reducing the cost of electricity during daylight. This type of energy may lead to surplus of energy during this period.

3.2.3 Seawater Pumped Hydroelectric Storage Plants

The seawater PHS, as the name suggests, uses the sea water to generate energy. Similarly, as the other PHS, it presents two reservoirs and a machinery system to explore and save the gravitational energy in relation to the water level.

Currently there is only one seawater PHS operating in the world, located in Okinawa Island in Japan. The innovative system has a nominal power of 30 MW and began operating in 1999. The upper reservoir is located at an altitude of 600 meters and the hydropower plant has a total head of 136 meters. The artificial upper reservoir has an octagonal shape with a maximum width of 252 meters and a depth of 25 meters. The reservoir total capacity of 654000 m^3. The Figure 28 shows the Okinawa Plant.

Figure 28 Okinawa PHS, Japan 30 MW nominal power

There are several projects under developments around the world.

The Dead Sea Power Project is being developed since 2007 and it is expected to produce 1500 to 2500 MW. The project planning presents ambitious civil working since it is expected to create a 72 km tunnel below the surface to flow the water to the upper reservoir. A side objective of the project is to preserve and restore the Dead Sea Ecosystem, through a desalination facility before the energy generation one. The desalinated water will satisfy the water needs of the region. The project was only approved in December 2018 due to diplomatic complications between Israel and Jordan.[17]

In 2013 there was an evaluation and proposal of a 480 MW seawater PHS in Glinsk, Ireland. The seawater PHS would allow to store the surplus electricity coming from wind turbines, which are frequent in Ireland. It was concluded that it would require a high storage capacity to be economic viable. At the moment only the feasibility test is done, but is part of Ireland's Energy Policy 2030.[18]

In West Australia, the Cultana seawater PHS is under development and has a nominal power of 225 MW. The feasibility study is already done with the cooperation of the University of Melbourne and the Australian Renewable Energy Agency (ARENA). According to ARENA, the project is currently subject to engineering design and it is expected be operational by 2023.[19]

There was a feasibility study for a seawater PHS in 2018 in the São Miguel's Island, Azores in Portugal. The case study was produced by the Research Institute for Energy, MIT Portugal and the Department of Mechanical Engineering from Instituto Superior Técnico. The study concluded that São Miguel presents good conditions for a seawater PHS plant, such as the possibility of using artificial or natural lagoons at higher altitude close to the seaside. The possibility of Seawater PHS would reduce the island dependency in fossil fuels (53%). So far the autonomous government from Azores has made no decision.[20]

3.2.4 Wind/Solar Pumped Hydroelectric Storage Plants

PHS systems are a good alternative to improve the intermittence of the wind and solar power output. Unfortunately, these hybrid systems present limitations on their usage.

The wind energy power requires regions with high average velocities and high wind frequencies. Moreover, the region requires the presence of lagoons or artificial reservoirs. The abovementioned restrictions advise that the research for wind-PHS hybrid systems be mainly in islands and mountains. The pumped storage activity which normally is correlated to the profit, with the aggregated system behaves differently. While if there is an excess of wind power in the electrical grid the PHS pumps are activated, in the case of a deficit on the demand both wind and water turbine power generate power. This concludes that PHS is mainly oriented to fill the wind energy gaps.

Kaldellis et al. proposed and sized a PHS system to exploit the surplus of energy resulting from the wind farms (30 MW installed capacity) in the island of Lesbos, Greece. This surplus energy is rejected by the electrical grid due to limitations in the power lines. Kaldellis's project predicted that the construction of a PHS system with 10,5 MW installed capacity would reduce the annual curtailment by 10%. In Gaidolf, Germany, a similar project with an installed capacity of 16 MW will start its operation in 2019. There are several projects similar to this in Kenya, Turkey and Spain.[21]

The solar energy is also intermittent and exterior factors limit the output power, such as: daylight-only operation, cloud shadowing, inclination and azimuth. In the literature, photovoltaic panels are the solar technology that is typically coupled with PHS system. This type of hybrid power plants is still under development. Margeta and Glasnovic analyzed a possible upgrade from a traditional hydropower plant (Zavrelje/Dubrovnik, Croatia) with photovoltaic panels through the development mathematical model. [21][22]

A major advantage of these hybrid plants is the improvement of the dynamic safety and reliability of the interconnected electrical grid, through the usage of turbine-generator group. Furthermore, if the generators are supplied only by wind or power energy, the energy produced by the PHS (including the water arriving from the runoff) is green energy. The presence of an aggregated system allows the increase of renewable energy sources penetration on the region, promoting the independence from fossil fuels. This option is very relevant for isolated locations since they are normally disconnected from national electric grids. The main drawbacks are the strong investment costs required.

3.2.5 Pumped Hydroelectric Storage Plants with batteries supporting system

The Battery Energy Storage (BES) has presented great developments in the overall efficiency, cycle of life and production cost on the past years. Even though it is being mainly used in electric vehicles, there is one innovative hybrid system composed by a PHS and batteries.

In 2017, in the Pfreimd hydro power plant group (137 MW nominal power) in Bavaria, Germany, a BES system group was implemented. The BES system has 12,5 MW nominal power and 13 MWh installed energy capacity. The BES supplies energy for grid and ancillary services and were designed to work between 25-75% of State of Charge. When the BES is outside of this limit, the PHS starts charging or discharging to bring the BES within the desired limits.

The system is a group of 3 individual pumped storage units and BES to facilitate the grid-integration and operation. Each unit is composed by a separate turbine, a separate pump and a motor-generator with 2 shafts connecting to the turbine and pump.

The hybrid system due to their fast-starting pumping is mainly used to cover the ancillary services.

The separation of 3 pumped storage units and the decoupling of the system allows the pumps to work in a wide range of flow rates, resulting in a flexible plant management, thus increasing the profit. Furthermore, the BES design allows for very small response time when electricity is requested from the grid. The batteries under study are the Li-ion batteries, thanks to the reduction of their specific power cost on the past decade.

The hybrid system presented a single disadvantage related with technological infrastructure, since the aggregation of the system would require the control and to monitor the combined high voltage installations with the electrical grid.

The study concludes that the PHS and BES system has a good performance and that the two technology should be seen as “partners”, because of their high capacity storage and fast ramping functionality.[23]

3.3 Review of the historical development of PHS

The first projects of PHS started in the beginning of the 1890’s in the Alpine region and started developing in the first half of the XIX century across the world.

Historically the biggest development on the technology were during the 1960 and 1990 Europe, USA and Japan.

The majority of the PHS plants in Europe are in France, Germany, Austria, Italy, Spain, Switzerland and Portugal. Most recent developments in have been in Austria (430 MW with Reisseck II in 2013), Spain (852 MW with the expansion of La Muela 2013 and Portugal (880 MW with Gouvães started in 2016).

Japan is a very populated country with a very big fossil fuel resource limitation. They require to import 95% of primary energy and for this reason most of their electricity is produced through nuclear power plants. Moreover, Japan has not electrical interconnection with the neighbor countries, so it is required a big storage system to improve the inland management. The PHS were developed as an auxiliary system to produce energy during the peak hours.

USA PHS expansion during the 60’s and 90’s period relates to the implementation of nuclear power plants and the oil energetic crisis in 1970’s. The uncertainty of new wells and the price of oil, obliged USA to search for new energy sources and new types of storage such as PHS or CAES.

The development of PHS in China started in 1995 and presents several types of reasons, such as: the rapid growth of electric consumption (due to the economic evolution), need to improve the grid availability, governmental and regional objectives in reduction of CO_2 emissions, to increase the penetration of renewable energies and to remediate the lack the of transmissions infrastructures in its rural area.

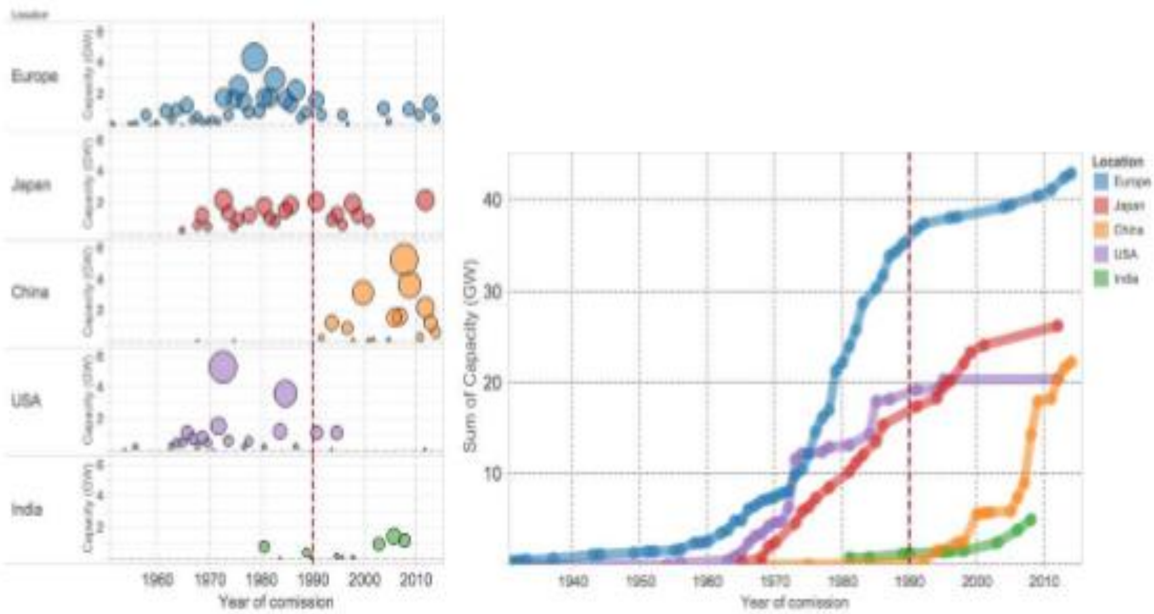


Figure 29 Historical deployment of PHES in Europe, Japan, China, USA and India

The Table 7 expresses the installed capacity around the world by country. Japan has the highest installed capacity with more than 25 GW. Even though China only started in second half of the 90’s the construction of PHS, in 2016 it already as nearly 21,6 GW of installed capacity surpassing the USA’s installed capacity of 20,9 GW. As for Europe the more relevant countries are Italy (7,1 GW) and Spain (6,9 GW).

Table 7 Installed Pumped Hydroelectric Storage Capacity by country, 2016 [24]

Country	Installed Pumped Hydroelectric Storage Capacity (MW)
Japan	27438
China	21545
USA	20858
Italy	6680
Spain	6889
Germany	6388
France	5894
India	5072
Austria	4808
South Korea	4700
UK	2828
Switzerland	2687
Taiwan	2608
Australia	2542
Poland	1745
Portugal	2574[2]

The Table 8 expresses the most relevant PHS systems and their characteristics.

[2] Value corrected using ENTSO-E database

Table 8 Largest PHS Installed capacity systems in the world [15]

Location	Plant Name	Year	Installed Capacity (MW)	Hydraulic Head (m)
Australia	Tumut	1973	1690	
China	Tianhuangping	2001	1800	590
China	Guangzhu	2000	2400	554
France	Grand maison	1987	1800	955
Germany	Markersbach	1981	1050	
Germany	Goldisthal	2002	1060	
Iran	Siah Bisheh	1996	1140	
Italy	Plastra edolo	1982	1020	1260
Italy	Chiotas	1981	1184	1070
Italy	Presenzano	1992	1000	
Italy	Lago delio	1971	1040	
Japan	Imaichi	1991	1050	524
Japan	Okuyoshino	1978	1240	505
Japan	Kazunogowa	2001	1600	714
Japan	Matanogowa	1999	1200	489
Japan	Ohkawachi	1995	1280	411
Japan	Okukiyotsu	1982	1040	470
Japan	Okumino	1995	1036	485
Japan	Okutataragi	1998	1240	387
Japan	Shimogo	1991	1040	387
Japan	Shintakesagawa	1981	1280	229
Japan	Shin toyne	1973	1150	203
Japan	Tamahara	1986	1200	518
Luxembourg	Vianden	1964	1096	287
Portugal	Gouvaes	2018	1188	
Russia	Zagorsk	1994	1200	539
Russia	Kaishador	1993	1600	
Russia	Dneister	1996	2268	
Taiwan	Mingtan	1994	1620	380
UK	Dinorwig	1984	1984	545
USA	Castaic	1978	1566	350
USA	Helms	1984	1212	
USA	Ludington	1973	1980	110
USA	Blenheim-gilboa	1973	1200	340
USA	Lewinston-Niagara	1961	2880	
USA	Racoon Mt	1979	1900	310
USA	Bath county	1985	2700	380

The Table 9 PHS Installed capacity systems in Italy and Portugal, source ENTSO-E [25]Table 9 shows the PHS installed capacity in Italy and Portugal. The data was obtained from the ENTSO-E website and references to the beginning of 2017.

Useful and complete data can also be found, in the case of Italy on Terna, and for Portugal on the EDP websites, with a relatively overestimation when compared to ENTSO-E's information. The Table 9 will define the nominal power for the simulations in chapter 6.

Table 9 PHS Installed capacity systems in Italy and Portugal, source ENTSO-E [25]

Italy	Installed capacity (MW)	Portugal	Installed Capacity (MW)
Entrecque-chro	1064	Frades II	780
Presenzano	1005	Alqueva	508
Roncovalgrande	1000	Aguieira	336
Edolo	950	Foz Tua	261
Anapo c.le	500	Salamonde II	220
S.Massenza 1	377	V.Nova II (Frades)	191
Bargi centrale	281	Baixo Sabor Montante	153
S.Fiorano	272	Vilarinho F.	125
Taloro 1	240	**Total**	**2574**
Fadalto	210		
Provvidenza	139		
Gargnano	137		
Entrecque Rovina	125		
Riva de Garda	117		
Capriati	113		
Guadalami	80		
Pracomune	35		
Telessio	35		
Total	**6680**		

4 Storage in the Energy Market

The energy (electric) market is one crucial instrument for the fulfilment of the energy requirements of a nation. Normally, operations such as generation, transmission and distribution of energy are considered vital for the state, while the energy market is neglected. On the contrary, the energy market is responsible for the management of two important operations: regulated energy production and management of the safety and reliability of the transmission network. On the past decades there was a transition from the regulated market to a liberalized market. In the regulated market the production is controlled by the state presenting a regulated tariff, while the liberalized market has several competitors and the prices result on a balance between the producers and distributors. The Figure 30, exemplifies the behavior of both markets.

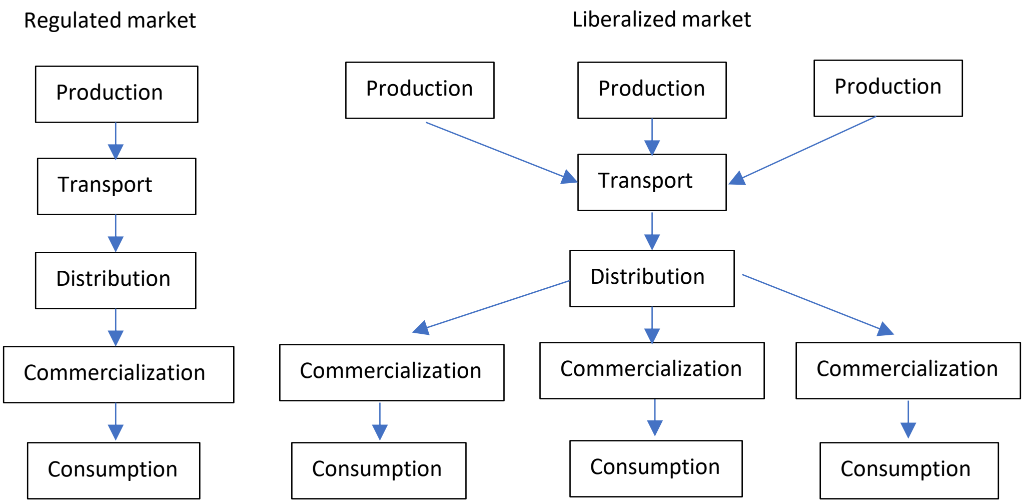


Figure 30 Regulated and liberalized market

The liberalized market increases the competitiveness between the producers, requiring them to improve their processes and managements, in order to practice the best prices. The advantages are: avoiding the control from a monopoly, best prices for the consumer, optimization and improvement of each stage (production, transport, distribution and commercialization), improvement of the intercommunications between countries (when applied) and independency from the regulated authority.

The electric liberalized market respects the same economic principles as other types such as cars or cellphone markets. The markets search for an optimization of the supply and demand curves. As observed in Figure 31, there are 3 possible cases:

- On the right side of the equilibrium point or market clearing price, there is an excess of generation in the market in relation to what the buyers are disposed to pay, therefore there is a surplus of supply: for any price higher than p* in the graph below, the quantity offered will be higher than the quantity demanded;

• On the left side of the market clearing price, the producers are generating a smaller amount than what the buyers desire, resulting in a shortage of supply: for any price lower than p*, the quantity offered is lower than the quantity demanded;

• The market clearing price is the one for which the quantity offered and demanded equalize (q* in the graph), leading to a complete disappearance of any surplus/shortage of supply.

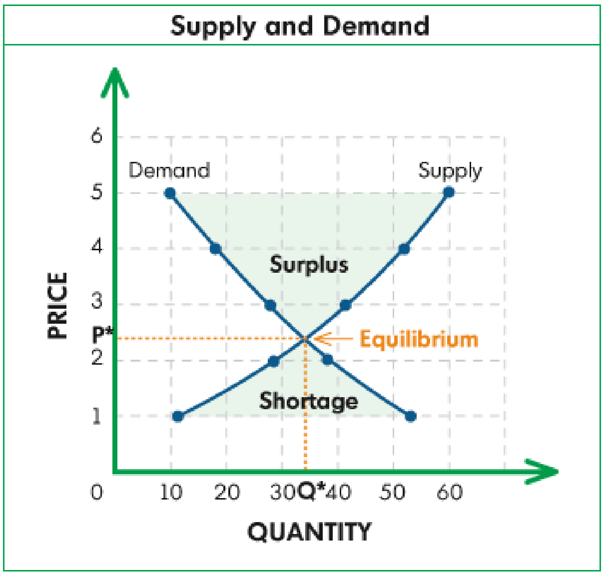


Figure 31 Supply and demand curves[26]

A proper regulation of the electric market is very important, since the stockage of energy is problematic. The demanded power curve (demand curve) is predicted based on several complex algorithm (controlled by the regulatory authority). The supply power curves are computed by the producers, expressing how much they are willing to generate and the relative price. Then the producers send the curves to the regulatory authority, which after designing the supply demand diagram, starts determining the market clearing price. The market clearing priced is defined specialized algorithm (different from the one used to compute the demand power curve), whose purpose is to maximize the welfare for the producers and intermediate consumers.

The regulatory authority is responsible to define each producer’s quota, time period and power supplied. A report is emitted to inform the transmission network company, of the days planning.

The European Union has stipulated several directorates, obliging the liberalization of the energetic market on the state members. Now, all countries all state members have a liberalized market except Hungary and Estonia. With the idea of creating a European Transmission Network (ENTSO-E) there are regional market areas including several countries, such as the Nordics regions, Southeast region and MIBEL (Iberian Market).

4.1 Rules of Energy Market in Italy

The Italian Energy Market was transitioned officially from the regulated market to the liberalized market in 1999, as requested from the European Union. However, only at the beginning of April 2004 the market was operative. Before, ENEL was a state-owned company and was responsible to supply the energy needs until 1992 when was gradually privatized. With the opening of the market, existing and new companies such as Edison, Agsm Energia, Acea Spa, A2A and Illumia appeared and got more influential in the market.

The electric network is controlled by two companies: Terna S.p.A. and Gestore Mercati Energetici (GME). Terna is an electricity transmission grid operator. Its main responsibilities are to ensure the transmissions and reliability of the network in Italy and "invest in innovative solutions for the energy market", both nationally and internationally. It is a private company with public service mission.

GME is the market operator responsible to analyze the supply and demand curves for the electric, gas and fuel market. GME is owned by the Ministry of Economy and Finance and follows the guidelines from the regulatory authority ARERA (Autorità di Regolazione per Energia Rete e Ambiente). The Figure 32 shows how the spot electricity market ("mercato a pronti") and the forward electricity market ("mercato a termine") are divided:

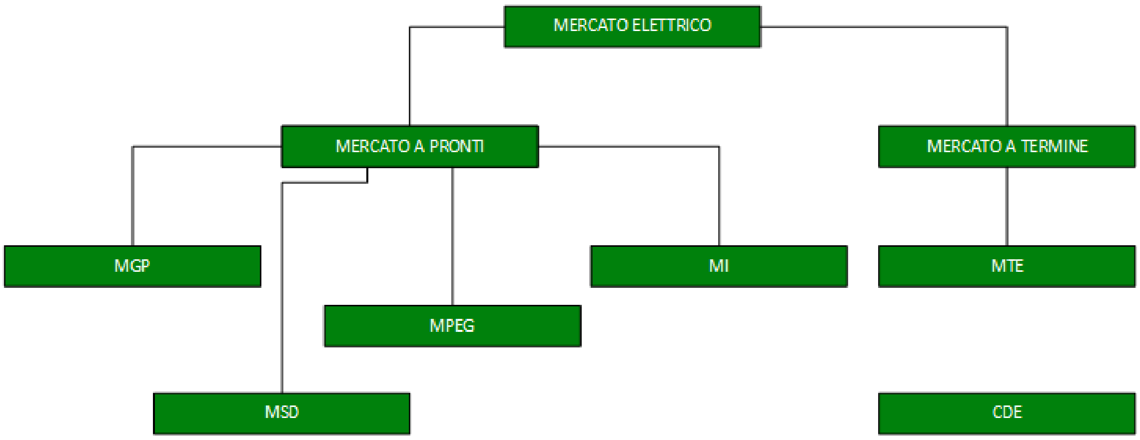


Figure 32 Structure of the Energetic Market, MGE

The spot electricity market is divided into 4 categories:

- The day a head market/spot market (MGP), which participants energy block sales consumed on the next day. For this trade, the participants bid the quantity of energy acquired and the maximum and minimum price willing to purchase and sell. The period of trade occurs on the morning before the day. This market allows the buyer to acquire energy after the bidding if there is availability from the supplier and the transmission grid. The price applied is a Prezzo Unico Nazionale, which consist on the average price of each geographical zone;
- The Intra-day Market (MI) allows the participants to exchange the schedules agreed in the MGP, by complementing with offers and bid demands. There are 7 possible sessions, which start on the day before the day of delivery and may finish on the day of delivery. The biddings are according to the regional prices;
- The Dayle Products Market, (MPEG) "is the venue for trading of daily products with the obligations of energy delivery";
- The Ancillary Services Market (MSD) allows Terna S.p.A to manage and monitor the electrical grid. This market is responsible to safeguard the reliability and safety of the grid, solving problems related with congestions, real-time balances and regulate the network's frequency. Furthermore, MSD can also be used to create momentary energy reserves. This market presents 6 sessions.

The Forward Market (MTE) takes care of forward contracts for energy. The participants agree on price previously to protect themselves from the possible spikes of the price. The producers fix a future PUN which can cover possible losses from low PUNs during a period (short positions) and the re-sellers have (long positions) in order to avoid high PUNs. This type of market can be used to protect the base and peak load durations.

The last type of market is the Delivery of Electricity Derivatives (CDE) and it uses financial electricity derivatives contracts for trading. These contracts called IDEX are traded in the Borsa Italiana S.p.A. The IDEX, allows the participants to request a physical amount of energy negotiated at the Energy Market. The participants need to have an electricity account at over the counter contract registration platform.

4.2 Rules of Energy Market in Portugal

In 1995, with the new European Directives demanding a gradual transition to a liberalized market, the Portuguese government approved the presence of private companies to compete against the regulated market. The regulated market was controlled by EDP, a company that was partially privatized in 1992. At the same time, ERSE (Entidade Reguladora do Sector Elètrico) was created as a regulatory authority, to control the transmission network, producers and the electrical market.

Similar to Italy, the transmission network is an independent sector, but it is a privatized company owned by the State Grid of China, Oman Oil, Lazard Asset Management LLC and many others. REN mission respects the European Directives objectives.

Even though the Portuguese electrical market is liberalized, EDP still presents around 50% of the quota, while Iberdrola, Endesa and Galp are only around 20%.

The Portuguese energy market is a combined market with Spain, called MIBEL (Iberian Electric Market). The participants from each country can take part of the offer/bidding negotiations. The MIBEL has 4 markets like Italy: Day-a-head market, Intraday Market, “Forward market” and Ancillary service market. They present the same general behavior as the Italian market with some exceptions.

The Day ahead Market and Intra-day Market result in combined supply and demand curves for Portugal and Spain, where the clearance market point defines the unitarian price for all regions. Additionally, MIBEL predicts capacity to satisfy the commercial agreements for both countries’ if they cannot support the energy intercountry flux. The transmission grid between the two Iberian states has a transport limitation of 2600 MW in the direction Portugal to Spain and 2 000 MW in the direction Spain to Portugal. In case the limit is surpassed, the two markets separate and each one applies a different unit price. For instance, if there was a higher power requirement from Portugal than 2600 MW, the Portuguese electrical market would establish a new electricity price and new producers. The Figure 33 shows the difference between MIBEL and the Iberian markets separated.

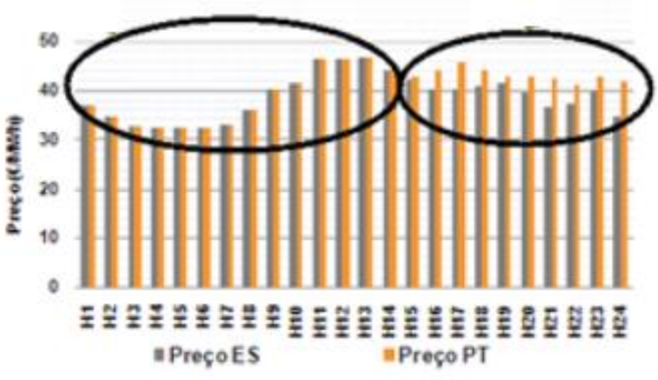


Figure 33 Market Splitting in MIBEL[27]

The Portuguese and Spanish governments plan to increase transmissions grid transport capacity to 3 000 MW (Portugal to Spain) and 3 600 MW (Spain to Portugal) by 2030 [28]. On the forward market energy suppliers and energy consumers trade energy amounts on a long-term horizon (i.e. days, weeks), in order to mitigate the risks of possible variations in prices. Most of the contracts traded on this market have standardized rules and pre-defined amounts and are dealt by a central compensation entity (câmara de compensação), which intermediates the requests from both suppliers and consumers.

4.3 Rules of Energy Market in Australia

The department of Environment and Energy is responsible to seek to realize the energy polices from the Australian government. The energy policies are supported and applied by the following bodies:

- Australian Energetic Market Commission, which is responsible to develop the market rules;
- Australian Energy Regulator, whose role is to monitor and investigate the compliance with the national energy legislation (promoted by Australian Energetic Market Commission);
- Australian Energy Market Operator, the manages the daily operations in the electrical and gas market;

The Australian Energy Market is divided into two Energy Markets [29]: The National Energy Market (NEM) where there is a transmission networks connecting 5 regions (Queensland, New South Wales, Victoria, South Australian and Tasmania). The NEM was created in 1998. The second electric market connects the Western Australia and the Northern Territory, designated as Wholesale Energy Market (WEM). The energy markets are not interconnected.

The NEM is a wholesale market with a two type of market: a spot market (day ahead market) and a financial “forward” market. The spot market behaves just like day a head market from Italy and Portugal, where producers and retailers submit their supply and demand curves to practice the best price. The NEM spot market registers the price for all 6 regions every 5 minutes and at the end of 30 minutes estimates an “average spot price” that defines the cost in a certain region. In the financial market, the operator takes into consideration the “average spot price” to allow the producers and retailers to agree on a price for a future demand. The Australian Energy Market in 2017 established a maximum and minimum spot price of (14 200 $/MWh and -1 000 $/MWh) to avoid the extremely high energy prices in Australia. The Grattan institute identified 3 causes: two very old coal power plants closed reducing the number of producers, the increased cost of fuel and gas and the possibility of the producers to take advantage of the system. In Australia the producers concentrated on suppling energy during a period so to create an artificial scarcity of supply during other periods. This behavior obliged a step raise of the prices [29][30].

The WEM presents the Ancillary services, the bilateral contracts, where the suppliers and consumers agree on the energy prices and Short-Term Energy Market, which works mainly as forward market. Moreover, the regulator uses other complexes mechanism to ensure the planning and the rights of generation energy for the regional producers

The current policy from the Australian Renewable Energy Agency (ARENA) is to increase the energetic storage capacity in the NEM so it promotes the renewable energy penetration. The strategy passes by growing the amount of BES systems and PHS in most of the regions.

Figure 34 PHS feasibility study in Australia, ARENA[29]

The creation of new projects, specially the "Battery of the Nation" in Tasmania, where it includes several PHS, will allow to supply energy to the continent and participate in the NEM through the transmission network that connects Tasmania to Victoria. The development of PHS, wind and solar will supply at 100% the energy demand of the island and contribute to the variable renewable energy penetrations goals from Australia

4.4 Rules of Energy Market in the United States of America

The energy policy in the USA is complex and has a low degree of homogeneity across each state. Since the early 1990s the general objective is, as for Europe, the transition from a regulated energy market to a liberalized one, with a view to increase the competitiveness of the price, improve the performance of the energy producers and eliminate monopolies. However, while in the EU there are clear rules compelling each country to pursue the deregulation of their markets, in the United States of America the federal government's action takes the form of a non-binding guideline (1992, Energy Policy Act). Each state can, therefore, decide whether to liberalize its energy market or not.

With the Energy Policy Act updates from 2005, an independent authority was created to regulate the interstate transmission systems (electricity, natural gas and oil). This authority, designated as Federal Energy Regulatory Commission (FERC), presents as main objectives: the review of interstate transmission systems proposals, licensing of hydropower projects, approval of the interstate wholesale energetic market prices, review of mergers and acquisitions between electricity companies, regulation of oil transportation and inspection of possible environmental damages in the natural gas, hydroelectric and oil pipeline projects.

The Figure 35 shows the liberalized markets in USA (Northeast, California and Texas). Most of the states still are regulated electricity markets. As explained before, the consumers are obliged to acquire energy from one producer from the region. Furthermore, the renewable energy technologies are controlled by some company. The liberalized market present 24 states with independent power producers and 18 states where the consumer chooses the retail company. These states' renewable penetration and type of contract are more elastic than the state regulated market. California has partially liberalized market.

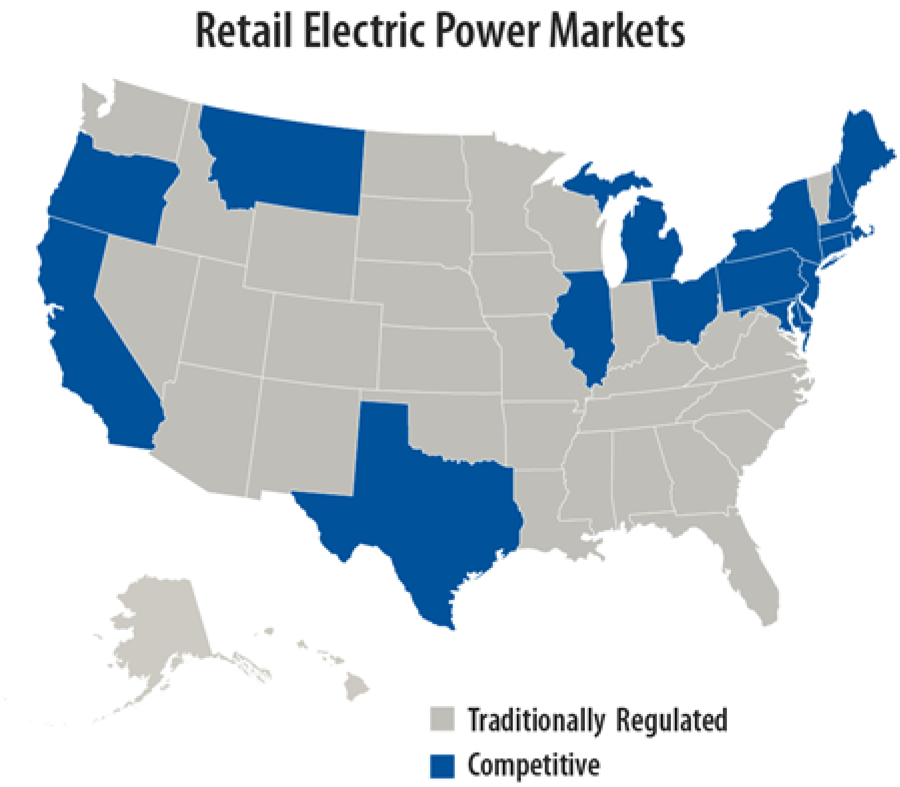


Figure 35 Retail Electric Power Markets in USA[31]

5 Understanding the PHS behavior

5.1 Graphical analysis of PHS behavior in Portugal and Italy

In the context of a national energy market, the role of the PHS system is twofold. It intervenes in the Day Ahead Market as a standard energy supplier and/or consumer, seeking to maximize its profit by either generating energy (therefore acting as a supplier) or by pumping it (therefore acting as a consumer). In both cases, the PHS system's behavior is subject to a price curve that is determined by the energy market operator in the ways described in Chapter 4. Additionally, it leverages possible energy imbalances by participating to the Ancillary Service Market.

The present chapter analyses the performance of the PHS systems in the Italian and Portuguese day ahead markets (therefore, in its role as standard energy supplier/consumer) according to 3 different variables: Cost of Electricity, Energy Pumped and Energy Generated. The Energy Pumped and Energy Generated datasets were obtained through the ENTSO-E website (European Network Transmission System Operators for Electricity) for both countries, whereas the price of electricity was obtained from a different source. The Italian price of electricity was obtained from Day Ahead Market (GME), while the Portuguese price was obtained through MIBEL (the day ahead market from Portugal and Spain) in Rede Energética Nacional (REN). The data is from the year 2017.

5.1.1 Graphical analysis of PHS behavior in Italy

The Figure 36 shows the relationship between the Energy pumped and the Cost of Electricity through the year of 2017. The timestep observed in the graph is daily and its tendency during each day is easily observed. The right side has axis correspondent to cost of electricity (in blue) and the E. pumped is represented in the left axis (in orange).

Timewise, the amount of energy pumped tends to be higher in Winter and Autumn, whereas the price increases in autumn-winter and lowers in spring-summer.

There are around 8735 points (the ENTSO-E has no information on the November 9th so the day is not studied), so the trends cannot be distinguished in a simple graphic. The Energy Pumped presented a maximum of 3250 MWh (at 14:00 in 17/04/17) and a minimum of 0 MWh (several periods). As for the Price data, it presented a maximum of 170 (at 17:00 in 13/12/2017) and a minimum of near 10,00 €/MWh (from

13:00 to 15:00 in 21/05/17). The general (hourly) standard deviation from the Energy Pumped and Price, through 2017, are 446 and 16, respectively.

Although a clear dynamic between the 2 variables is not visible at this level, it is nonetheless worth to notice that, besides an hourly dependence between the two variables, the prices and the Energy Pumped present a dependency on the seasons.

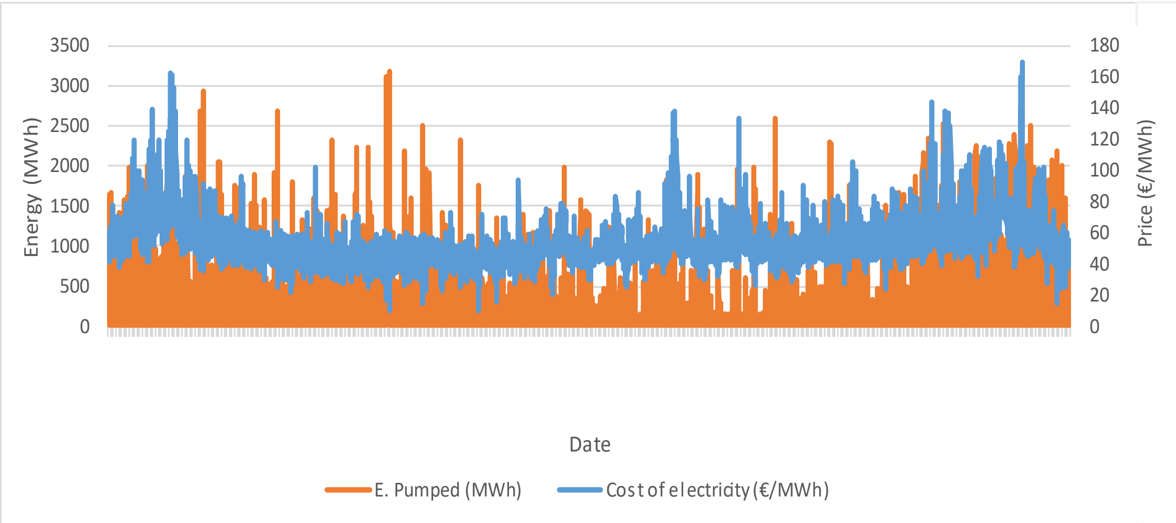


Figure 36 Energy Pump and Cost of electricity variation in Italy during 2017

The Figure 37 is like the previous one, except studies the relationship between the price and Energy Generated. The right-side axis corresponds to cost of electricity (in blue) and the left side is the Energy Generated (in green).

The Energy Generated presented a maximum of 3650 MWh (at 19:00 in 21/09/17) and a minimum of 0 MWh (several periods). The price presents the same values as the previous graphic. The general (hourly) standard deviation from the Energy Generated and Price, through 2017, are 466,14 and 16,34, respectively.

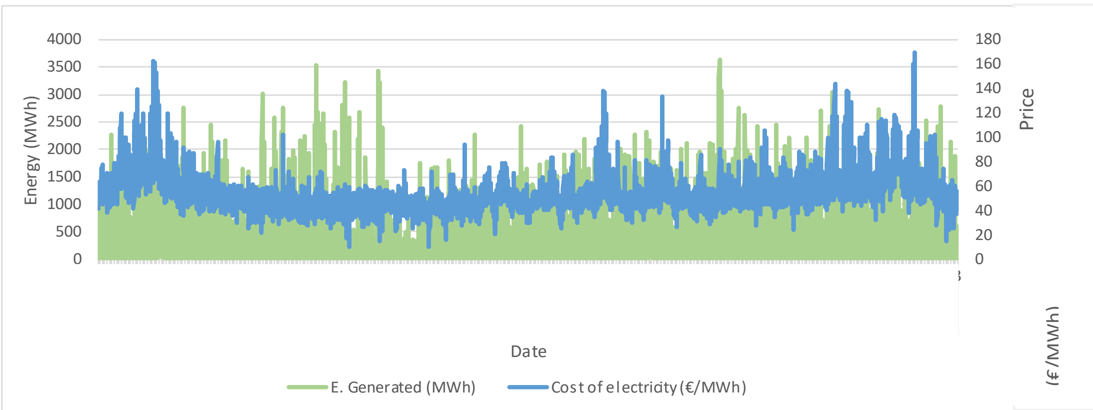


Figure 37 Energy Generated and Cost of electricity variation in Italy during 2017

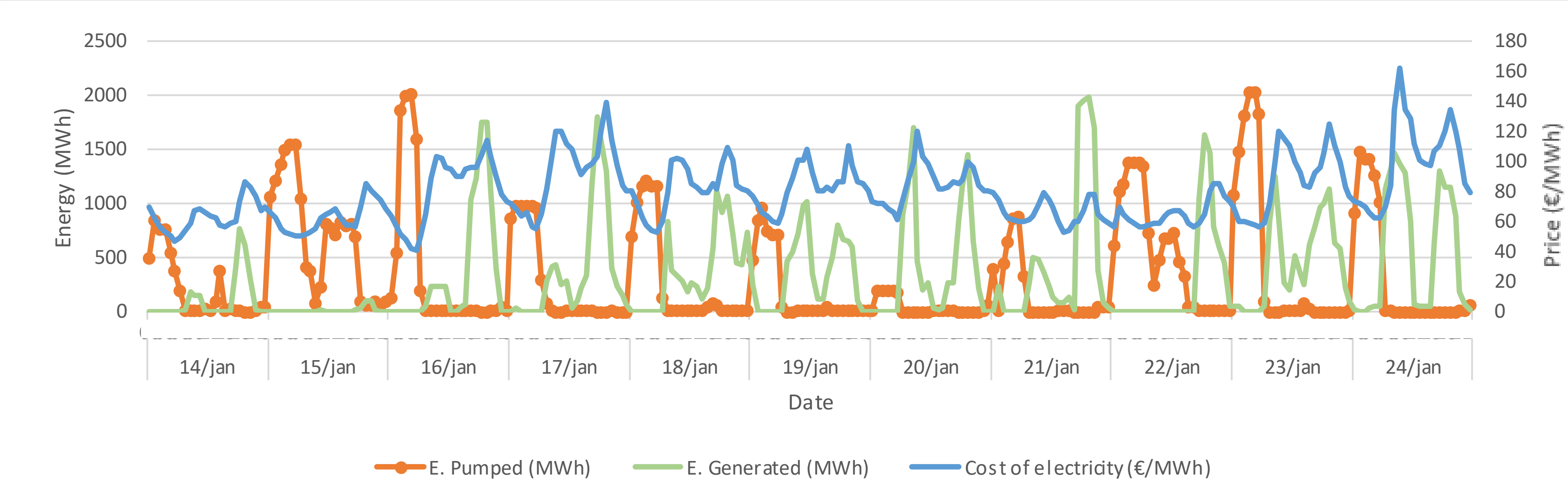
The next series of graphs (Figure 38) shows the observed data in study divided according to each season (winter, spring, summer and fall). As both countries are Mediterranean countries and they present similarities in their climate, such as the 4 seasons. They were considered in the following way:

- Winter season from December to February;
- Spring season from March to May;
- Summer season from June to August;
- Fall season from September to November

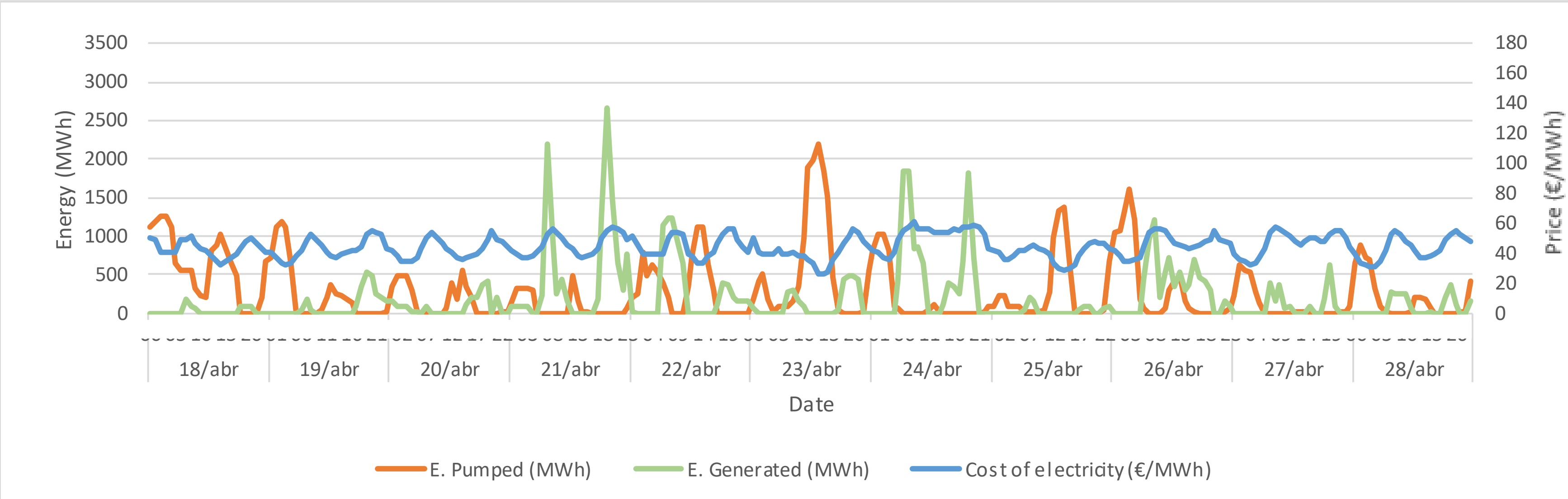
For a better comprehension of the behavior during each season, the graphics were simplified for one/two representative weeks. The reduction of the points allows a better understanding of the hour dependence in each season. The Table 10 expresses the average results observed in each graphic.

Table 10 Average Price Values in 2017, Italy

	Winter	Spring	Summer	Autumn
High average Price (€/MWh)	100	60	55	80
Low average Price (€/MWh)	60	40	40	40
High average Energy Pumped (MWh)	1600	1000	750	750
Low average Energy Pumped (MWh)	0	0	0	0
High average Energy Generated (MWh)	1500	1100	1600	2000
Low average Energy Generated (MWh)	0	0	0	0



Energy (MWh)
2500
2000
1500
1000
500
0
14/jan
15/jan
16/jan
17/jan
18/jan
19/jan
20/jan
21/jan
22/jan
23/jan
24/jan
Date
180
160
140
120
100
80
60
40
20
0
Price (€/MWh)
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)



Energy (MWh)
3500
3000
2500
2000
1500
1000
500
0
18/abr
19/abr
20/abr
21/abr
22/abr
23/abr
24/abr
25/abr
26/abr
27/abr
28/abr
Date
180
160
140
120
100
80
60
40
20
0
Price (€/MWh)
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)

Figure 38 PHS's Energy Pumped, Energy Generated and Price behavior during 10 average days in each Season, Italy

At the moment it was only identified the influence of the season in our data, missing a study of the variation through the day. After a short analysis of the average hour variation in the cost of electricity some conclusions were observed and can be expressed on the Table 11:

Table 11 Average Price, Energy Pumped and Energy Generated by hour, in Italy

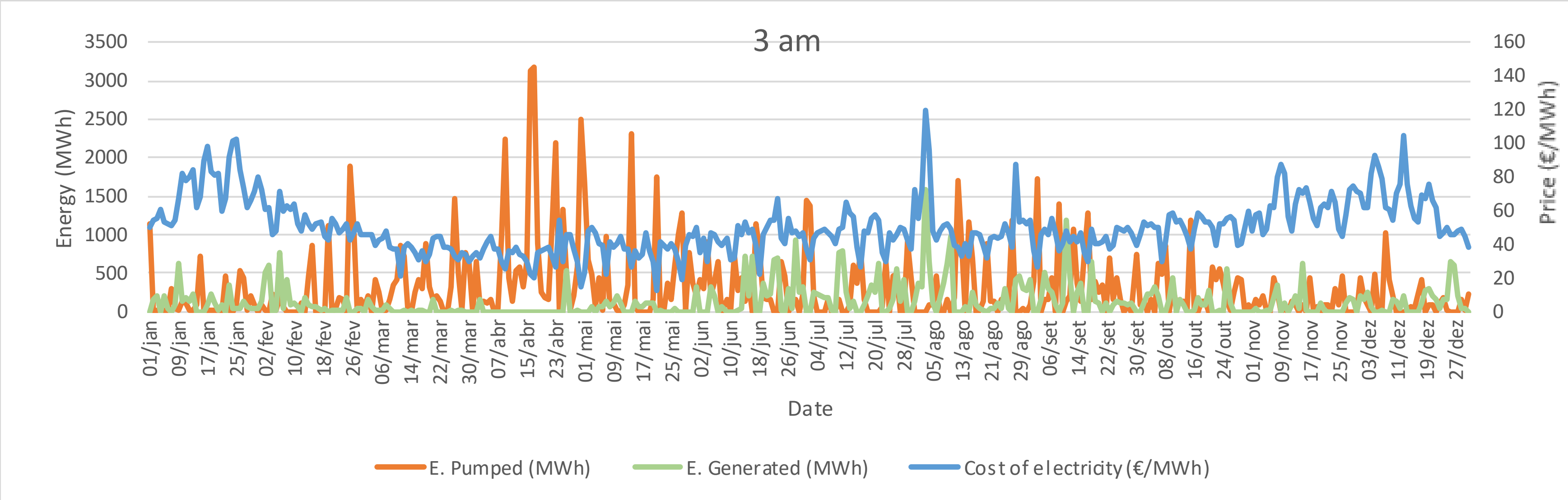
	PRICE	E. PUM	E. GEN		PRICE	E. PUM	E. GEN
0	49,75	448,9	29,7	**12**	51,5	290	112,1
1	46,14	671,2	19,8	**13**	49,72	**305,6**	125,4
2	43,6	825,3	9,2	**14**	51,11	261,8	165,5
3	42,22	**856,6**	8,7	**15**	53,6	161,2	243,5
4	42,1	769,7	11,9	**16**	57,16	74	403,6
5	43,95	499,2	40,2	**17**	60,67	25,5	771,9
6	48,73	168,9	237,8	**18**	64,61	14	**1083,4**
7	55,19	89,5	**521,2**	**19**	**67,7**	10	**1084**
8	**60,7**	71,5	463	**20**	65,42	14,1	644,5
9	60,14	85,4	316,5	**21**	60,89	24,9	281,9
10	57,48	116,4	225,2	**22**	55,5	54	124,7
11	55,24	189,1	145,8	**23**	51,66	179,9	88

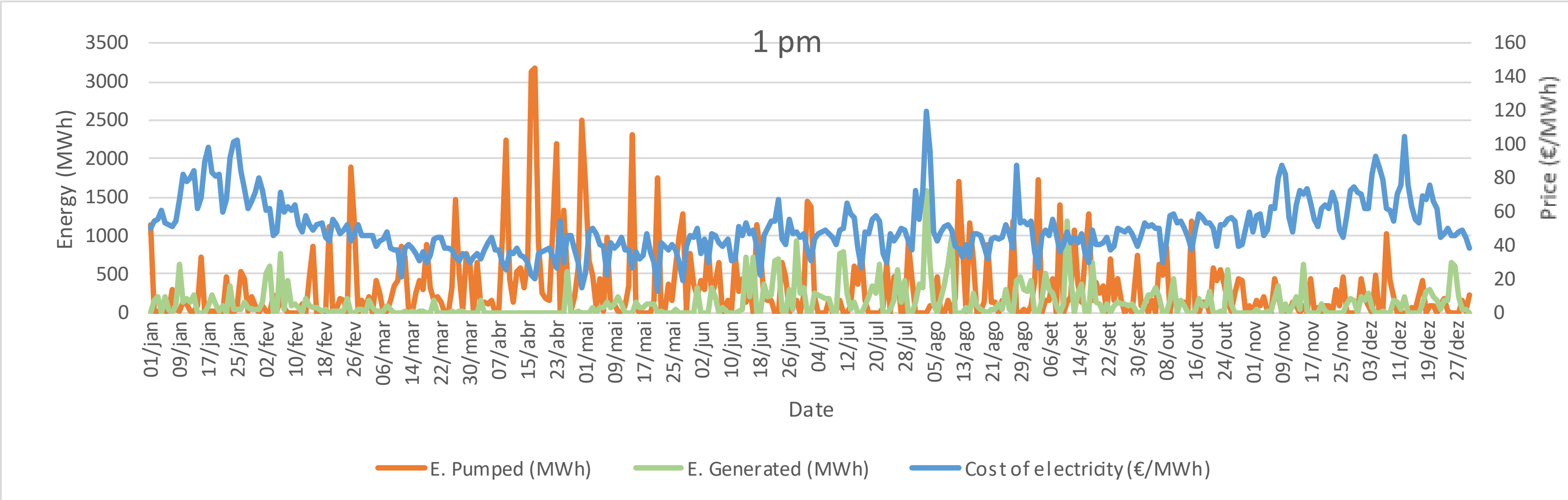
As observed in the Figure 39 we can understand the most relevant periods for the Reservoirs to pump and produce energy, according to the variation of price during the day. There are two upward peaks visible, the first near 8 and 9 a.m. and the second 7 and 8 p.m. The average price per hour graphic presents a lower 7,42 standard deviation, explaining the small deviation during the hours between 40 and 70 €/MWh.

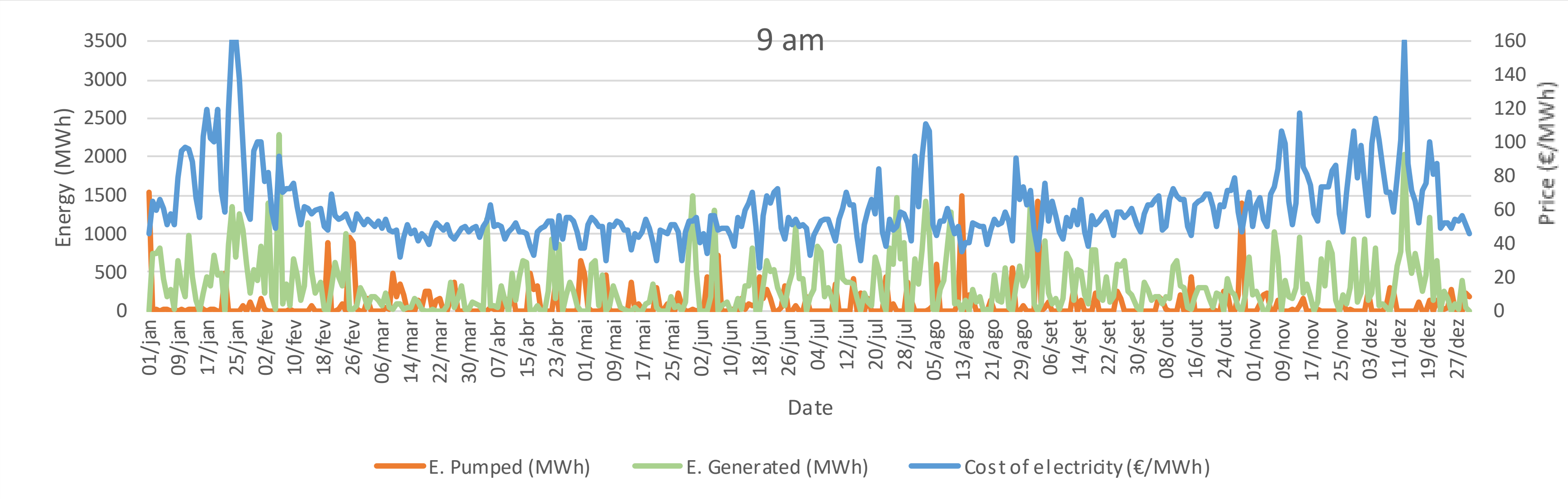
The Energy Pumped has two distinct peaks, one at around 3am and one at 1pm.The maximum and minimum observed in the table are 856,6 MWh and 305,6 MWh. The standard deviation is 273,15. Comparing the two variables Energy Pumped and Price, we see a negative correlation. Thus, if the price increase, we should expect to reduce the energy pumped to the reservoir.

Discussing the Energy Generated two distinct peaks are visible, one at around 9am and one at 6 and 7 pm. It is still worth to remember that, variations during the year are possible and are quite common: whereas as the maximum and minimum are 1083,4 MWh and 8,7 MWh. The standard deviation is 311,17. In this case the Price and the Energy Generated are positive correlated.

As an example of how the main variables are subjected to variations at each hour, 4 hours (3am, 1pm, 9am and 7pm) were designated to represent the peaks of Energy Pumped and Energy Generated. The correlations of price hour and price vs Energy Pumped (or Energy Generated) are observed in the Figure 39.


3 am
Energy (MWh)
Price (€/MWh)
3500
3000
2500
2000
1500
1000
500
0
160
140
120
100
80
60
40
20
0
Date
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)


1 pm
Energy (MWh)
Price (€/MWh)
3500
3000
2500
2000
1500
1000
500
0
160
140
120
100
80
60
40
20
0
Date
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)



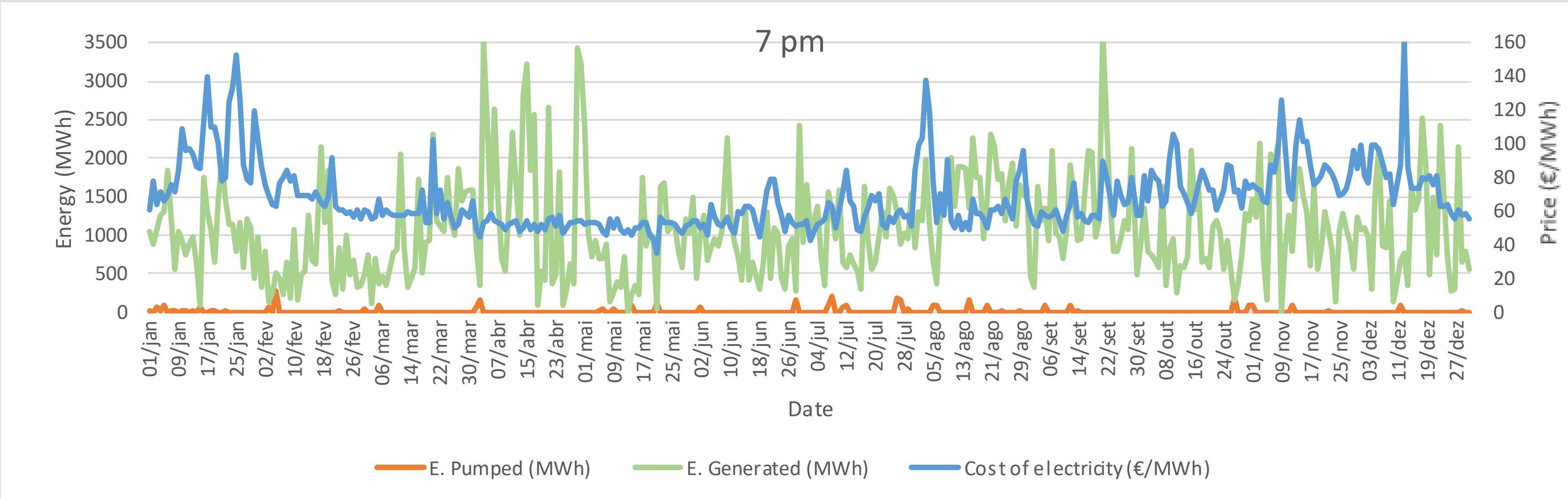


Figure 39 PHS's average Energy Pumped, Energy Generated and Price behavior at 3 am, 9 am, 1 pm and 7 pm, Italy

The Figure 40 presents the price and the Energy Pumped Average on the x axis and y axis, respectively. It simplifies the problem, since does not consider the time variation dependency. While the initial the graphics clearly show tendency correlated with the hours of the day and the seasons, the current graph ignores it. A secondary problem is the usage of the concept of Average Energy Pumped, which in case one or more points with the same price it will assume the mean average of the Energy Pumped (once again ignoring other possible factors). The graph has a logarithmic tendency explained by the equation y=-602,8 ln (x)+2683,3.

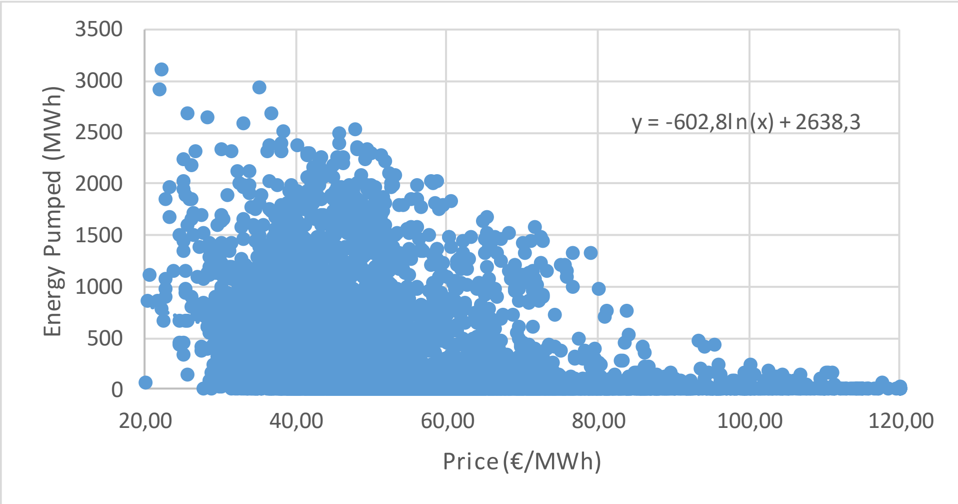


Figure 40 Energy Pumped in function Price, for the Italian PHS system

The Figure 41 presents on price and the Energy Generated Average on the x axis and y axis, respectively. Once again, it simplifies the problem since does not consider the time variation dependency. The graph has a logarithmic tendency explained by the equation y=737,51 ln (x)-2614,1.

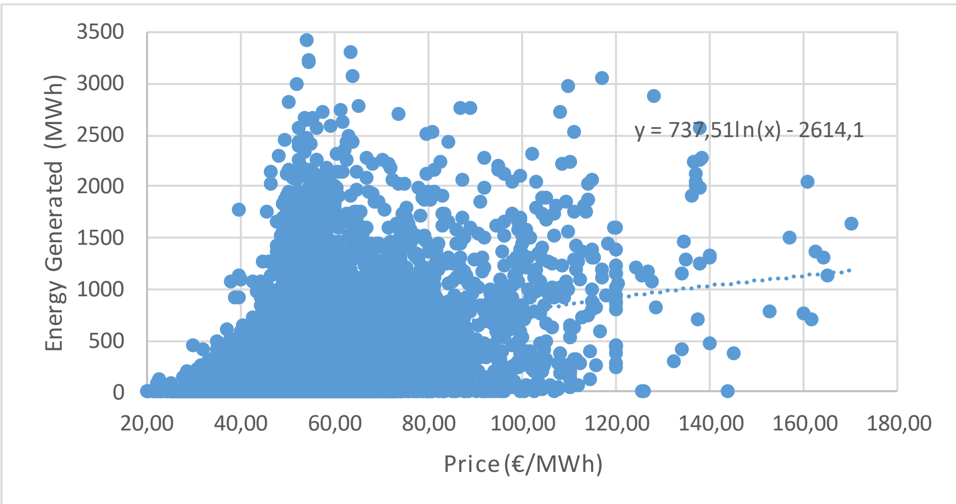


Figure 41 Energy generated in function of Price, for the Italian PHS system

5.1.2 Graphical analysis of PHS behavior in Portugal

The Figure 42 shows the relationship between the Energy pumped and the Cost of Electricity through the year of 2017. The timestep observed in the graph is daily and its tendency during each day is easily observed. The right side has axis correspondent to cost of electricity (in blue) and the E. pumped is represented in the left axis (in orange). The second graphic expresses the Energy Generated over the time period (in green).

Similar to the case of Italy, in Portugal we can also conclude that the amount of energy pumped tends to be higher in Winter, end of Autumn and beginning of spring. The Energy Generated presents a very similar graphic as trend of Pumped Energy.

There are around 8735 points (the ENTSO-E has no information on the November 9th so the day is not studied), so the trends cannot be distinguished in a simple graphic. The Energy Pumped presented a maximum of 2348 MWh (at 3:00 in 28/04/17) and a minimum of 0 MWh (several periods). As for the Price data, it presented a maximum of 103 (at 11:00 in 25/01/2017) and a minimum of near 2,88 €/MWh (from 06:00 in 05/02/17). The general (hourly) standard deviation from the Energy Pumped and Price, through 2017, are 443,6 and 12,1, respectively.

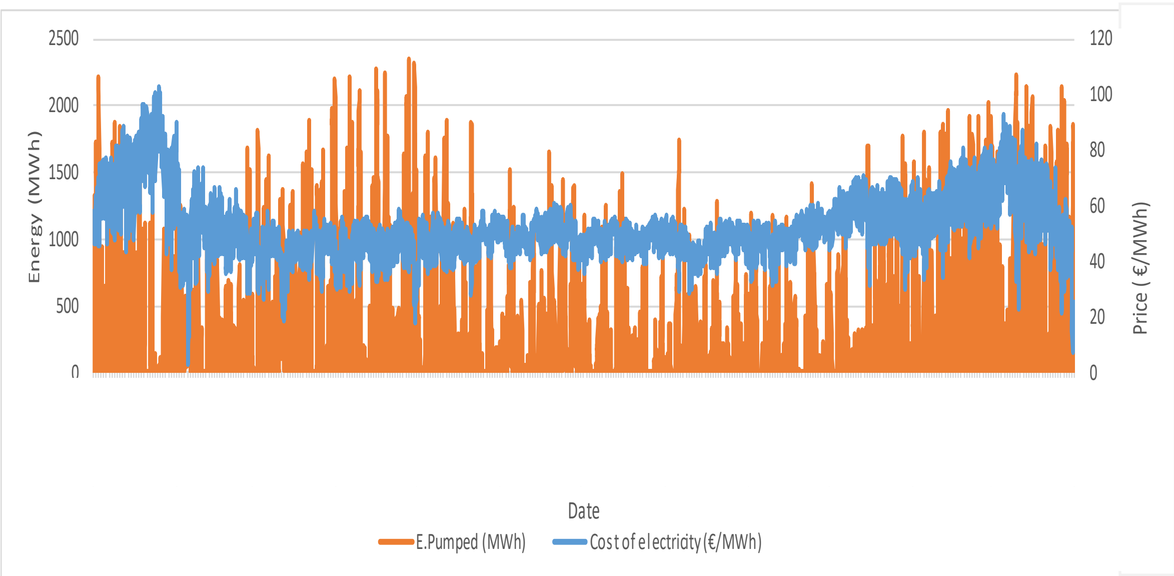


Figure 42 Energy Pumped and Cost of electricity variation in Portugal during 2017

The Figure 43 expresses the price and the energy generated. The Energy Generated presented a maximum of 2268 MWh (at 21:00 in 02/04/17) and a minimum of 0 MWh (several periods). The general (hourly) standard deviation from the Energy Generated and Price, through 2017, are 415,86 and 12,1, respectively.

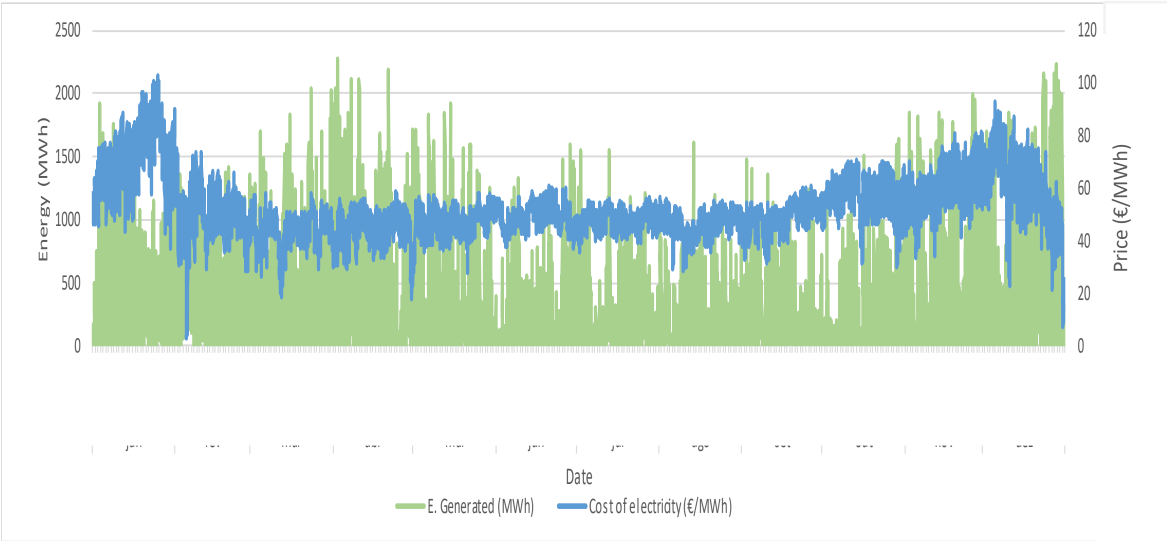
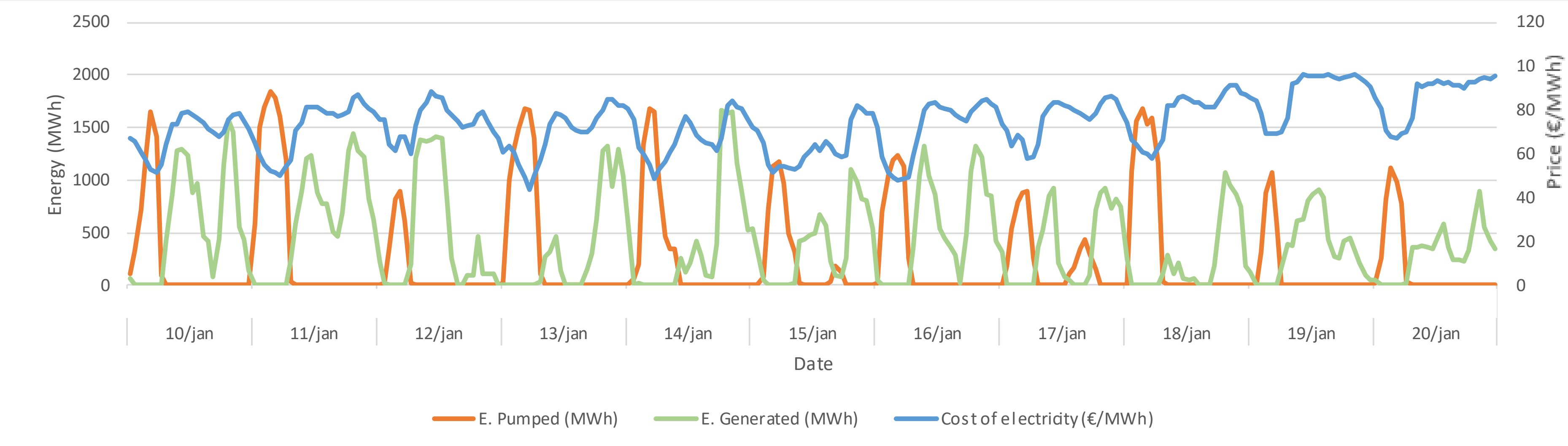
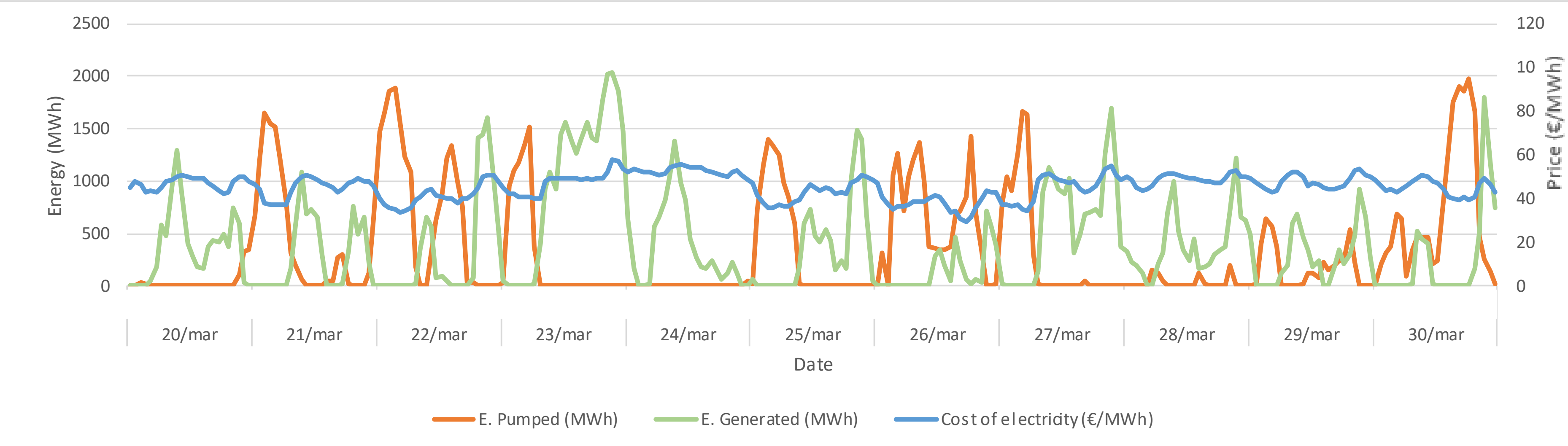
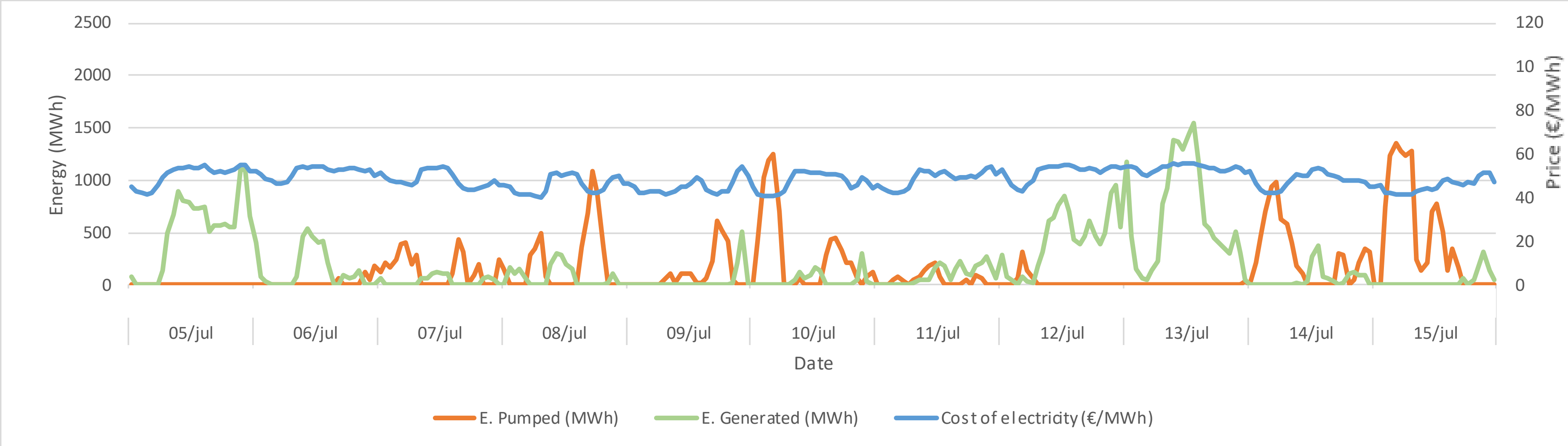


Figure 43 Energy Pumped and Energy Generated and Cost of electricity variation in Portugal during 2017


2500
2000
1500
1000
500
0
Energy (MWh)
120
10
80
60
40
20
0
Price (€/MWh)
10/jan
11/jan
12/jan
13/jan
14/jan
15/jan
16/jan
17/jan
18/jan
19/jan
20/jan
Date
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)


2500
2000
1500
1000
500
0
Energy (MWh)
120
10
80
60
40
20
0
Price (€/MWh)
20/mar
21/mar
22/mar
23/mar
24/mar
25/mar
26/mar
27/mar
28/mar
29/mar
30/mar
Date
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)



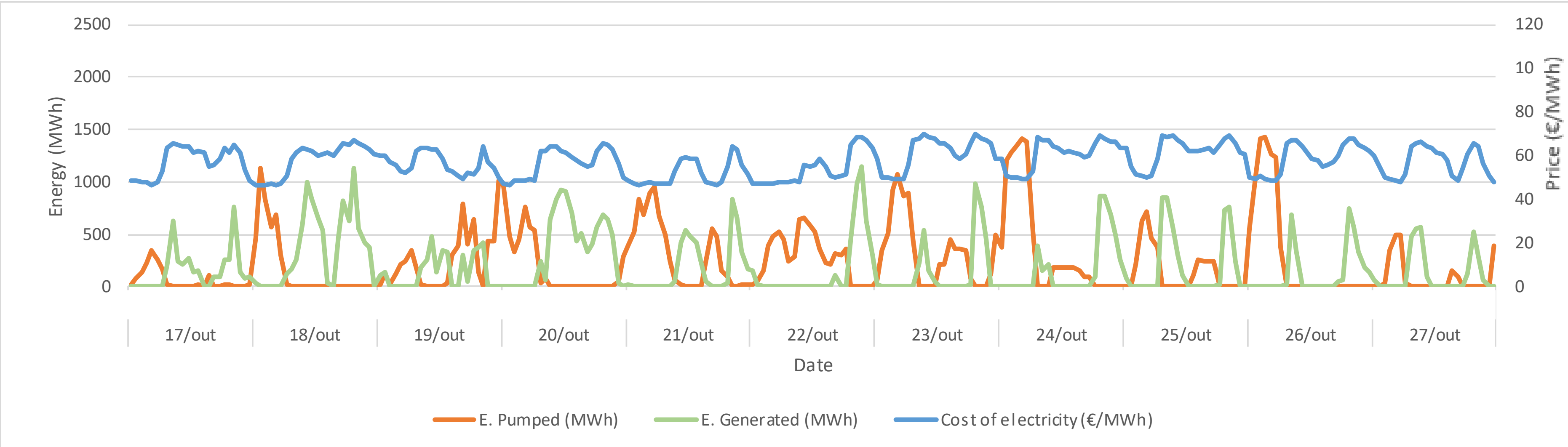


Figure 44 PHS's Energy Pumped, Energy Generated and Price behavior during 10 average days in each Season, Portugal

As both countries are Mediterranean countries, Portugal also presents the same 4 seasons. Once again, for a better comprehension of the behavior during each season, the Figure 44 is used to simplify the representation. The Table 12 expresses the average results observed in each graphic.

Table 12 Average Price Values in 2017, Portugal

	Winter	Spring	Summer	Autumn
High average Price (€/MWh)	90	53	55	70
Low average Price (€/MWh)	55	38	40	50
High average Energy Pumped (MWh)	1800	1700	1300	1000
Low average Energy Pumped (MWh)	0	0	0	0
High average Energy Generated (MWh)	1400	1400	1200	1000
Low average Energy Generated (MWh)	0	0	0	0

After a short analysis of the average hour variation in the cost of electricity some conclusions were observed and can be expressed on the Table 13:

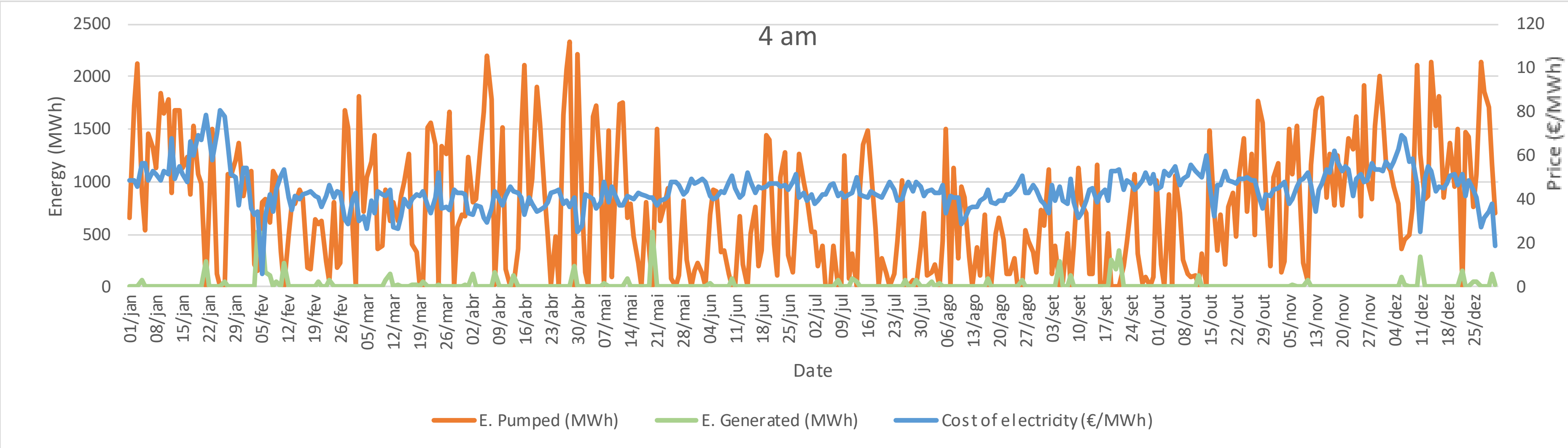
Table 13 Average Price, Energy Pumped and Energy Generated by hour, in Portugal

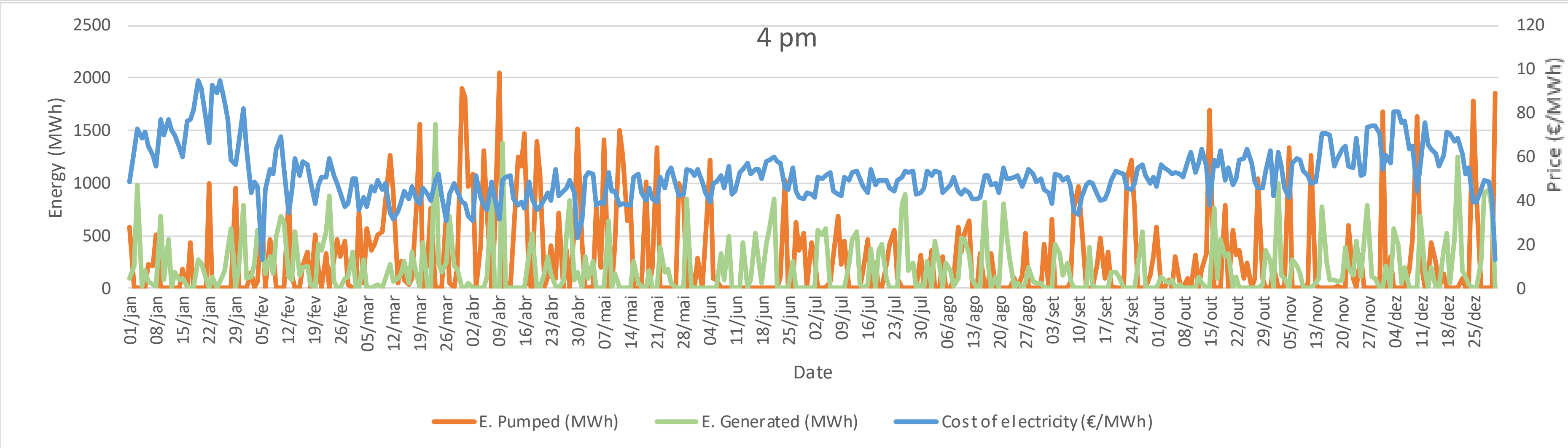
	PRICE	E. PUM	E. GEN		PRICE	E. PUM	E. GEN
0	52,32	165,1	188,2	**12**	55,3	111,1	389,9
1	49,63	359	72	**13**	55,01	115,4	368,9
2	46,99	495,2	42,4	**14**	54,13	162,9	255,4
3	45,37	642,4	25	**15**	52,56	229	187,7
4	44,45	**737**	17,4	**16**	51,42	**270,7**	179,6
5	44,5	709,6	22	**17**	51,34	257,2	214,7
6	46,06	494	50,5	**18**	52,84	197	315,9
7	49,06	325,1	187,7	**19**	55,72	126,7	544
8	53,09	235,1	337,6	**20**	57,93	48	700,1
9	54,65	170,8	443,4	**21**	**58,75**	19,7	**799,8**
10	**55,48**	129,8	**441,9**	**22**	56,77	34,4	568,5
11	55,45	111	410,6	**23**	53,74	88	301,6

As observed in the Table 13 we can understand the most relevant periods for the Reservoirs to pump and generate energy, according to the variation of price during the day. The two maximum prices observed are at 10 and 11 a.m. and the second 8 and 9 p.m. The average price per hour graphic presents a lower 10,41 standard deviation, explaining the small deviation during the hours between 40 and 70 €/MWh.

The Energy Pumped has two distinct peaks, one at around 4am and one at 4pm. The maximum and minimum observed in the table are 737,0 and 270,7 MWh. The standard deviation is 234,04. Just like in Italy, if the price increase, we should expect to reduce the energy pumped to the reservoir.

Discussing the Energy Generated two distinct peaks are visible, one at around 10am and one at 8 and 9 pm. The maximum and minimum are near 800 and 442 MWh. The standard deviation is 196,8. In this case the Price and the Energy Generated are positive correlated. Figure 45 represents the energy pumped and energy generated on the main 4 hours (4am, 4pm, 10am and 9pm).


4 am
Energy (MWh)
Price (€/MWh)
Date
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)


4 pm
Energy (MWh)
Price (€/MWh)
Date
E. Pumped (MWh)
E. Generated (MWh)
Cost of electricity (€/MWh)

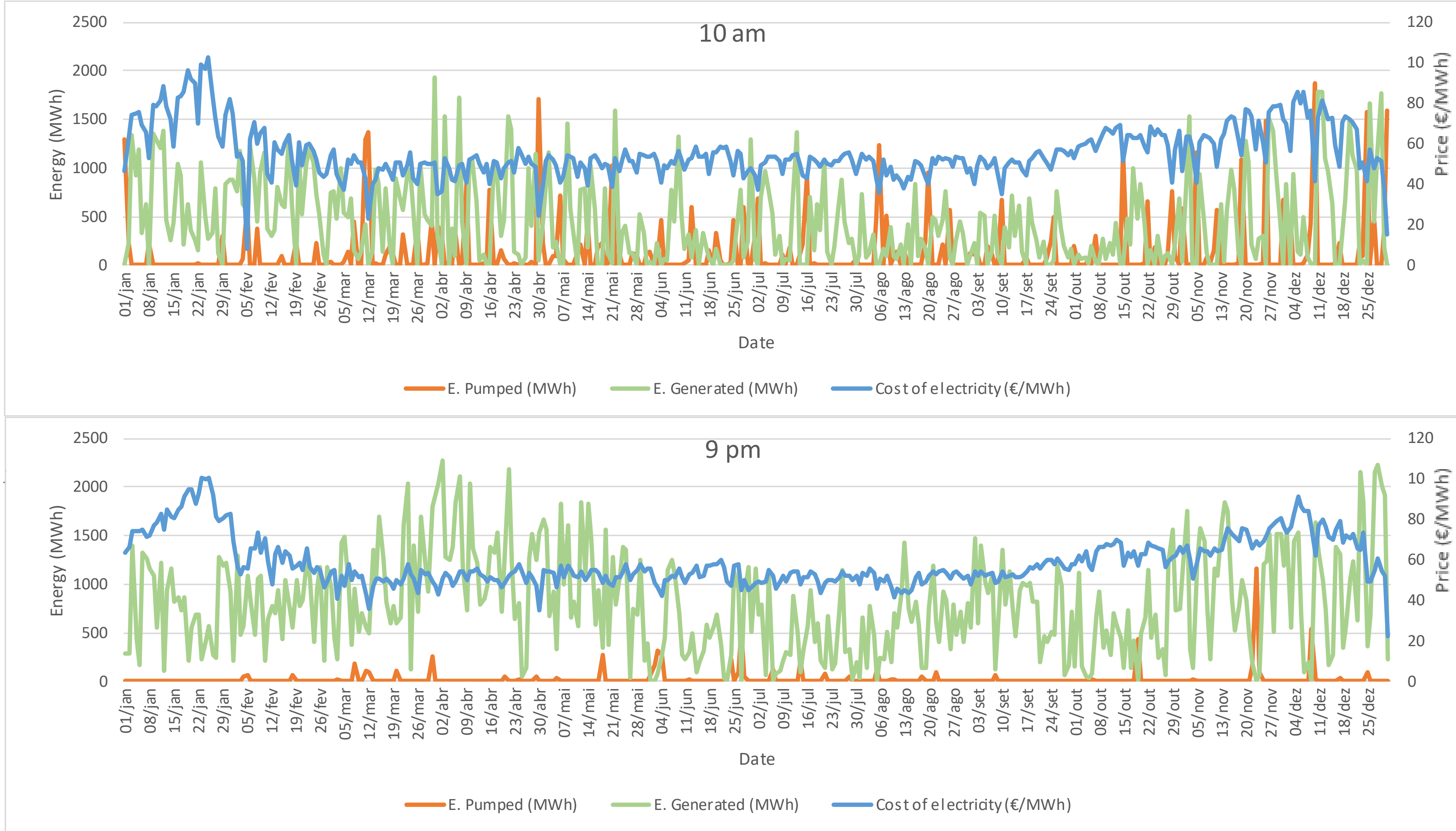


Figure 45 PHS's average Energy Pumped, Energy Generated and Price behavior at 4 am, 10 am 4 pm and 9 pm, Portugal

The Figure 46 presents on price and the Energy Pumped Average on the x axis and y axis, respectively. The graph has a logarithmic tendency explained by the equation y=-856,9 ln (x)+3626,2.

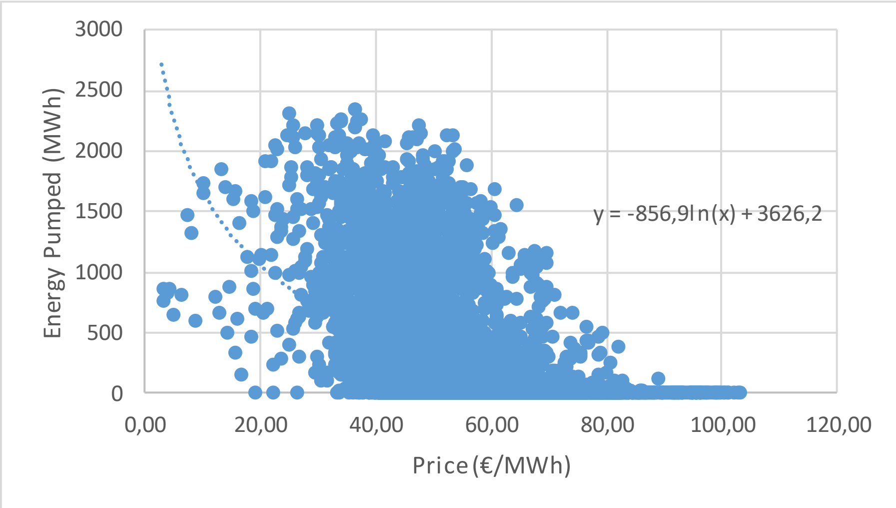


Figure 46 Energy Pumped in function Price, for the Portuguese PHS system

The Figure 47 represents the correlation between the Energy Generated and the Cost of the Electricity and has a logarithmic tendency explained by the equation y=580,98 ln (x)-1987,9.

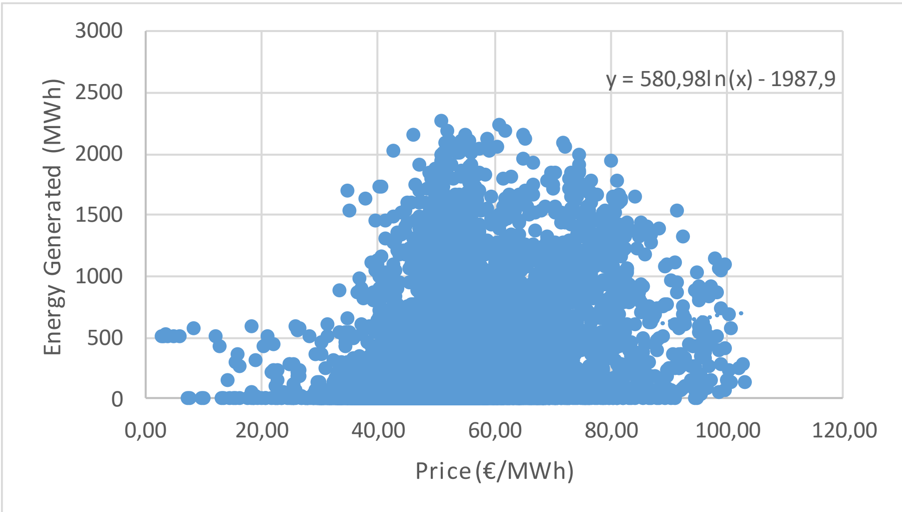


Figure 47 Energy Generated in function Price, for the Portuguese PHS system

5.1.3 Graphical analysis of Price characteristics in Italy and Portugal

To understand the behavior of the price, 4 analysis were done:

- $(Pavg)_d$

- (Avg of 5 highest hourly prices)$_d$
- (Avg of 5 lowest hourly prices)$_d$
- (Pmax/Pmin)$_d$

where d is the analysed day, Pmax is the 5 highest hourly price and Pmin is the 5 lowest hourly prices.

The first set of graphics study the price behaviour in Italy along 2017.

The Figure 48 displays the average daily price of electricity through the year. Price observations tend to remain within the 40€/MWh-60€/MWh range, except for a couple of visible peaks at during the month of January (90-100 €/MWh), the beginning of August and a relevant part of the month of December (reaching 110 €/MWh).

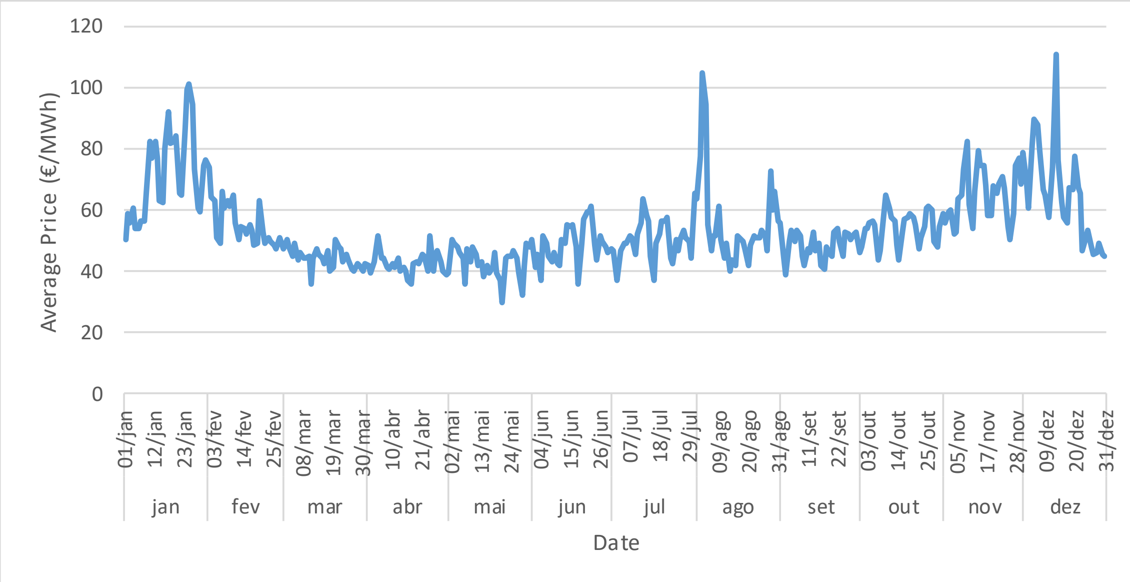


Figure 48 Average Price of electricity in Italy along 2017

The maximum and minimum hourly average price and the ratio between them are represented in the left and right graphics (Figure 49), respectively. The left graphic below shows the average of the five highest hourly prices per day curve (in blue) and the five lowest hourly price per day curve (in orange). In a brief comparison between the two curves, we see that they are like each other, presenting at the same time or upward peaks or downward peaks. Consequently, if there is an increase of the price during the day on the 5 highest prices, it will be observed an increase on the lowest 5 prices. The low average cost of electricity remains between 50 and 30 €/MWh. The curve presents two peaks above the high average (of 50 €/MWh) in January and the December. The high average prices fluctuate more than the previous curve. From February until July, the curve presents low values around 60 and 70 €/MWh. During the rest of the period, the values variate between 120 and 70 €/MWh. Moreover, the highest peaks are 3:

January and beginning August with 140€/MWh and mid-December with 160 €/MWh. The ratio between the 5 highest and 5 lowest average prices graphic shows a variation between 2,25 and 1,30. The major peaks observed are in the period of April and June, which is a season with relatively low values of price of energy.

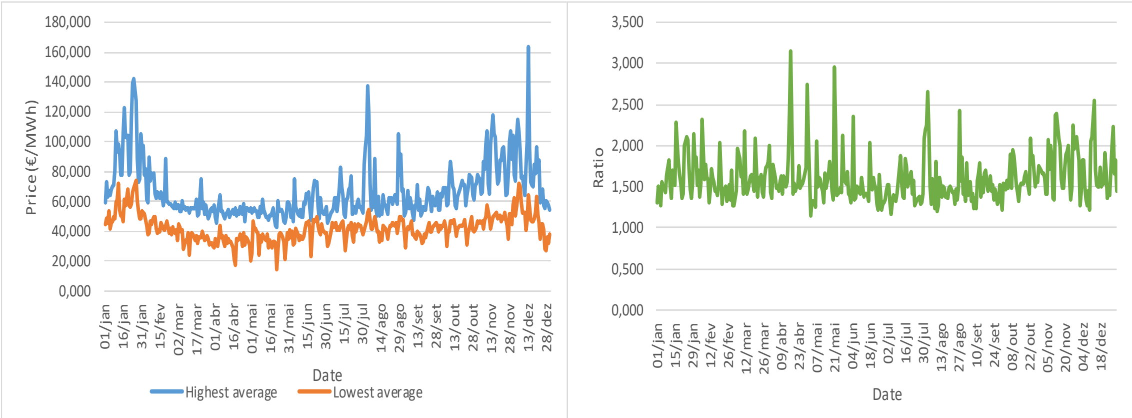


Figure 49 Right: 5th Highest average prices and 5th lowest average prices per day in Italy; Left: The ratio between 5th highest average prices and 5th lowest average prices per day in Italy

The second set (Figure 50) expresses the cost of electricity behavior in Portugal.

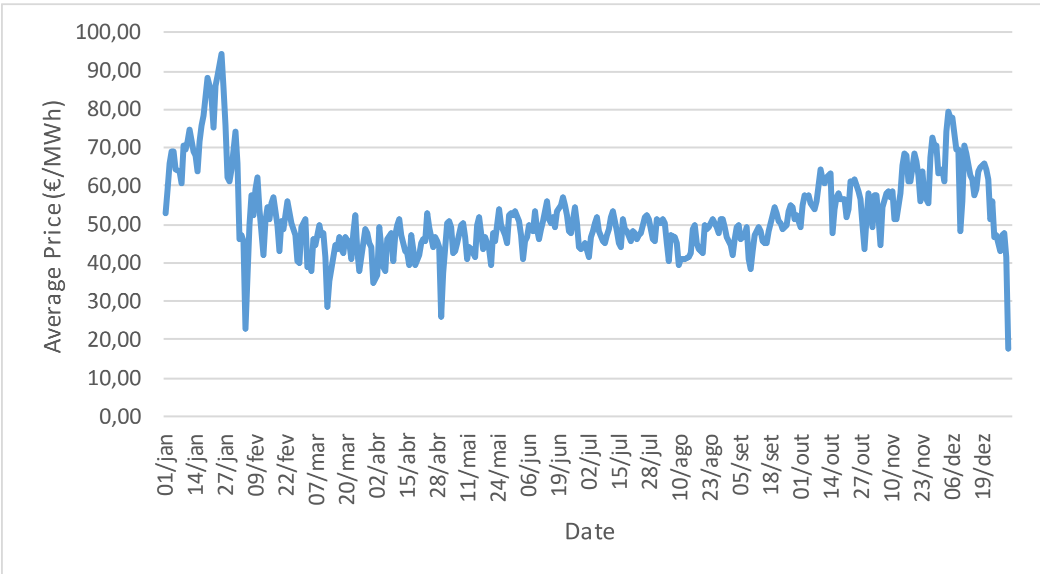


Figure 50 Average Price of electricity in Portugal along 2017

The average price observations tend to remain within the 35€/MWh-55€/MWh range, except for a couple of upward visible peak at during the month of January (90-95 €/MWh), followed by a downward peak in February (near 25€/MWh).

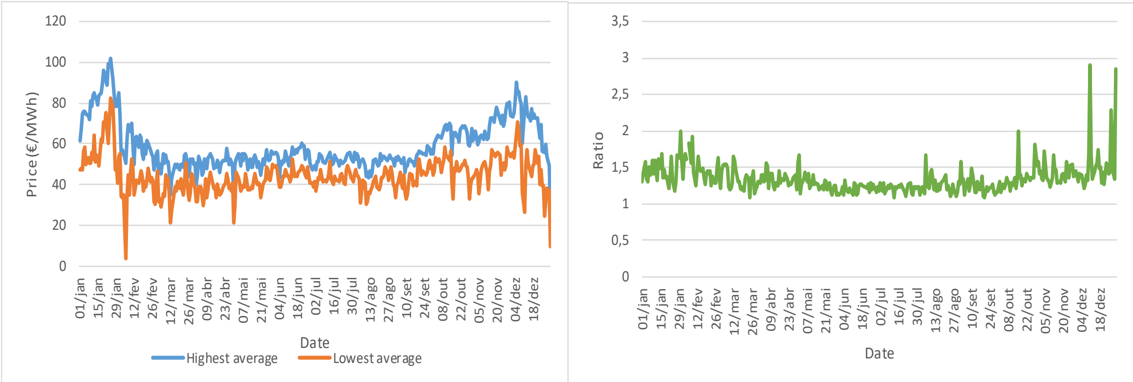


Figure 51 Right: 5th Highest average prices and 5th lowest average prices per day in Portugal; Left: The ratio between 5th highest average prices and 5th lowest average prices per day in Portugal

Similar to Italy, Portugal's *averages* curve, represented in Figure 51, has the same peaks and downwards tendencies. The difference between the higher average and low average from February to September are small, ranging from 35 to 55 €/MWh. On the other period, the higher average curve presents two maximum points of 100 (January) and 90 (December) and two minimum points of 45 and 35 (in the same period). The green graphic ratio confirms the low gaps between the two curves previously studied. The graphic normal behavior is below 1,5, meaning that the possible revenues from the activity would be quite low. To have a better observation a day in February needed to be excluded since its ratio was around 14.

5.2 Statistical analysis to understand the PHS behavior

While the graphical analysis describes superficially the trends affecting the PHS behavior, a statistical analysis permits a deeper comprehension of the collected data. The chapter presents a theoretical explanation on regression and dummy variables, the model chosen and its variables and several different parameters.

5.2.1 Linear regression and "Dummy variables"

The simplest type of linear regression is a Linear Regression with a Single Regressor. This model assumes that a dependent variable is modelled by one explanatory variable. Normally it is identified by the following equation:

$$Y_i = \beta_0 + \beta_1 X_1 + u_i$$

- Y_i is the dependent variable, or the regressant;
- X_1 is the independent variable, or the regressor;
- The term $\beta_0 + \beta_1 X_1$ is the population regression line;

- β_0 is the intercept of the regression;
- β_1 is the slope of the regression line;
- u_i is the error term;

For a good modelling it is important to have a great number of samples, that correlate properly the regressant with regressor. Sometimes neglecting part of the outliers allows a better estimation of the population regression line.

The population regression line is the relationship that holds between the independent variable Y and dependent variable X. Consequently, if the value of X is known using the population regression line is possible to predict a value of Y (the depend variable).

The population regression line presents two parameters: the slope β_1 and β_0 the intercept. The slope is the change associated to Y by unit of X and the intersect is the point at which the population intercept the Y axis. The intercept in most of the case does not have a meaningful interpretation.

Finally, u_i represents the error between the real Independent variable Y and Y_i estimated through the linear regression. The error term contains all the factors, which are not explained by the regressor X, that determinate Y for each of the computed observations.

The professors James H Stock and Mark W. Watson explain the linear regression problem in a simple way in their book "Introduction to Econometrics". A superintendent of an elementary school is making an appraisal to hire new professors. The superintendent knows that reducing the number of students per professor increases the quality of teaching, but on the other hand it increases the school's costs. After doing several experiments, changing the student/professor ratio, she reaches the equation:

$$Testscore = \beta_0 + \beta_{ClassSize}\Delta ClassSize$$

Using the population regression line, the Superintendent could expect to estimate the improvement in the Test Score, according to a possible change in the class sizes. The estimation should be seen as an average across the population studies. The errors between the prediction and the reality are independent from Student Teacher ratio, and for this particular case they could contain variables such as: Quality of teachers, quality of textbooks, less native speakers in a class and many others. The Figure 52 is an example of the linear regression and several samples.

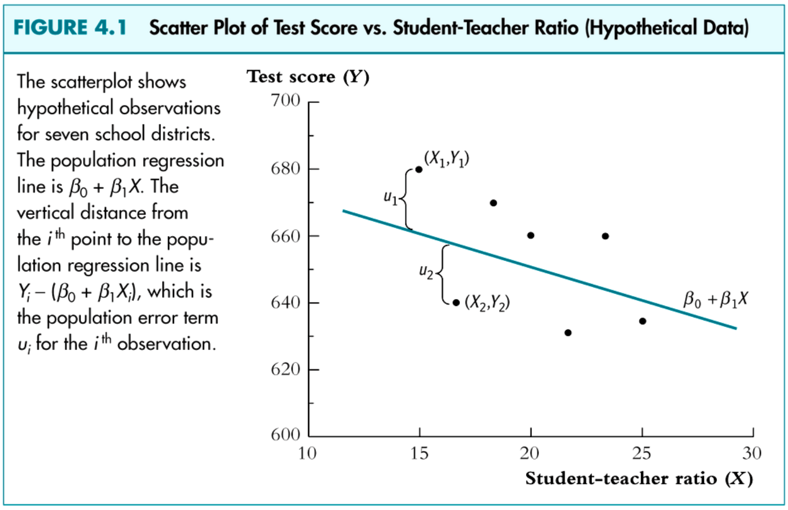


Figure 52 Scatter Plot of Test Score vs Student-Teacher Ratio

In most analyses, to perform a regression over only one independent variable entails that the quality of that same regression will not be high, as many other variables/phenomena that potentially have an explanatory power of the dependent variable Y remain “constrained” in the error term. It is therefore advisable, in order to increase the explanatory power of the regression, to clarify the role of these variables by adding them to the regression.

The Linear Multiple Regression Model is an extension of the linear regression, since it assumes that the dependent variable is modelled by several independent variables, as seen on the equation:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki} + u_i, i = 1, \ldots, n.$$

To analyze qualitative factors the best approach is to binarize the information. Qualitative factors are variables such as the presence of night time or day time, gender (i.e. male/female), or a firm offering a certain type of health insurance. Overall, these are variables that can only assume one value at a time (i.e. it can only be night or day, a person can only be male or female). In order to include these types of variables in the regression, a special set of variables is built, commonly called dummy variables. These hold value equal to 1 if a characteristic is present (i.e. the person is a male), and 0 otherwise (i.e. the person is a female). For qualitative variables having more than 2 values, several dummies are built.

Using the previous example from the professors Stock and Watson, we can assume a binary variable which would be the presence of nonnative speakers in a neighborhood. The dummy variable has a coefficient δ_0. δ_0 is the difference of performance between a class with only native speakers and a class with nonnative speaker students. The Superintendent can readapt the size of the class to achieve the ideal test score performance. If the δ_0<0, a class without nonnative students will perform better. The use of dummy variable results on a shift of the linear regression function.

$$Testscore = \beta_0 + \beta_{ClassSize}\Delta ClassSize + \delta_0 NonNativeSpeakers$$

If the equation presented two dummy variables, i.e. Non-Native Speakers and Native Speakers, it would introduce a perfect collinearity between the two elements. This is called a dummy variable trap and would make the model fail. Therefore, to explain the behavior of a phenomena through the dummy variables, we should always use the number of events minus 1.

5.2.2 Multiple linear regression to understand the PHS behavior and no price division

With the study of the last chapters (graphical analysis on PHS behavior in Italy and Portugal) a linear multiple regression was modelled to understand the PHS behavior. The data presents the following categories: Months, Days, Hours, Prices, Energy Pumped and Energy Generated (obtained through the ENTSO-E website)[25] and the unitarian cost of electricity from Italy and Portugal obtained from GME[32] and REN[33], respectively.

The regression presents the following 2 classes of binary variables: Seasonal variables and Hourly variables. The seasonal variables are winter, spring, summer and autumn, while the hours variables are expressed 4 categories:

- Category 1, from 11 p.m. to 6 a.m. for Italy and from 1 a.m. to 8 a.m. for Portugal;
- Category 2, from 7 a.m. to 10 a.m. for Italy and from 9 a.m. to 1 p.m. for Portugal;
- Category 3, from 11 a.m. to 3 p.m. for Italy and from 2 p.m. to 6 p.m. for Portugal;
- Category 4 from 4 p.m. to 10 p.m. for Italy and from 7 p.m. to midnight for Portugal;

In order to avoid the dummy variable trap only the binary columns from Winter, Spring, Summer and categories 1, 2 ,3 were added to the database. In the Table 14 we can observe the data analyzed.

Table 14 Coefficient, Pvalues and Rsquared results from a multiple linear regression with hour and season binarization

		Energy Pumped		Energy Generated	
		Italy	Portugal	Italy	Portugal
Coefficient	Intercept	457,565	1072,87	-20,301	-133,916
	Category 1	410,236	273,350	-413,068	-337,991
	Category 2	36,538	38,103	-212,246	-123,432
	Category 3	144,296	91,672	-372,738	-254,097
	Winter	164,062	161,205	-73,426	113,676
	Spring	-55,457	-68,433	54,699	197,937
	Summer	-83,724	-182,105	93,844	38,25
	Price	-7,015	-17,344	10,208	10,082
Pvalues error	Intercept	0,0000	0,0000	**0,363**	0,0000
	Category 1	0,0000	0,0000	0,0000	0,0000
	Category 2	0,003	0,0006	0,0000	0,0000
	Category 3	0,0000	0,0000	0,0000	0,0000
	Winter	0,0000	0,0000	0,0000	0,0000
	Spring	0,0000	0,0000	0,0000	0,0000
	Summer	0,0000	0,0000	0,0000	0,00061
	Price	0,0000	0,0000	0,0000	0,0000
Errors	R Squared	0,301	0,326	0,350	0,259
Observations		8735	8735	8735	8735

A good regression should present high R square values (ideally near 1, most of the times 0,5). The P-values are important parameter since they explain the importance of the independent variables. The P-value results from the analysis of the null hypothesis of an independent variable, i.e. the coefficient of the independent variable is 0. If the null hypothesis has a high value, the chances of the coefficient being 0 are high, while if the value is low (below 0,05) the null hypothesis is insignificant. Thus, the variable is representative of the system.

The only high p-value observed is the intercept in the Energy generated in Italy, which unfortunately cannot be discarded. From the Table 14, we can write the equation describing the Energy Pumped and Generated for Italy and Portugal. The binary variables such as category 1, 2 and 3, only present values 0 and 1. Obviously if category 1 is active (1), categories 2 and 3 are disactivated (0).

$$E\ Pumped_{Italy} = 457{,}57 + 410{,}24 \times cat1 + 36{,}54 \times cat2 + 144{,}30 \times cat3 + 164{,}06 \times winter - 55{,}46 \times spring - 83{,}72 \times summer - 7{,}015 \times Price$$

$$E\ Pumped_{Portugal} = 1072{,}87 + 273{,}35 \times cat1 + 38{,}10 \times cat2 + 91{,}67 \times cat3 + 161{,}21 \times winter - 68{,}43 \times spring - 182{,}11 \times summer - 17{,}34 \times Price$$

$$E\ Generated_{Italy} = -133{,}92 - 413{,}07 \times cat1 - 212{,}25 \times cat2 - 372{,}74 \times cat\ 3 - 73{,}43 \times winter + 54{,}70 \times spring + 93{,}84 \times summer + 10{,}21 \times Price$$

$$E\ Generated_{Portugal} = -20{,}31 - 337{,}99 \times cat1 - 123{,}43 \times cat2 - 254{,}1 \times cat\ 3 + 113{,}68 \times winter + 197{,}94 \times spring + 38{,}25 \times summer + 10{,}08 \times Price$$

5.2.3 Multiple linear regression to understand the PHS behavior, with 5th maximums and minimums average prices included

The current study presented the same dummy variables as the previous study (graphical analysis of the prices in Italy and Portugal), such they were the seasonal variables and the hourly variables. Moreover, the major difference on this approach is the inclusion of averages Price of Energy. In this case, the average prices are:

- A **maximum average** which consists on the mean average of the 5 highest prices of each day;
- A **minimum average** which consists on the mean average of the 5 lowest prices of each day;
- **Ratio** between maximum and minimum average.

For the regression purposes two extra columns were added with the maximum and minimum average per day for the 24 hours of each day. The purpose is to understand the impact of these variables in the equation, reinforcing the Price influence as an independent variable.

An initial analysis was run to eliminate the variables with high p value:

Table 15 Coefficient, Pvalues and Rsquared results from a 1st multiple linear regression with hour and season binarization and maximum average price, minimum average price and ratio

		Energy Pumped		Energy Generated	
		Italy	Portugal	Italy	Portugal
Pvalues error	Intercept	0,168	0,000	0,036	0,000
	Category 1	0,000	0,000	0,000	0,000
	Category 2	**0,181**	0,0466	0,000	0,000
	Category 3	0,000	**0,312**	0,000	0,000
	Winter	0,000	**0,239**	0,003	0,000
	Spring	**0,097**	0,000	**0,179**	0,000
	Summer	0,000	**0,112**	0,000	**0,42**
	Maximum Price	0,035	0,000	0,000	0,000
	Minimum Price	0,000	0,000	0,002	0,000
	Ratio	0,000	0,000	**0,501**	**0,505**
	Price	0,000	0,000	0,000	0,000

After the brief analysis (Table 15) the following variables were eliminated: category 2 (from Energy Pumped in Italy), Category 3 (from Energy Pumped in Portugal), Winter (Energy Pumped in Portugal), Spring (Italy), Summer (Portugal) and the Ratio from Energy Generated, because they had values higher than 0,05. While doing the second regression of the Energy Pumped in Portugal **the category 2** presented a value of 0,084, thus it was neglected. The Table 16 shows the obtained results from the 3rd multiple linear regression after discarding the non-representative categories.

Table 16 Coefficient, Pvalues and Rsquared results from a 3rd multiple linear regression with hour and season binarization and maximum average price, minimum average price and ratio

		Energy Pumped		Energy Generated	
		Italy	Portugal	Italy	Portugal
Coefficient	Intercept	-138,857	566,500	217,329	348,429
	Category 1	307,534	85,782	-326,014	-110,256
	Category 2	-	-	-193,669	-99,919
	Category 3	79,781	-	-319,967	-150,456
	Winter	152,164	-	-29,414	105,857
	Spring	-	76,417	-	106,624
	Summer	-34,526	-	77,362	-
	Maximum price	2,267	35,807	-3,891	-11,64
	Minimum Price	8,322	-9,407	-7,48	-28,752
	Ratio	287,538	-67,275	-	-
	Price	-13,227	-38,417	15,787	37,125
Pvalues error	Intercept	0,097	0,000	0,000	0,000
	Category 1	0,000	0,000	0,000	0,000
	Category 2	-	-	0,000	0,000
	Category 3	0,000	-	0,000	0,000
	Winter	0,000	-	0,009	0,000
	Spring	-	0,000	-	0,000
	Summer	0,000	-	0,000	-
	Maximum Price	0,035	0,000	0,000	0,000
	Minimum Price	0,000	0,000	0,000	0,000
	Ratio	0,000	0,000	-	-
	Price	0,000	0,000	0,000	0,000
Errors	R Squared	0,344	0,441	0,375	0,432
Observations		8735	8735	8735	8735

Finally, we reach the Energy equations for the model:

$$E\ Pumped_{Italy} = -138{,}86 + 307{,}534 \times cat1 + 79{,}781 \times cat3 + 152{,}16 \times winter - 34{,}53 \times summer + 2{,}27 \times Max.Price + 8{,}32 \times Min.Price + 287{,}54 \times Ratio - 7{,}015 \times Price$$

$$E\ Pumped_{Portugal} = 566{,}50 + 85{,}78 \times cat1 + 76{,}42 \times spring + 35{,}81 \times Max.Price - 9{,}41 \times Min.Price - 67{,}28 \times Ratio - 38{,}42 \times Price$$

$$E\ Generated_{Italy} = 217{,}33 - 326{,}01 \times cat1 - 193{,}67 \times cat2 - 313{,}97 \times cat\ 3 - 29{,}41 \times winter + 77{,}36 \times summer - 3{,}89 \times Max.Price - 7{,}48 \times Min.Price + 15{,}79 \times Price$$

$$E\ Generated_{Portugal} = 348{,}43 - 110{,}26 \times cat1 - 99{,}92 \times cat2 - 150{,}46 \times cat\ 3 + 105{,}86 \times winter + 106{,}62 \times spring - 11{,}64 \times Max.Price - 28{,}75 \times Min.Price + 37{,}13 \times Price$$

5.2.4 Multiple linear regression to understand the PHS behavior, using price as a binary category

The last model presents the same dummy variables as the initial study, while analyzing the price as a category. This methodology regroups the Price of Energy into 7 categories: very low, low, medium low, medium, medium high, high and very high. The binarization of these variables will allow to understand the added value of each category for each one of the equations. We expect that most of the price will be situated between the low and high classes, remembering that the maximum prices (excluding the outlawyers) are 135 and 105 €/MWh for Italy and Portugal, respectively, the categories are:

- Very low – from 0 to 19,28€/MWh for Italy and from 0 to 14,85 €/MWh for Portugal;
- Low – from 19,29 to 38,57€/MWh for Italy and from 14,86 to 29,71€/MWh for Portugal;
- Medium Low – from 38,58 to 57,85 €/MWh for Italy and 29,72 to 44,75 €/MWh for Portugal;
- Medium – from 57,86 to 77,14 €/MWh for Italy and 44,76 to 59,43 €/MWh for Portugal;
- Medium high – from 77,15€/MWh to 96,42 for Italy and 59,444 to 74,29 €/MWh for Portugal;
- High – from 96,43 to 115,71€/MWh for Italy and 74,30 to 89,15€/MWh for Portugal;
- Very High – from 115,72 until maximum for Italy and 89,16 until maximum for Portugal.

As before the initial step is to exclude the independent variables which do not represent well the regression; they can be observed in Table 17.

Table 17 Coefficient, Pvalues and Rsquared results from a 1st multiple linear regression with hour and season binarization and categorization of price

		Energy Pumped		**Energy Generated**	
		Italy	Portugal	Italy	Portugal
Pvalues error	Intercept	0,052	0,001	0,000	0,000
	Category 1	0,000	0,000	0,000	0,000
	Category 2	0,001	0,001	0,000	0,000
	Category 3	0,000	0,000	0,000	0,000
	Winter	0,000	0,000	0,000	0,000
	Spring	0,000	0,000	**0,205**	0,000
	Summer	0,000	0,000	0,000	0,000
	Very low	0,000	0,000	0,000	**0,918**
	Low	0,000	0,000	0,000	0,000
	Med-low	0,000	0,000	0,000	0,000
	Med	**0,069**	0,000	0,000	**0,241**
	Med-high	**0,992**	0,014	0,000	0,020
	High	**0,888**	**0,637**	0,000	0,000

From the analysis we exclude the following variables: Spring (Energy Generated in Italy, Very Low (Energy Generated in Portugal), Med (Energy Pumped in Italy and Energy Generated in Portugal), Med-High (Energy Pumped in Italy) and High (Energy Pumped). Which lead to the following regressions, Table 18.

Table 18 Coefficient, Pvalues and Rsquared results from a 2^{nd} multiple linear regression with hour and season binarization and categorization of price

		Energy Pumped		Energy Generated	
		Italy	Portugal	Italy	Portugal
Coefficient	Intercept	-29,958	-115,86	1370,012	396,806
	Category 1	420,442	278,650	-467,583	-337,724
	Category 2	38,773	36,288	-222,925	-122,756
	Category 3	126,127	90,013	-407,074	-250,95
	Winter	137,368	83,913	-64,834	136,214
	Spring	-98,950	-82,378	-	209,601
	Summer	-84,450	-177,253	72,781	45,988
	Very Low	1696,439	884,649	-973,363	-
	Low	466,731	1135,778	-942,812	-215,574
	Med Low	120,379	592,763	-847,422	-191,789
	Med	-	251,118	-705,934	-
	Med High	-	77,753	-541,94	128,052
	High	-	-	-299,088	291,578
Pvalues error	Intercept	0,007	0,000	0,000	0,000
	Category 1	0,000	0,000	0,000	0,000
	Category 2	0,001	0,001	0,000	0,000
	Category 3	0,000	0,000	0,000	0,000
	Winter	0,000	0,000	0,000	0,000
	Spring	0,000	0,000	-	0,000
	Summer	0,000	0,000	0,000	0,000
	Very Low	0,000	0,000	0,000	-
	Low	0,000	0,000	0,000	0,000
	Med Low	0,000	0,000	0,000	0,000
	Med	-	0,000	0,000	-
	Med High	-	0,000	0,000	0,000
	High	-	-	0,000	0,000
Errors	R Squared	0,338	0,338	0,333	0,266
Observations		8735	8735	8735	8735

$$E\ Pumped_{Italy} = -29{,}96 + 420{,}44 \times cat1 + 38{,}77 \times cat2 + 126{,}13 \times cat3 + 137{,}37 \times winter - 98{,}95 \times spring - 84{,}45 \times summer + 1696{,}44 \times VeryLow + 466{,}73 \times Low + 120{,}38 \times Med.Low$$

$$E\ Pumped_{Portugal} = -115{,}86 + 278{,}65 \times cat1 + 36{,}29 \times cat2 + 90{,}01 \times cat3 + 83{,}91 \times winter - 82{,}38 \times spring - 177{,}25 \times summer + 884{,}65 \times VeryLow + 1135{,}78 \times Low + 592{,}86 \times Med.Low + 251{,}12 \times Med + 77{,}75 \times MedHigh$$

$$
\begin{aligned}
E\ Generated_{Italy} &= 1370{,}01 - 467{,}58 \times cat1 - 222{,}93 \times cat2 - 407{,}07 \times cat3 \\
&- 64{,}83 \times winter + 72{,}78 \times summer - 973{,}36 \times VeryLow \\
&- 942{,}81 \times Low - 847{,}42 \times Med.Low - 705{,}93 \times Med \\
&- 541{,}94 \times MedHigh - 299{,}09 \times High
\end{aligned}
$$

$$
\begin{aligned}
E\ Generated_{Portugal} &= 396{,}81 - 337{,}72 \times cat1 - 122{,}76 \times cat2 - 250{,}95 \times cat3 \\
&+ 136{,}21 \times winter + 209{,}6 \times spring + 45{,}99 \times summer - 215{,}57 \times Low \\
&- 191{,}79 \times Med.Low + 128{,}05 \times MedHigh + 291{,}58 \times High
\end{aligned}
$$

5.3 Economic balance resulting from the linear regressions

The present chapter expresses the outcomes of the best multiple linear regression. The multiple linear regression to understand the PHS behavior, with 5th maximums and minimums average prices included is the scenario which presents a better approximation to the real PHSs' generation and consumption. The reason for its selection is because presents the best pvalues and r squared values. The energy equations are:

$$
\begin{aligned}
E\ Pumped_{Italy} &= -138{,}86 + 307{,}534 \times cat1 + 79{,}781 \times cat3 + 152{,}16 \times winter \\
&- 34{,}53 \times summer + 2{,}27 \times Max.Price + 8{,}32 \times Min.Price \\
&+ 287{,}54 \times Ratio - 7{,}015 \times Price
\end{aligned}
$$

$$
\begin{aligned}
E\ Pumped_{Portugal} &= 566{,}50 + 85{,}78 \times cat1 + 76{,}42 \times spring + 35{,}81 \times Max.Price \\
&- 9{,}41 \times Min.Price - 67{,}28 \times Ratio - 38{,}42 \times Price
\end{aligned}
$$

$$
\begin{aligned}
E\ Generated_{Italy} &= 217{,}33 - 326{,}01 \times cat1 - 193{,}67 \times cat2 - 313{,}97 \times cat\ 3 \\
&- 29{,}41 \times winter + 77{,}36 \times summer - 3{,}89 \times Max.Price \\
&- 7{,}48 \times Min.Price + 15{,}79 \times Price
\end{aligned}
$$

$$
\begin{aligned}
E\ Generated_{Portugal} &= 348{,}43 - 110{,}26 \times cat1 - 99{,}92 \times cat2 - 150{,}46 \times cat\ 3 \\
&+ 105{,}86 \times winter + 106{,}62 \times spring - 11{,}64 \times Max.Price \\
&- 28{,}75 \times Min.Price + 37{,}13 \times Price
\end{aligned}
$$

The Table 19 below represents the monthly and yearly profit in both countries, through the usage of the real data.

Table 19 The monthly revenue for Portugal and Italy through ENTSO-E exported data (expressed in thousands €)

	Italy	Portugal
Jan	7281,06	12347,12
Feb	3575,90	9502,58
Mar	2784,98	3163,92
Apr	1756,62	1805,76
May	244,67	2378,80
Jun	5594,38	434,17
Jul	9436,80	3354,02
Aug	13822,14	3190,19
Sep	8849,00	2140,76
Oct	4029,02	576,89
Nov	7843,74	5317,47
Dec	3877,78	7126,45
Total (millions €)	69,10	51,34

The total revenue for Italy and Portugal was 69,10 and 51,34 million €. The Italian PHSs present higher earnings during January, August, September and November. September presents a contradiction, since is one of the months with higher revenues and the lowest prices of electricity. The Portuguese PHSs earning are focused on the winter period (from November until February). This period has a total of 34,29 million €, representing 66,80% of the total revenues from 2017.

6 Simulation and results

6.1 Simulation of Italy and Portugal's energy balance in PHS

The statistical and graphical analysis presented in Chapter 5 allowed to understand the behavior of PHS systems in terms of relation between the price of electricity and the generated and pumped energy during the year, concluding that today practices could be approximated by a multiple linear equation with seasonal variables, time period variables, the average of the 5th maximum daily prices, the average of 5th minimum daily average prices and the ratio between the maximum and minimum daily prices.

With countries (such as Switzerland, Australia, Austria) exploring and implementing new energy storage systems, it is important to ensure the best usage of the technology. As mentioned in Chapter 5, the PHSs' role in the energy market is to either leverage the energy imbalances of the national grid, or to act as a standard energy supplier with a profit objective. The below simulation aims at studying the PHSs' behavior in this second role, through the analysis of its participation to the day ahead energy market in Italy and Portugal. The behavior is explicated via the determination of several operational strategies entailing the maximization of the profit given a series of constraints on the prices, with a view to identify the one ensuring the highest profit.

From a theoretical perspective, it is expected that the maximized profit will be higher when the number of price constraints is lower.

A set of three strategies is studied, and the results are compared in order to understand which one leads to higher profit.

The profit to be maximized is given by the following expression, where n is the total number of operational hours:

$$Profit = \sum_{i=1}^{n} Price_i \times Energy\ Generated_i - \sum_{i=1}^{n} Price_i \times Energy\ Pumped_i$$

The Operational Strategies establish different relationships between the pumped energy and generated energy equations and the price of electricity, on the day ahead market. From an operational perspective, the prices for Italy and Portugal were obtained from GME[32] and REN [33], respectively. Furthermore, the ENTSO-E[25] website supplied the source for PHSs' energy pumped and energy generated for both countries. The 3 data sets are hourly based and reference to 2017 (with exception to 9th November).

In all simulations, the study of price represents a crucial characteristic of the simulation, since it selects the type of action used by the PHSs. The simulation uses two price thresholds to limit the PHS pumping and generation activities:

- A *minimum price* threshold above which is considered economically convenient to start generating energy;
- A *maximum price* threshold below which is considered economically convenient to start pumping energy.

Every time these thresholds are not optimized two problems may occur:

- if the minimum price thresholds are too low, the reservoirs may discharge too rapidly, and the system will lose the chance to sell energy at higher prices
- if the maximum price thresholds are too high, the reservoirs will pump too much water and may lose the possibility to sell the stored energy.

In this work, three Operational Strategies are identified and investigated:

- Optimization of the present scenario through a multiple linear equation limited by a price threshold, the strategy allows to understand how the usage of thresholds affect the present trend;
- Optimization at full pump and turbine power with limitation by price threshold, which analysis the effect of all PHS discharging and pumping at maximum capacity as soon as the prices reaches a stablished threshold;
- Optimization with a linear variation to full installed capacity, the gradual growth permits to simulate a realistic approach from the PHSs' management. Moreover, it analyzes if using the full capacity during all year creates a limitation on the pumping and generation hours.

The operational strategies will be compared with the Operational Strategy 1. Italy and Portugal PHSs' behavior will be compared based on the computed power output at a certain hour (which can be pumped and generated) in relation to their nominal power during the year of 2017.

All simulations assume the PHS system as a single global storage capacity system for a country. This limitation comes from constraints from the dataset.

It was assumed that the reservoir storage should be between 0 or a third of the total capacity. Thus, Italy initial stored energy is assumed equal to 33% of the Total Energy Storage capacity, while for Portugal it was estimated at 20% of the Total Energy

Storage capacity, since the latter is very large. Table 20 details the storage capacity and the assumed stored energy on January 1st.

Table 20 - Storage Capacity and Stored Energy in Italy and in Portugal.

		Units (GWh)
Italy	Total Energy Storage Capacity	700
	Stored Energy at the beginning January	234
Portugal	Total Energy Storage Capacity	2091
	Stored Energy at the beginning January	500

The function Solver allowed to maximize the profit for each operational strategy. Given the complexity of the problem, a non-linear function is required. The implemented model presented constraints to ensure the respect of the PHSs' storage capacity.

6.2 Operational Strategy 1: Optimization of the present scenario through a multiple linear regression limited by a price threshold

The first operational strategy that is proposed starts from the PHS production and consumption trends analyzed in Chapter 5 and impose that they are subject to the setting of price thresholds. These limits essentially choose when it is economically more convenient to pump and generate energy. The equations describing the energetic behavior are drawn from the multiple linear regression to understand the PHS behavior, with 5th maximums and minimums average prices included and are the following:

$$E\ Pumped_{Italy} = -138{,}86 + 307{,}534 \times cat1 + 79{,}781 \times cat3 + 152{,}16 \times winter - 34{,}53 \times summer + 2{,}27 \times Max.Price + 8{,}32 \times Min.Price + 287{,}54 \times Ratio - 7{,}015 \times Price$$

$$E\ Pumped_{Portugal} = 566{,}50 + 85{,}78 \times cat1 + 76{,}42 \times spring + 35{,}81 \times Max.Price - 9{,}41 \times Min.Price - 67{,}28 \times Ratio - 38{,}42 \times Price$$

$$E\ Generated_{Italy} = 217{,}33 - 326{,}01 \times cat1 - 193{,}67 \times cat2 - 313{,}97 \times cat\ 3 - 29{,}41 \times winter + 77{,}36 \times summer - 3{,}89 \times Max.Price - 7{,}48 \times Min.Price + 15{,}79 \times Price$$

$$E\ Generated_{Portugal} = 348{,}43 - 110{,}26 \times cat1 - 99{,}92 \times cat2 - 150{,}46 \times cat\ 3 + 105{,}86 \times winter + 106{,}62 \times spring - 11{,}64 \times Max.Price - 28{,}75 \times Min.Price + 37{,}13 \times Price$$

The Figure 53 represents PHS's behavior for the operational strategy 1, where the energy generated, and energy pumped per hour are represented by the multiple linear regressions above. Moreover, there are 2 thresholds that create three possibilities for the PHS system. The thresholds are the maximum price for pumping energy (Max PP) and the minimum price for generating energy (Min PG).

The index *s* from the threshold's variates from 1 to 4 and expresses the seasons from the year, starting in the winter and ending in the Autumn. On the other hand, the prices' index *p* defines the hour of the day and the index *n* expresses the day of the year. The PHS may have 3 possible actions:

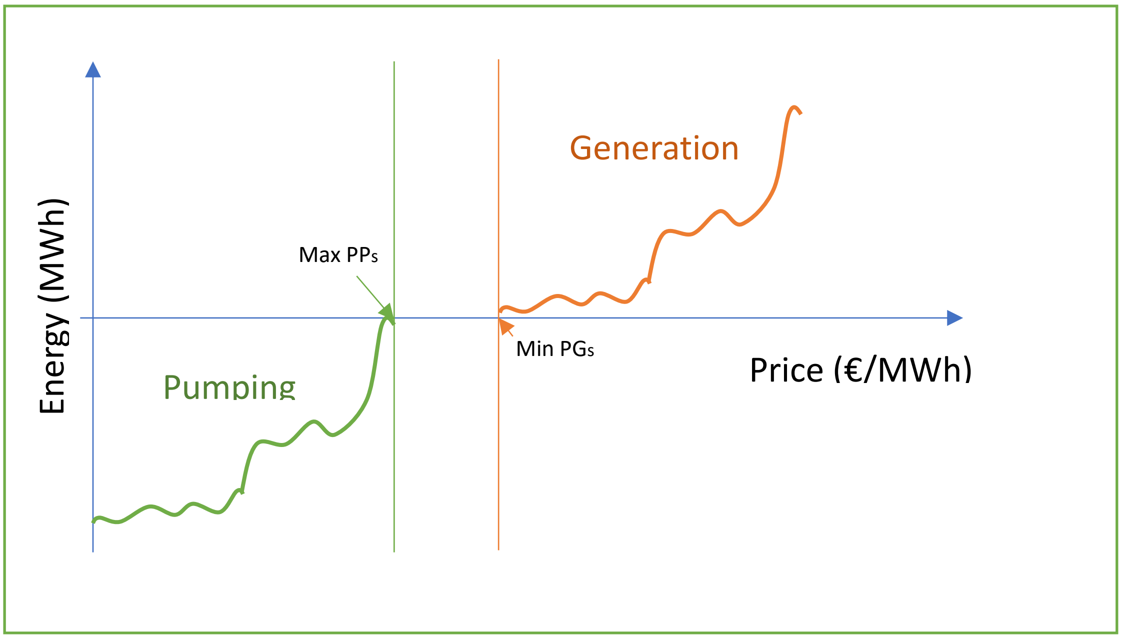


Figure 53 Operational Strategy 1

- If $Price_{p,n} < Max\ PP_s$, the PHS system may pump energy from the lower reservoir to the higher reservoir (in case the upper reservoir is not completely full);
- If $Price_{p,n} > Min\ PG_s$, the PHS system may generate energy, releasing water from the upper reservoir (as long as there is stored energy in the upper reservoir);
- If $Max\ PP_s < Price_{p,n} < Min\ PG_s$, the PHS will do no actions, keeping the same amount of energy stored in the higher reservoir.

The $Max\ PP_s$ and the $Min\ PG_s$ are related so that when one is set, the other changes accordingly. The relation is expressed by the following function:

$$Min\ PG_s = \frac{Max\ PP_s}{\eta_{Turbine} \times \eta_{Pump} \times \eta_{Penstock}}$$

where:

- $Min\ PG_s$ is the Minimum Price for generating energy during a period i;
- $Max\ PP_s$ is the Maximum Price for pumping energy during a period i;
- η_{Pump} is the overall efficiency of the pump, assumed equal to 82%[34][35];
- $\eta_{Turbine}$ is the overall efficiency of the turbine, assumed equal to 92%[36];
- $\eta_{Penstock}$ is the efficiency that accounts for losses along the penstock, for which a good approximation is 95%[37].

For the maximization of profit under operational strategy 1, Max PP is the variable to be optimized. Since there is one price threshold for each season, the optimization must consider 4 parameters to account for the whole year.

Table 21 summarizes the optimized thresholds resulting from the calculation, for each season, for Italy and for Portugal.

Table 21 Optimized price thresholds for optimal strategy 1, by season and by country.

		Winter	Spring	Summer	Autumn
Italy	Max PP (€/MWh)	40,03	47,01	44,57	41,00
	Min PG (€/MWh)	55,83	65,57	62,16	57,18
Portugal	Max PP (€/MWh)	38,00	43,00	41,74	39,00
	Min PG (€/MWh)	53,00	59,97	58,21	54,39

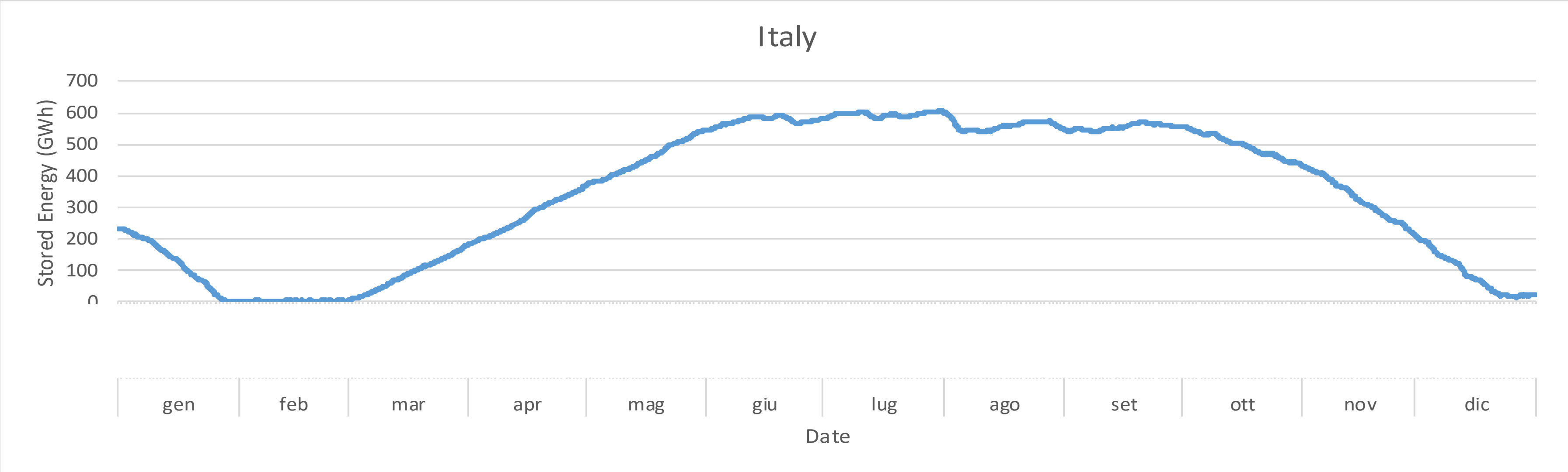
Opposing to the electricity price trends, the lower Max PP and Min PG are in Winter and Autumn. As it is expected, the gap between the two thresholds grows if the Max PP has a higher value. In Table 22, the ratio between the price thresholds and the average price is presented for each season and for both countries. The change from absolute to relative values allows to easily comprehend if, depending on the season, the system should mostly pump or generate. For instance, in winter the Italian PHS have the Min PG/AP ratio of 0,86, therefore the system generates energy even if the price is below the average price. On the other hand, during the spring we observe that the Max PP/AP is 1,08, leading to a higher number of pumping hours.

Table 22 Optimized price thresholds for Operation Strategy 1, scaled to the average price, by season and by country.

		Winter	Spring	Summer	Autumn
Italy	Average Price (AP) (€/MWh)	64,59	43,47	51,68	55,99
	Max PP/AP	0,62	1,08	0,86	0,73
	Min PG/AP	0,86	1,51	1,20	1,02
Portugal	Average Price (AP) (€/MWh)	61,00	44,92	48,14	55,00
	Max PP/AP	0,62	0,96	0,87	0,71
	Min PG/AP	0,87	1,34	1,21	0,99

Figure 54 and Figure 55 represent the PHS stored energy, the pumped or generated power, and the cost of electricity under operational strategy 1 in Italy and Portugal, respectively.

Observing both countries graphs, it is clear that the reservoirs are emptier in the months of February and December. Most of the generation occurs from October until February, which is also the period when prices of electricity are higher, hence it is more convenient to sell energy. Therefore, the PHS systems will generate higher amounts of energy, leading to the reduction of stored energy in the reservoirs. On the other hand, it is possible to identify one period along the year where the reservoirs predominantly store energy which is the Spring season (in the case of Portugal it extends until mid-September). This pattern was also expected, since these are the months with the lower prices of electricity. Between June and September, the reservoirs tend to stay at high capacity (500-600 GWh) with small fluctuations.



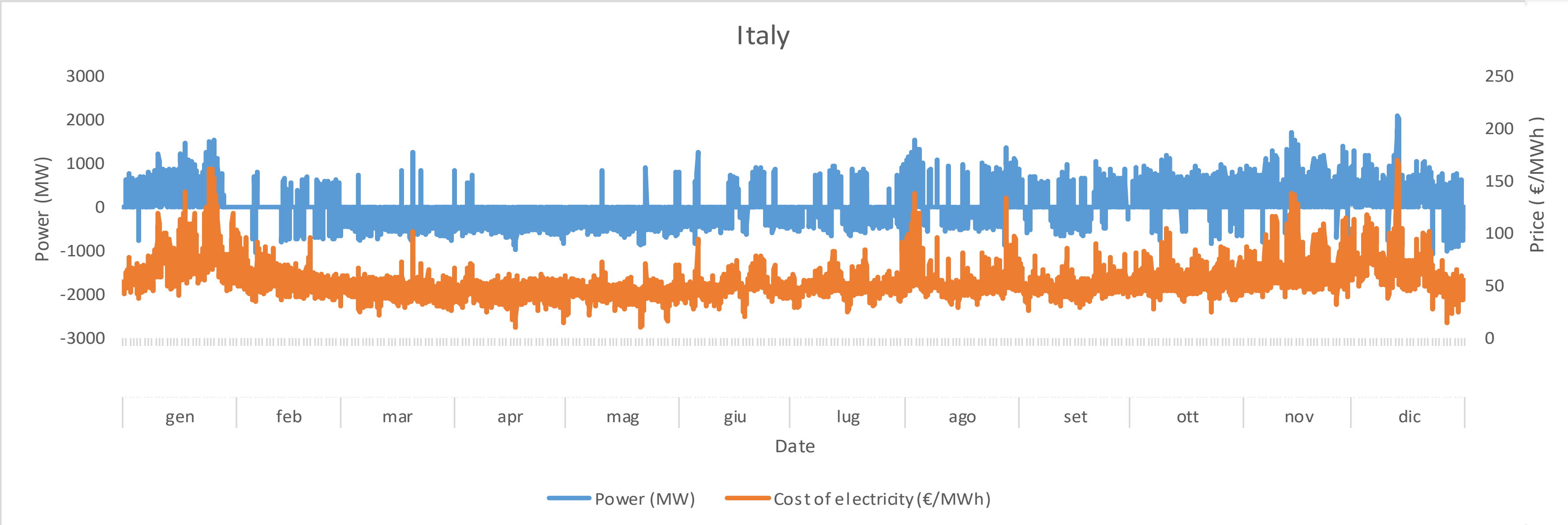
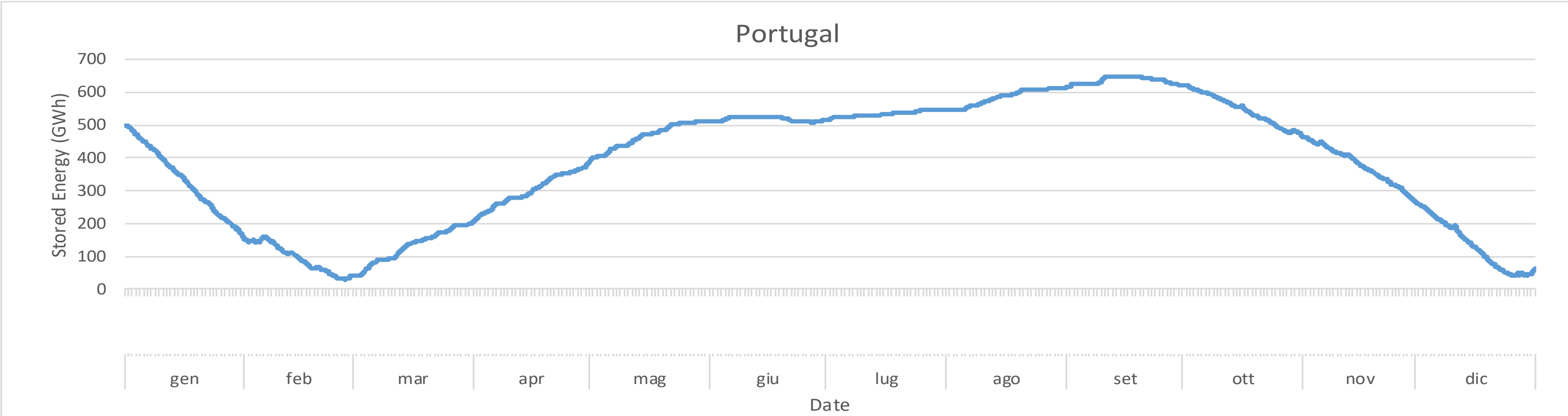


Figure 54 Stored energy and exchanged power (positive if generated, negative if pumped), and cost of electricity under Operational Strategy 1 for Italy



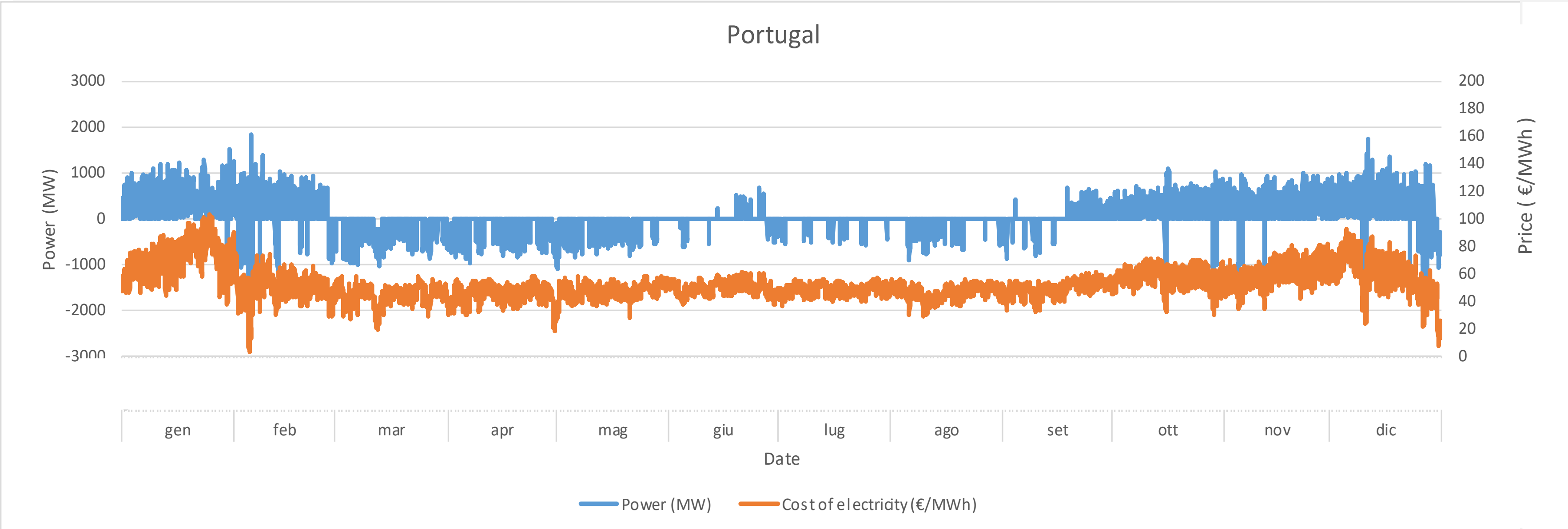


Figure 55 Stored energy and exchanged power (positive if generated, negative if pumped), and cost of electricity under Operational Strategy 1 for Portugal

Table 23 Revenues for Operational Strategy 1 (thousands of €).details the profits per month. As it was expected, the months with the highest prices are the months with highest profit. In particular, the month of January represents more than 1/3 of the expected profit for both countries.

Table 23 Revenues for Operational Strategy 1 (thousands of €).

Profits	Italy	Portugal
Jan	20577	27678
Feb	751	8864
Mar	-6449	-6025
Apr	-6814	-6661
May	-6136	-4971
Jun	-75	132
Jul	1163	-1227
Aug	8350	-2546
Sep	985	332
Oct	9287	10441
Nov	18379	13855
Dec	17688	16794
Tot (million €)	57,71	56,65

The Figure 56 compares the results of the analyzes using both the ENTSO-E data and the operational strategy 1 for the two countries in consideration. The figure shows the number of working hours a PHS system is working at a given power. To simplify the comparison the computed power is divided by nominal power for each country. If the ratio is positive the PHSs are generating, while if the ratio is negative the system is pumping.

Analyzing the ENTSO-E data, two observations are immediate: Italy does not work at nominal power, since the maximum ratio for generation is 0,5 for few hours and the PHS turbines work for nearly 3000 hours below a power of 2000 MW (30% P/Pn). As for the Portuguese PHSs turbines, they worked nearly 500 hours above half of their nominal power, and a total of 4000 during the year 2017. The Portuguese PHSs pumps work nearly 600 hours more than Italian's and always with higher power.

Looking at the Operational Strategy 1, at the first glance, it can be seen that all values are lower than the ENTSO-E data for both countries.

While Italy's operational strategy 1 (light blue line) estimates 2000 hours of energy generation at less than 20% of the nominal power, Portugal's (light orange) generates energy for 600 hours more, with a maximum of 40% of the nominal power. The Italian PHS pumps energy at very low values (less than 20% of the nominal power) for several hours. Portugal PHSs pumps nearly 1000 hour with lower power than 50%.

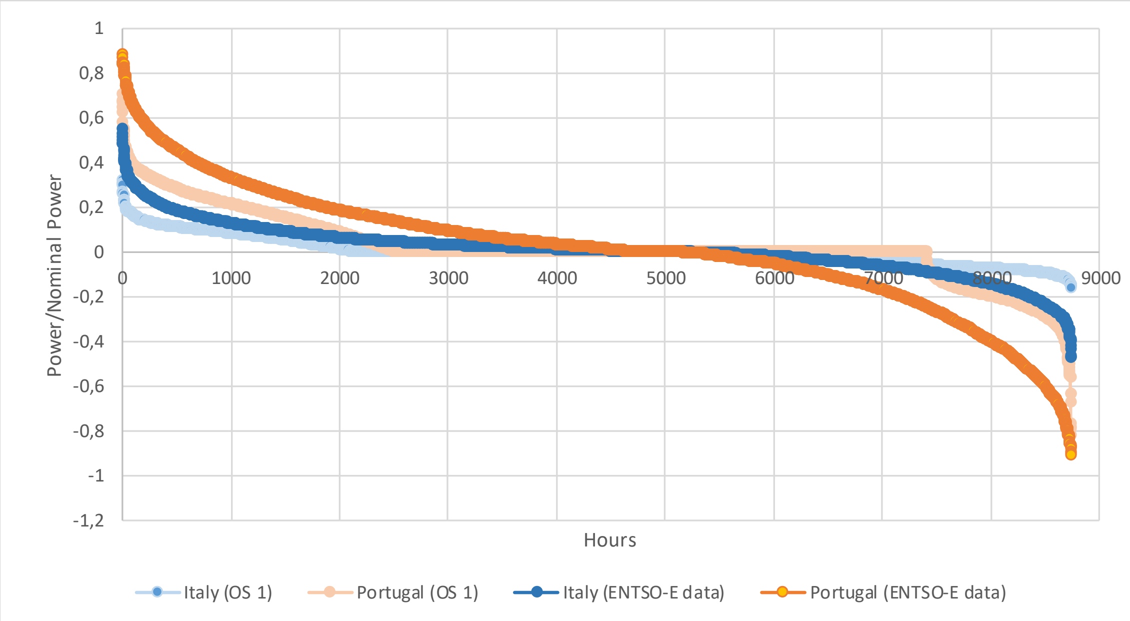


Figure 56 Operation Strategy 1 and ENTSO-E historical data: a: power/ nominal power ratio by working hours for Italy and Portugal

It is interesting to have a broad evaluation of the dynamics of the stored energy during the year. This can easily be obtained by computing the difference between the amount of stored energy at the 31st December 2017 and the one at the 1st January 2017. If the difference is positive, the PHS has a higher amount of stored energy at the of the year which could be used at the beginning of the following year. If the difference is negative, the PHS would require pumping water to recover the amount of stored energy present in the reservoir on the 1st January 2017. Moreover, the profit/cost linked to the

positive/negative value can be obtained by multiplying these same values by the average energy price for the month of December.

In practice, Italy required to fill up the reservoirs with 208,7 GWh and presented a cost of 13,6 million €, while Portugal needed to charge the PHS with 437,4 GWh and a cost of 26,0 millions of €.

6.3 Operational Strategy 2: Optimization as an ideal system working with an on/off at installed capacity with limitation by price threshold

Operational strategy 2 has the same main assumptions as the previous operational strategy in respect to the initial stored energy and relationship between the price thresholds. This operational strategy assumes that all nominal power works at the same time, i.e. pumping or turbinating at full capacity. The installed nominal capacities come from Table 9 and are:

- 6680 MW for Italy;
- 2574 MW for Portugal.

Figure 57 explains qualitatively the logic of this strategy: Max PP and Min PG are the price thresholds and the PHS operation can only occur at nominal power.

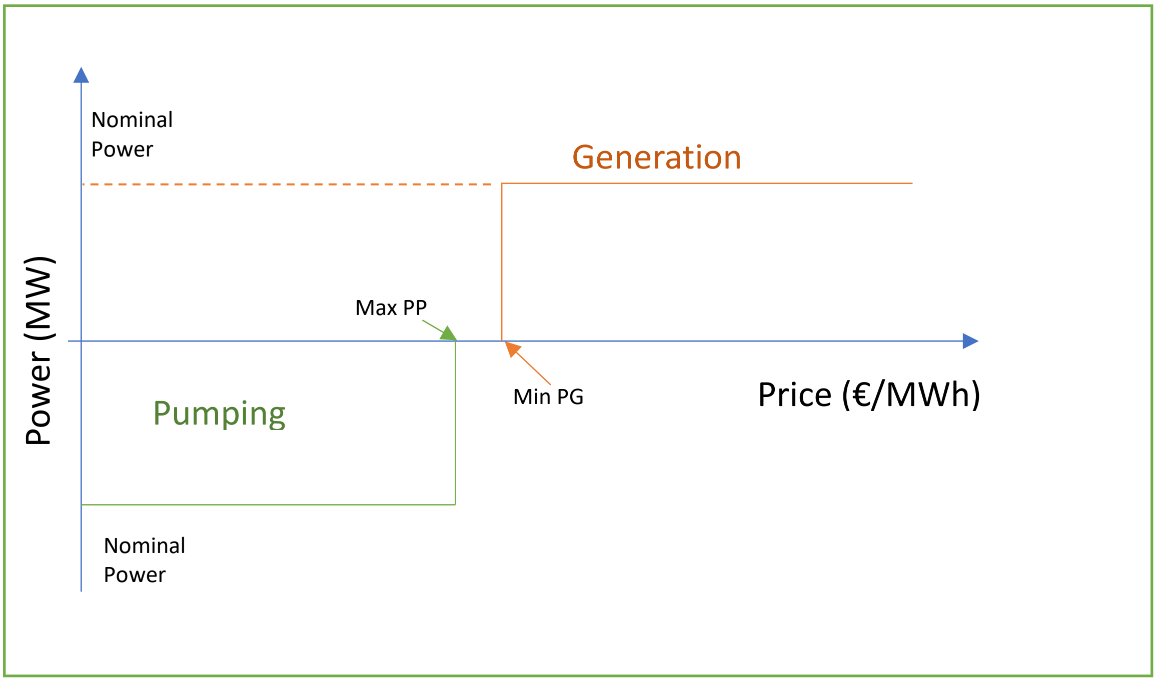


Figure 57 Optimization Strategy 2: PHS operates at nominal power, depending on price thresholds.

Table 24 expresses the resulting optimized thresholds for each season in Italy and Portugal:

Table 24 Optimized price thresholds for Operational Strategy 2, by season and by country.

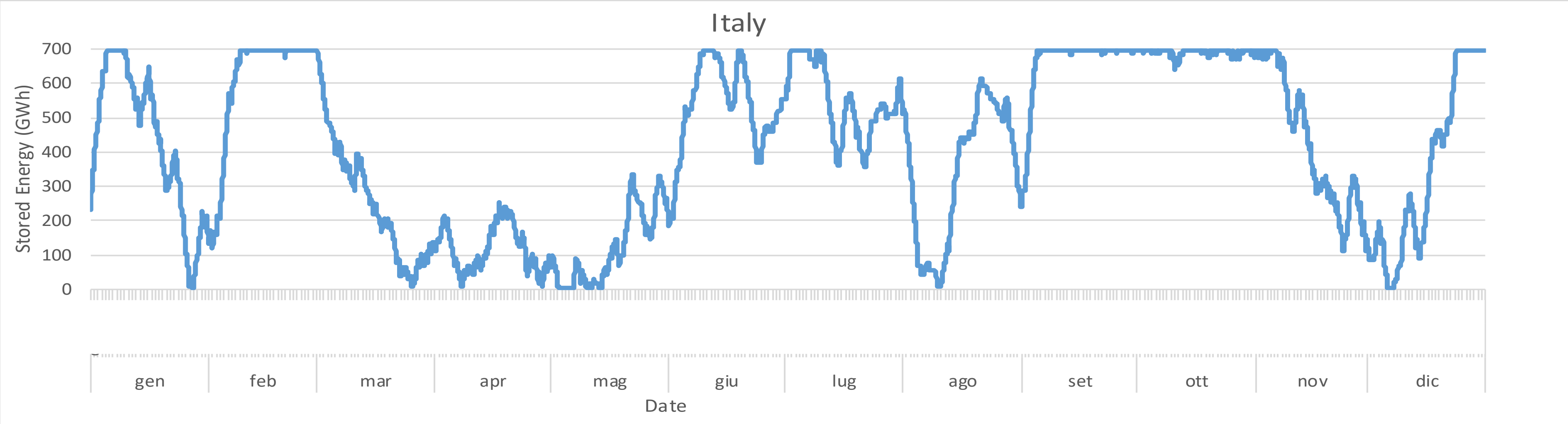
		Winter	Spring	Summer	Autumn
Italy	Max PP (€/MWh)	60,10	36,08	42,26	51,41
	Min PG (€/MWh)	83,82	50,32	58,94	71,70
Portugal	Max PP (€/MWh)	42,43	44,00	39,45	43,45
	Min PG (€/MWh)	59,18	61,37	55,02	60,60

It can be noted that, when compared to the operational strategy 1, the prices thresholds in Italy change considerably in all seasons. Maintaining the operational strategy 1 as reference, the new price thresholds in Winter and Autumn increase by around 20 and 10 €/MWh respectively, whereas for Spring (the season with the lowest average prices) the price reduced by almost 10 €/MWh. The Portuguese case shows smaller variations. The highest variations are during the Winter and Autumn in which there was an increment of price around 5 €/MWh (if comparing the same operational strategies).

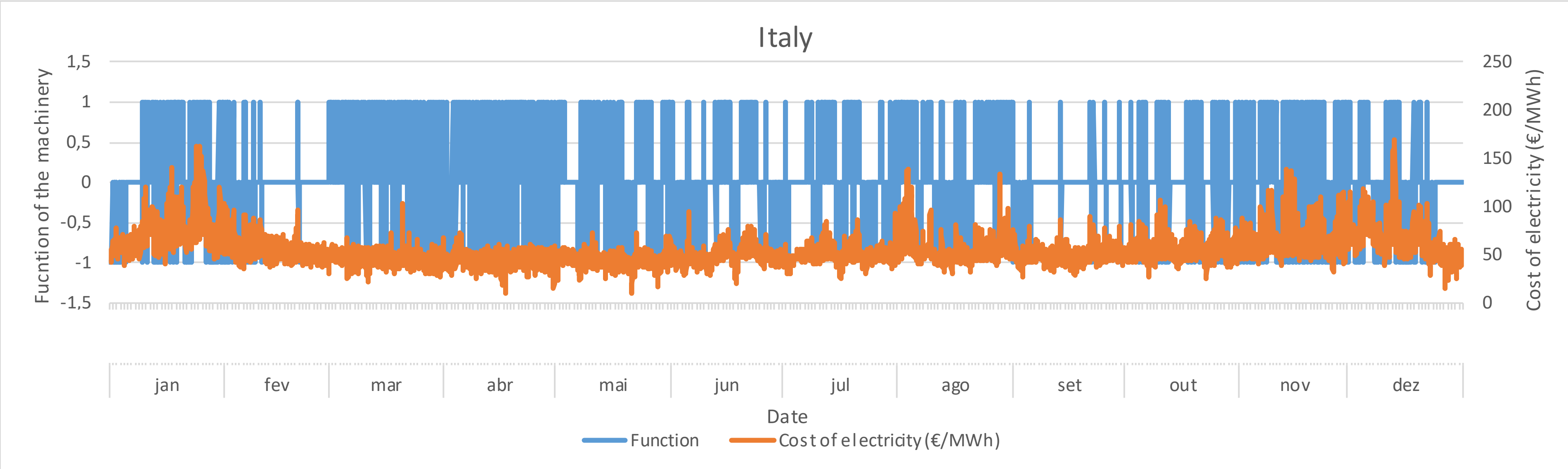
Table 25 Operational Strategy 2: Price threshold rationalized

		Winter	Spring	Summer	Autumn
Italy	Max PP/AP	0,93	0,83	0,82	0,92
	Min PG/AP	1,30	1,16	1,14	1,28
Portugal	Max PP/AP	0,70	0,98	0,82	0,79
	Min PG/AP	0,97	1,37	1,14	1,10

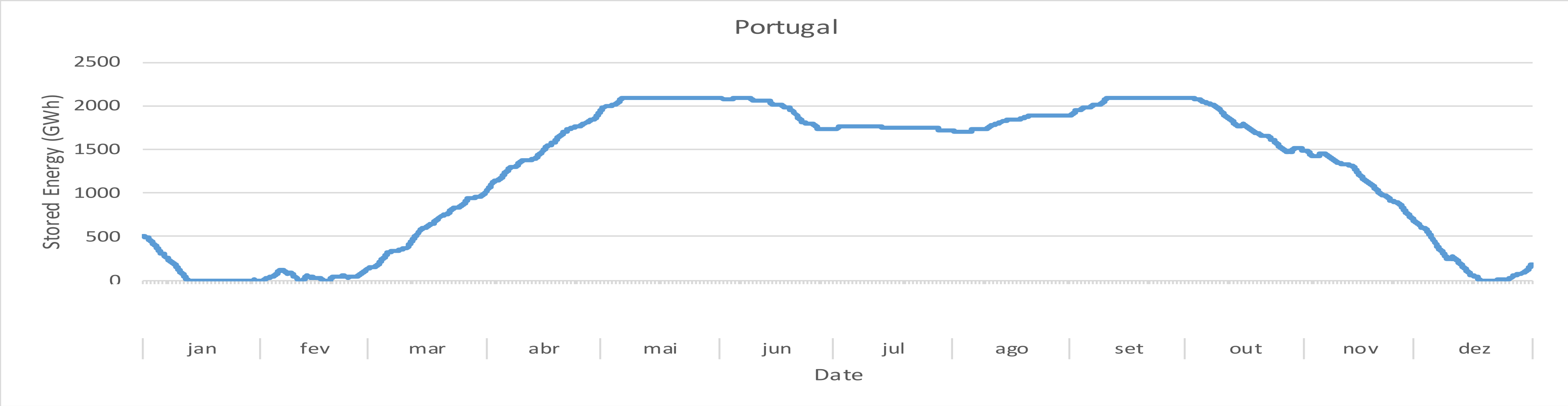
Observing Table 25, the new ratios are closer to 1, indicating there are no seasons in which the system has a greater predisposition for pumping or generating energy, except the Portuguese PHSs Spring. In Italy, even though Winter and Autumn present the higher ratios, those are also the periods with higher price peaks when compared to the average, i.e. the system is saving energy to explore at higher prices. As referred before, the Portuguese spring presents a higher tendency to pump energy. Contrarily to the Italian winter, this season present low price peaks.



Italy
Stored Energy (GWh)
700
600
500
400
300
200
100
0
gen
feb
mar
apr
mag
giu
lug
ago
set
ott
nov
dic
Date



Italy
Fucntion of the machinery
1,5
1
0,5
0
-0,5
-1
-1,5
Cost of electricity (€/MWh)
250
200
150
100
50
0
jan
fev
mar
abr
mai
jun
jul
ago
set
out
nov
dez
Date
Function
Cost of electricity (€/MWh)



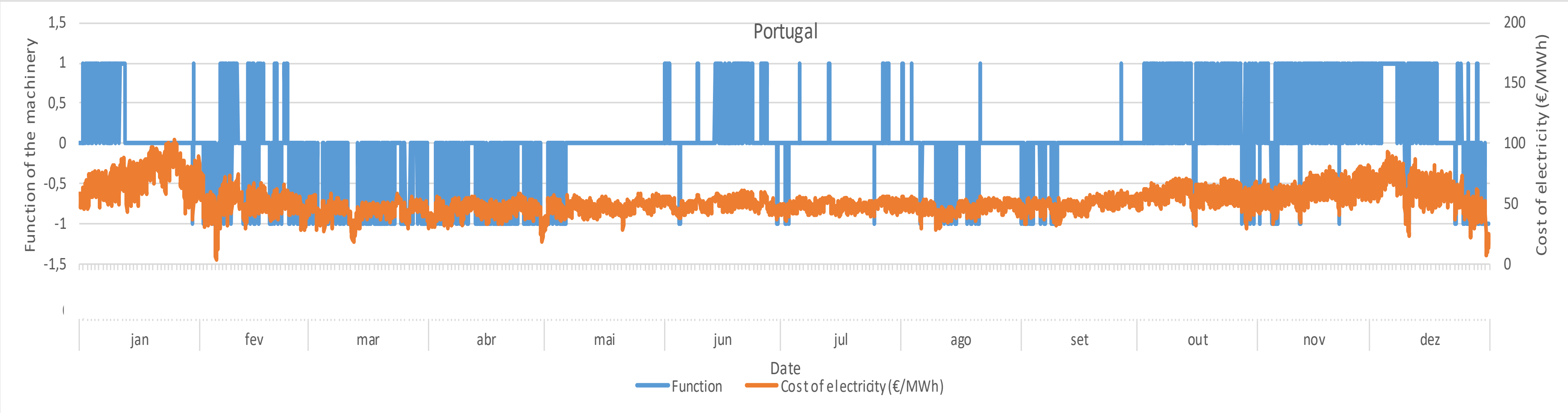


Figure 58 Stored energy and exchanged power at nominal capacity (positive if generated, negative if pumped), and cost of electricity under Operational Strategy 2

The new operational strategy (Figure 58) presents some very distinct changes in the Italian PHS. A first observation permits to understand the big fluctuations in the energy storage during all year. Secondly, we observe that, contrarily to the long periods of charging and discharging in the operational strategy 1, in the new operational strategy consumption and generation occur daily. On the other hand, the Portuguese PHS presents a similar behavior to the operational strategy 1. We observe a storage period during the first half of the year and a discharge and generation period starting at the end of September. Moreover, we perceive a shortage period during the months of January and February.

When analyzing the Italian PHS system working at nominal power, i.e. full capacity, the discharge and charge of the storage system is extremely rapid. As an example, we observe that the system can charge completely from the 28th January until 9th February if the prices are convenient. The major difference is observed in the months of Autumn, where the reservoirs remain full (without pumping nor generating tendency) for the months of September and October (Lower prices) so the system can generate energy on the next months.

Table 26 Revenues for Operational Strategy 2 (thousands of €)

Profits	Italy	Portugal
Jan	63557	36293
Feb	-21896	2461
Mar	48034	-33649
Apr	24308	-35173
May	14972	-12787
Jun	2809	20830
Jul	25891	1541
Aug	58408	-5355
Sep	-17051	-8111
Oct	10444	41996
Nov	80654	57093
Dec	172	46455
Tot (million €)	290,30	118,40

Portugal presents a similar trend on the profits as in the previous operational strategy, since the months of March, April and May have losses during this period. On the operational strategy 2 August and September also present minor losses. We observe large profit increases in the months of January and June, October, November and December.

Under this optimistic analysis the Italian PHS system presents a much higher profit, increasing it by 500% compared to the operational strategy's 1 profit. All months, except February and September, present a positive revenue. Comparing the two countries, we understand that thanks to the higher nominal power in Italy (Italy's nominal power is 2,6 higher than Portugal), Italy has a greater potential to generate better revenues.

The Figure 59 shows the number of working hours at a given power resulting from the Operational Strategy 2 and ENTSO-E data. Looking at the graph and comparing the 2 cases, a reduction in the number of working hours for the turbines and pumps can be seen for both countries. Moreover, the Operational Strategy 2 works full at nominal capacity, as imposed by the rules.

Analyzing the results from the Operational Strategy 2, Italy and Portugal estimate nearly 1400 hours of energy generation. The Italian PHS pumps nearly 200 hours more than the Portuguese's.

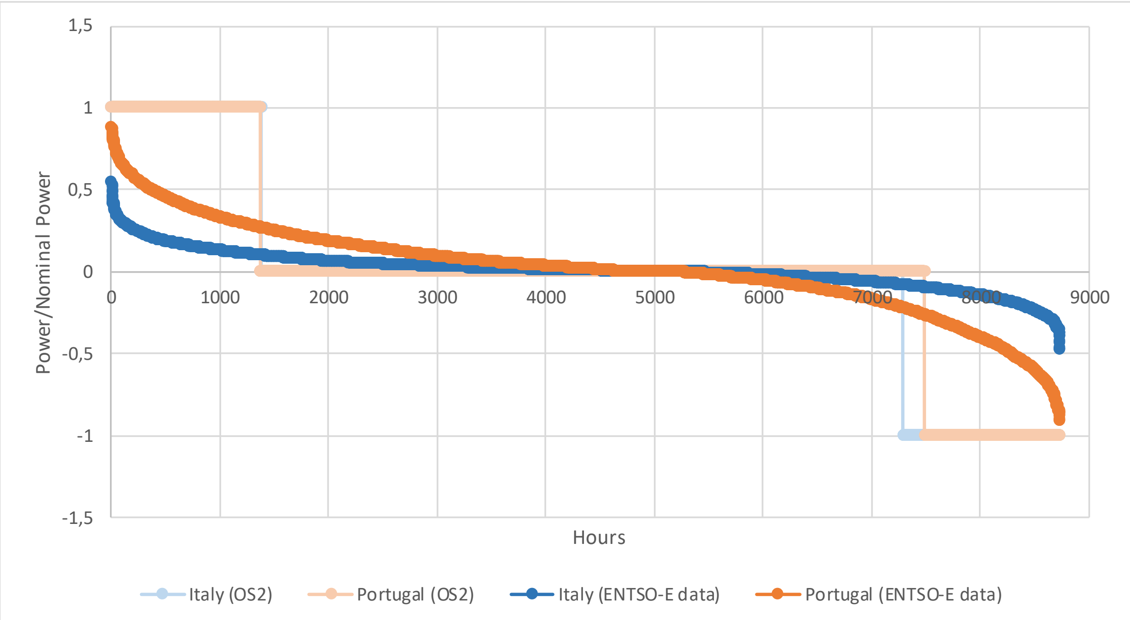


Figure 59 Operation Strategy 2 and ENTSO-E historical data: power/ nominal power ratio by working hours for Italy and Portugal

Finally, the Italian PHS at the end of the year has 695,80 GWh store exceeding energy by 460,92 GWh when comparing with the 1st January 2017, allowing to explore a possible profit of 30,05 million of €. Portugal reservoirs required to fill up the reservoirs with 314,03 GWh to obtain the same amount of energy from the beginning of the year and a cost of 18,66 million of €.

6.4 Operational Strategy 3: Optimization using linear equations to describe pumping and turbine power

In this operational strategy the power equations are described by linear equations. The purpose of this model is to create a scenario to study what is the effect of grading the pumped power and generated power in the profit maximization.

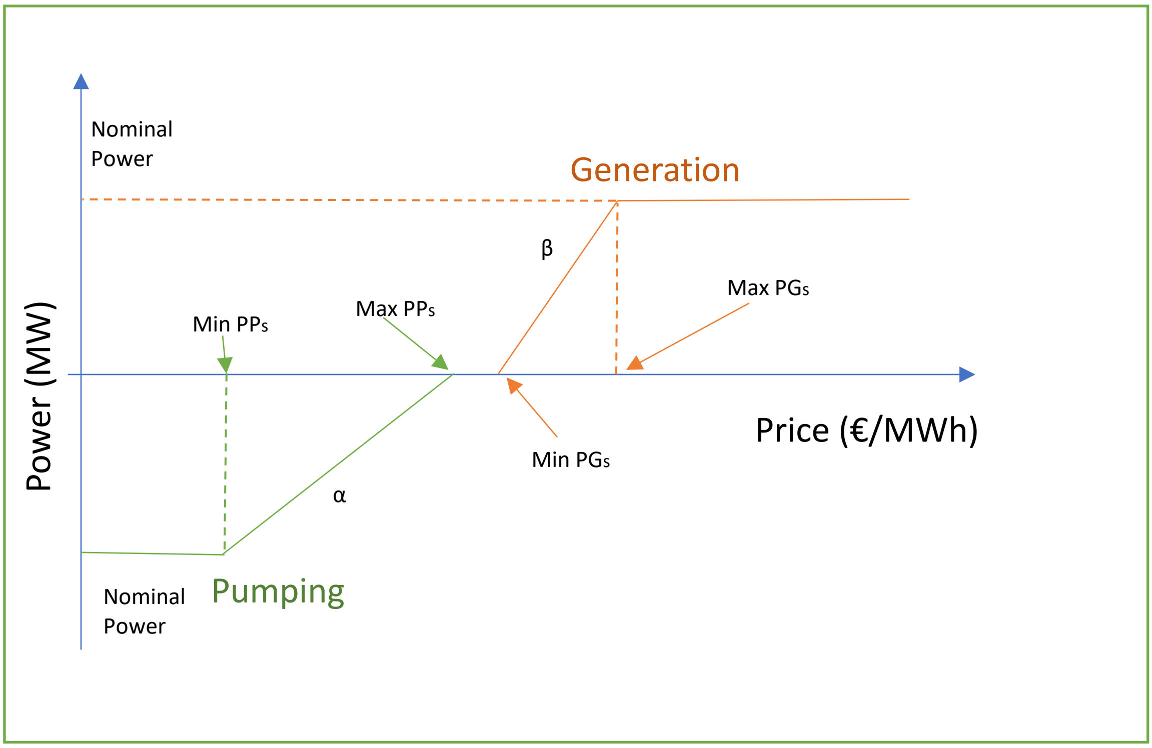


Figure 60 Optimization Strategy 3: Linear Power depending on price thresholds

The Figure 60 shows two thresholds for each equation, resulting in a gradual increase or decrease of the power pumped and power generated equations. The thresholds are the following:

- $Min\ PP_s$ is the Minimum Price for pumping energy during the season s;
- $Max\ PP_s$ is the Maximum Price for pumping energy during the season s;
- $Min\ PG_s$ is the Minimum Price for generating energy during the season s;
- $Max\ PG_s$ is the Maximum Price for generating energy during the season s;

This operational strategy is divided in 2:

- Operational strategy 3.a: linear power variation at fixed Min PP and Max PG
- Operational strategy 3.b: linear power variation at variable inclination.

The operational strategy 3.a imposes the $Min\ PP_s$ and the $Max\ PG_s$ assuming that if below and above theses values, the PHSs would pump and turbinate at nominal power, respectively. These values were chosen based on a visual analysis of the statistical data from chapter 5. The investigation presents 1 fixed pairs of thresholds by the user ($Min\ PP$ and $Max\ PG$) and 1 variable pair of thresholds ($Max\ PP$ and $Min\ PG$) for each season. Thus, the simulation presents 4 optimizable parameters.

The operational strategy 3.b models the pair of thresholds ($Max\ PP$ and $Min\ PG$) and the linear coefficients of the pumped power and generated power equations (α and β, respectively). For the present modulation the thresholds are optimized each season and the linear equations are yearly. The operational strategy presents a total of 4 variable price thresholds and 1 optimizable coefficient for each energy equation.

6.4.1 Operational Strategy 3.a: linear power variation at fixed Min PP and Max PG

This operational strategy fixes the values of $Min\ PP_s$ and the $Max\ PG_s$ thanks to a visual analysis of the statistical data analysis of the chapter 5. After studying the variations "price-energy" each season, 2 prices were selected:

- a low price ($Min\ PP_s$) from which, we assumed, all PHS are on pumping function;
- high price ($Max\ PG_s$), where all PHS are generating energy.

Similarly, to before $Max\ PP_s$ and $Min\ PG_s$ are related by the roundtrip efficiency. As explained before the index s represents the seasons and the indexes p and n indicate the day and hour. The power equations according to the thresholds are the following:

$$\begin{cases} Pumped\ power_{p,n} = P_{Nominal} & if\ Price_{p,n} \leq Min\ PP_s \\ Pumped\ power_{p,n} = P_{Nominal} \times \dfrac{Price_{p,n} - Max\ PP_s}{Max\ PP_s - Min\ PP_s} & if\ Min\ PP_s < Price_{p,n} \leq Max\ PP_s \\ Generated\ Power_{p,n} = P_{Nominal} \times \dfrac{Price_{p,n} - Min\ PG_s}{Max\ PG_{p,n} - Min\ PG_s} & if\ Min\ PG_s < Price_{p,n} \leq Max\ PG_s \\ Generated\ Power_{p,n} = P_{Nominal} & if\ Price_{p,n} \geq Max\ PG_s \end{cases}$$

The nominal power of this operational strategy is the same as the previous one. The results of the thresholds can be observed on the following table:

Table 27 Operation Strategy 3.a prices threshold (€/MWh)

		Winter	Spring	Summer	Autumn
Italy	Min PP (€/MWh)	40,00	25,00	30,00	35,00
	Max PP (€/MWh)	56,96	36,49	42,43	55,85
	Min PG (€/MWh)	79,47	50,92	59,20	77,92
	Max PG (€/MWh)	95,00	60,00	70,00	90,00
Portugal	Min PP (€/MWh)	35,00	35,00	30,00	30,00
	Max PP (€/MWh)	40,37	49,57	39,54	36,24
	Min PG (€/MWh)	56,30	69,17	55,17	50,57
	Max PG (€/MWh)	85,00	80,00	70,00	70,00

The Table 27 shows the imposed thresholds with a green background. When comparing the price limitations for pumping and turbinated power with operational strategy 1, we observe some differences in the Italian and Portuguese's PHS behavior.

Italy presents small variations during each season, having as major changes Winter and Autumn with an increment near 15 €/MWh and spring with a reduction of 10 €/MWh.

The simulation of the Portuguese scenario also presents several changes in the prices. There is a decrease in the cost of electricity in Summer and Autumn around 2,5 €/MWh, while Winter and Spring electricity's price expresses a growth on the of 2 and 6,5 €/MWh, respectively.

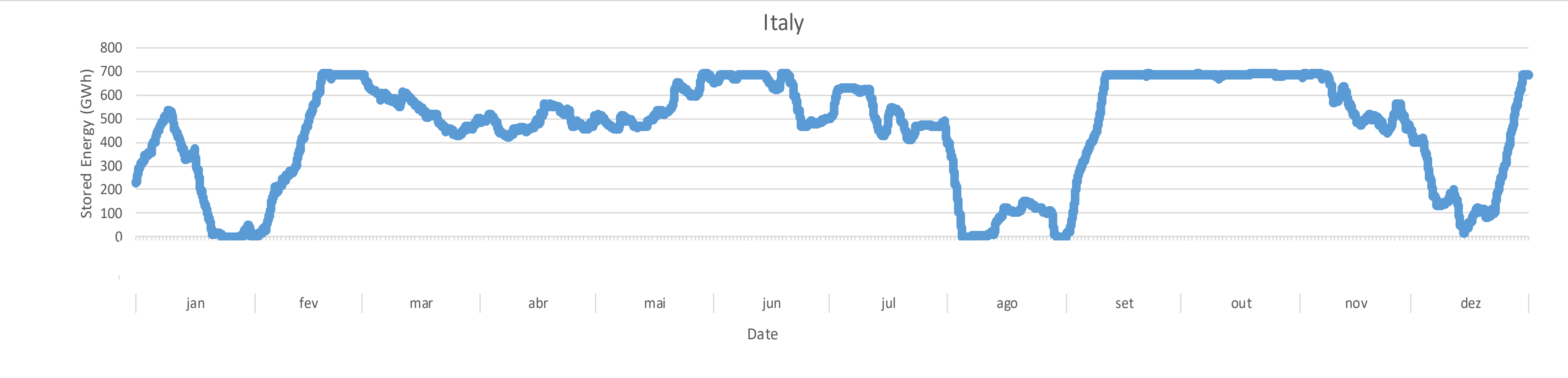
Observing Table 28 the ratios are quite variable. In both Portugal and Italy, the price thresholds which limit the usage of pumping and turbinating at nominal power are distant from 1. Therefore, for the PHS to pump or generate at nominal power, the price should be much lower or higher than the average price of the season, respectively.

Table 28 Operational Strategy 3.a: Price threshold rationalized

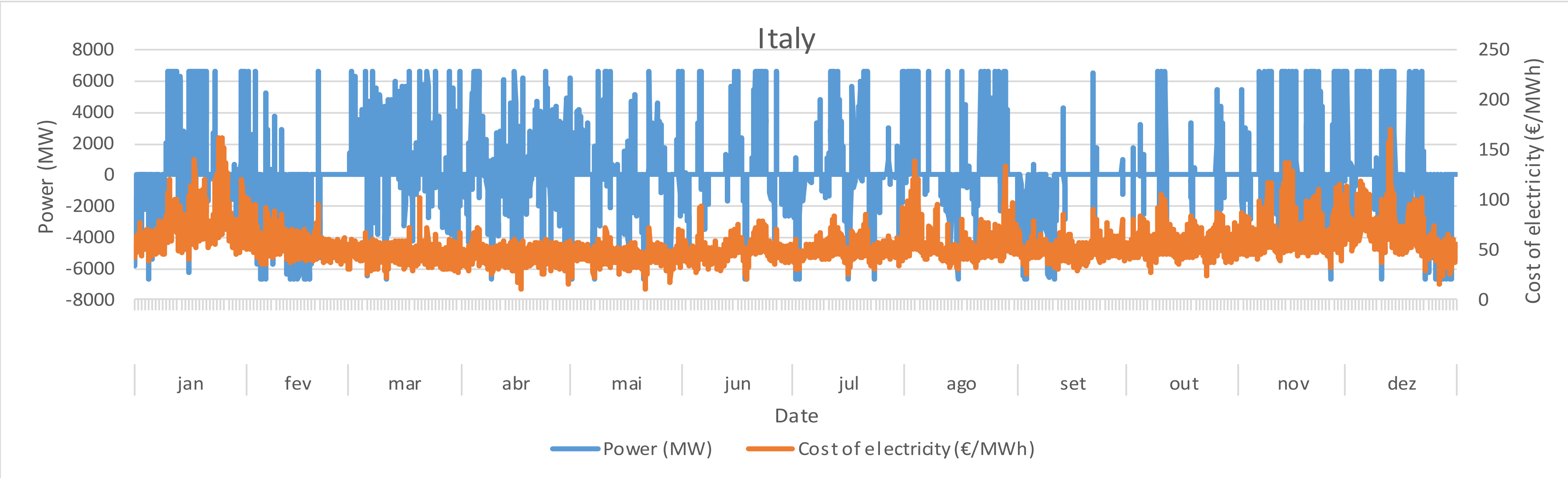
		Winter	Spring	Summer	Autumn
Italy	Min PP/AP	0,62	0,58	0,58	0,63
	Max PP/AP	0,88	0,84	0,82	1,00
	Min PG/AP	1,23	1,17	1,15	1,39
	Max PG/AP	1,47	1,38	1,35	1,61
Portugal	Min PP/AP	0,57	0,78	0,62	0,55
	Max PP/AP	0,66	1,10	0,82	0,66
	Min PG/AP	0,92	1,54	1,15	0,92
	Max PG/AP	1,39	1,78	1,45	1,27

In Italy, Winter and Autumn are the periods which present the higher ratios, thus the PHS system requires higher prices to generate energy in these seasons.

The simulation shows that for Portugal, the optimized thresholds present low values during the Winter, Summer and Autumn, opposing to Spring which have higher ratios. Similar to operational strategy 1, the system predominantly uses the Spring season to stock energy, so it can produce on the other seasons.



Italy
Stored Energy (GWh)
800
700
600
500
400
300
200
100
0
jan
fev
mar
abr
mai
jun
jul
ago
set
out
nov
dez
Date



Italy
Power (MW)
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
Cost of electricity (€/MWh)
250
200
150
100
50
0
jan
fev
mar
abr
mai
jun
jul
ago
set
out
nov
dez
Date
Power (MW)
Cost of electricity (€/MWh)

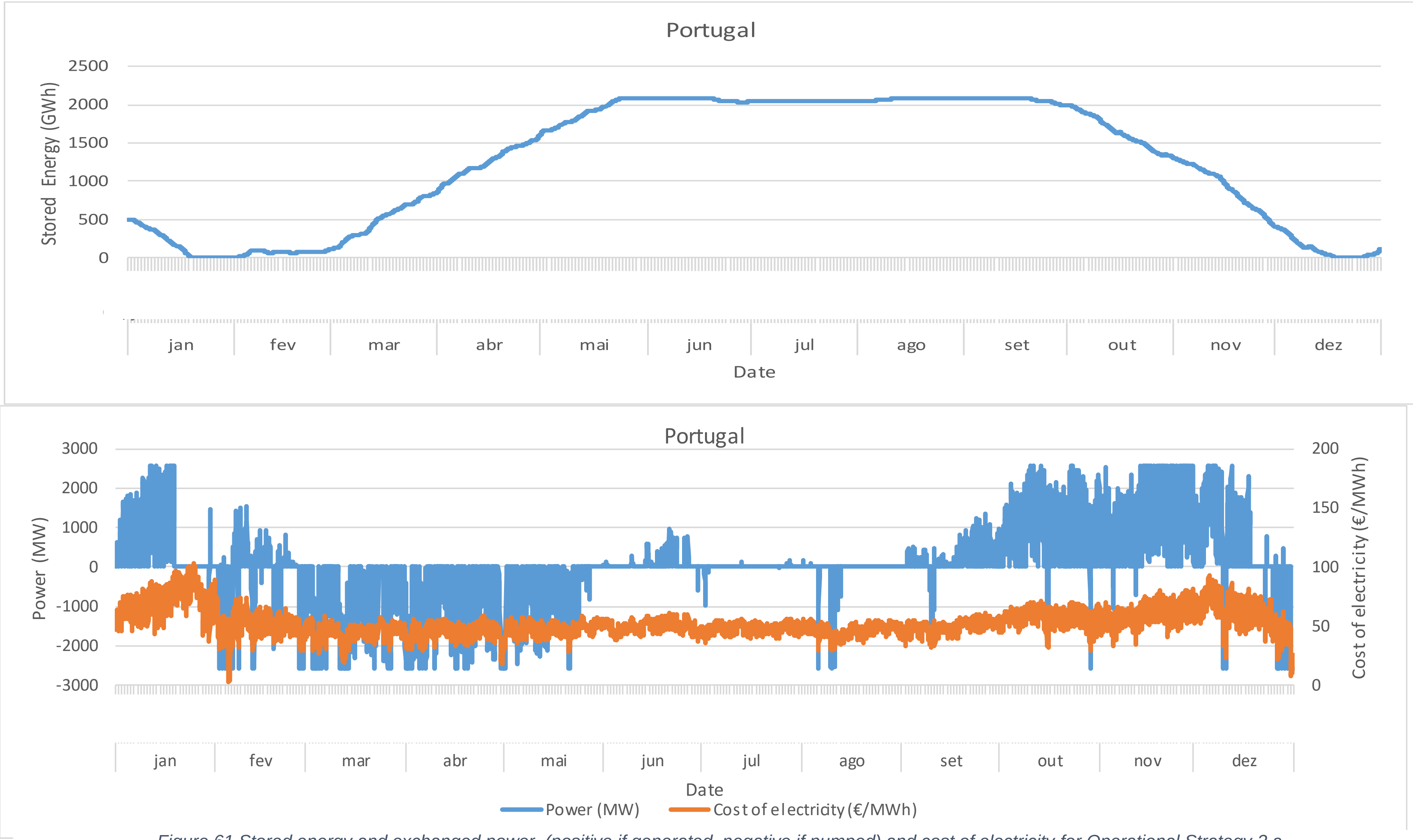


Figure 61 Stored energy and exchanged power (positive if generated, negative if pumped) and cost of electricity for Operational Strategy 3.a

The Figure 61 shows the stored energy under operational strategy 3.a with optimized parameters presents great similarities with the one of operational strategy 2, for both countries. The implementation of the linear power equations in Italy results in a moderate reduction of the variations of PHS. The main difference between operational strategy 3.a and 1 in Italy is transition to a strategy which permits to charge and discharge the storage daily. Moreover, the operational strategy 3.a and 2 are similar, presenting the difference that the storage system does not discharge completely during the spring, remaining at 400 GWh stored energy.

Portugal's new operational strategy presents a similar trend as the operational strategy 2. The main difference is a neither energy is produced or generated from June to September. Once more the PHSs are in shortage from mid-January until end of February.

Table 29 Revenues for Operational Strategy 3.a (thousands of €)

Profits	Italy	Portugal
Jan	43150	37736
Feb	-28081	-372
Mar	19839	-28555
Apr	10366	-28413
May	4195	-19253
Jun	16124	3102
Jul	20610	-122
Aug	50092	-1543
Sep	-28317	5930
Oct	2588	44027
Nov	41801	60261
Dec	25158	29207
Tot (million €)	177,52	102,01

Portugal presents a similar behavior on the profits as the previous operational strategies since the months of March, April and May have losses during this period, due to the necessity of filling the system. The months of July and August present minor losses. On the contrary, with the new thresholds implemented the Portuguese PHSs September present profits, resulting from the generated energy from this period. The new operational strategy presents a reduction of near 16,40 million € in profits, when compared with operational strategy 2.

Under this linear analysis the Italian PHS system when compared to operational strategy 1, all months in spring presented a positive revenue due to the strategy change. The current operational strategy 3.a presents an increase near 300% on the revenue.

Similar to the operational strategy 2, Italy's nominal power allows to potentialize higher profits than Portugal.

Looking at the Figure 62, Italy's operational strategy 3.a shows a different behavior from the ENTSO-E, generating at nominal power for nearly 400 hours and reducing gradually until 0 at the 1200 hours. Italy's PHS pumps estimate near 1800 working hours. The operational strategy 3.a shows a reduction of the working hours.

Portugal PHSs in operational strategy 3.a presents values of Power/ Nominal power higher than ENTSO-E data. On the same analyzes, a small reduction of working hours from turbines and pump are observed.

Lastly, the generation of energy from Italian PHSs decreases more rapidly than Portuguese's for operational strategy 3.a., as we see from the Italians PHS turbine function, which only works for 1700 hours, compared to the Portuguese's, which work for more than 2200 hours. The PHSs pumps behave similar for both countries

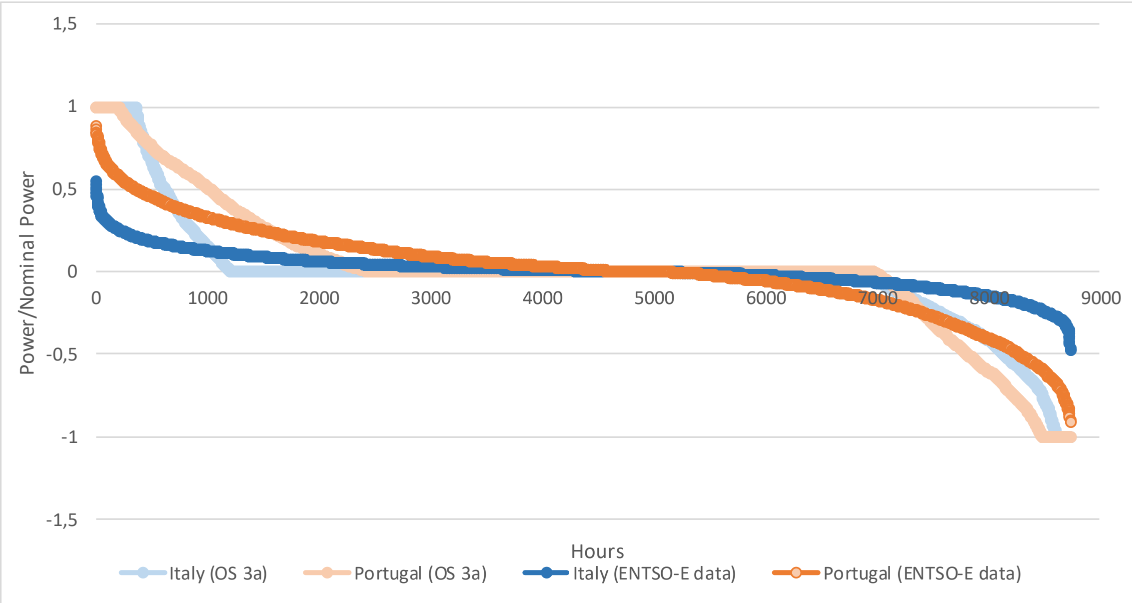


Figure 62 Operation Strategy 3.a and ENTSO-E historical: a: power/ nominal power ratio by working hours for Italy and Portugal

At the end of the year, Italy would require discharge 458,01 GWh to reach the same stored energy as the 1st January 2017 and presenting a possible revenue of 29,82 million €. On the other hand, Portugal needed to charge the PHS with 378,66 GWh with a cost of 22,50 million of €.

6.4.2 Operational Strategy 3.b: linear power variation at variable inclination

The last operational strategy 3.b represents a small variation from the operational strategy 3.a. The current strategy chooses to variate the price threshold and the linear coefficients (α and β) instead of fixing the lower and upper limits. As referred before the linear coefficients have the same inclination during all year and there are 4 price thresholds ($Min\ PP_s$) which correspond to a price of each season. The operational strategy presents a total of 6 variables parameters.

The power equations according to the thresholds and linear coefficients are the following:

$$\begin{cases} Pumped\ power_{n,p} = P_{Nominal} & if\ Price_{n,p} \leq Min\ PPE_s \\ Pumped\ power_{n,p} = \alpha\ (Max\ PP_s - Min\ PP_s) - \alpha(Price_{n,p} - Min\ PP_s) & if\ Min\ PP_s < Price_{n,p} \leq Max\ PP_s \\ Generated\ Power_{n,p} = \beta\ (Max\ PG_s - Min\ PG_s) - \beta(Max\ PG_s - \ Price_{n,p}) & if\ Min\ PG_s < Price_{n,p} \leq Max\ PG_s \\ Generated\ Power_{n,p} = P_{Nominal} & if\ Price_{n,p} \geq Max\ PG_s \end{cases}$$

The nominal power of operational strategy 3.b is the same as the previous one. The results of the thresholds can be observed on the following table:

Table 30 Optimized price thresholds for Operation Strategy 3b, by season and by country.

		Winter	Spring	Summer	Autumn
Italy	α	-7493,50	-7493,50	-7493,50	-7493,50
	β	3190,7	3190,7	3190,7	3190,7
	Min PP (€/MWh)	53,16	34,61	41,10	47,51
	Max PP (€/MWh)	54,06	35,51	42,01	48,41
	Min PG (€/MWh)	75,09	49,32	58,35	67,24
	Max PG (€/MWh)	77,22	51,45	60,48	69,37
Portugal	α	-2955,2	-2955,2	-2955,2	-2955,2
	β	1998,6	1998,6	1998,6	1998,6
	Min PP (€/MWh)	44,32	40,04	36,61	39,89
	Max PP (€/MWh)	46,62	42,34	38,91	42,19
	Min PG (€/MWh)	64,75	58,80	54,04	58,60
	Max PG (€/MWh)	68,15	62,20	57,44	62,00

Table 30 shows the price thresholds and the linear coefficients. As explained before, the optimal values of α, β, Max PP and Min PG are variated in order to maximize the profit of 2018. The Min PP is obtained through the variation of α (green color), while the max PG is obtained through β (yellow color).

The Italian linear coefficients present very high values, leading to very small difference between prices for Pumping (PP) and prices for Generation (PG) (approximately 1 €/MWh). This information allows to understand, that to maximize the PHS profit using a linear equation is to choose a similar strategy to operational strategy 2.

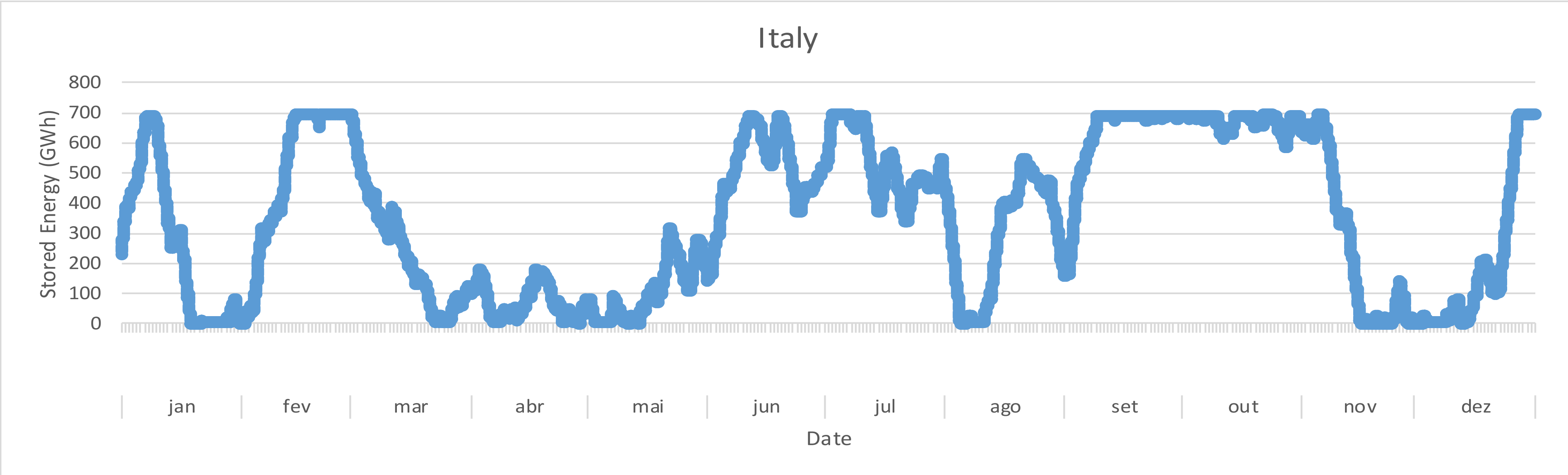
The inclinations of α and β on the Portuguese power equations are less steep than Italian case, but still demonstrate a small difference between PP and PG (approximately 3,5 €/MWh)

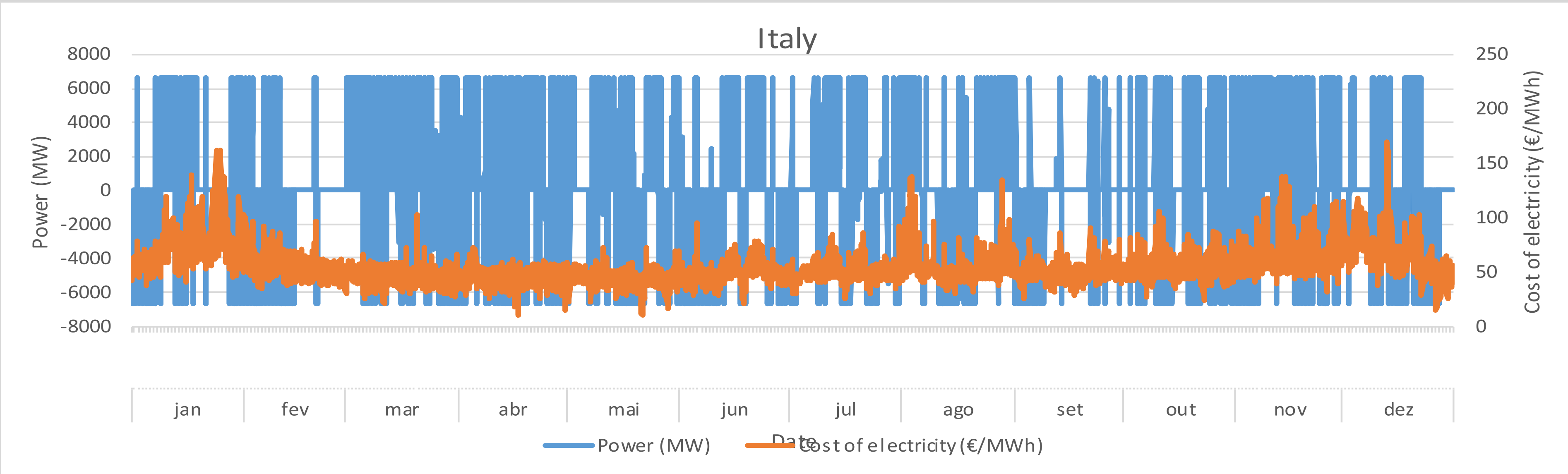
Table 31 Operational Strategy 3.b: Price threshold rationalized

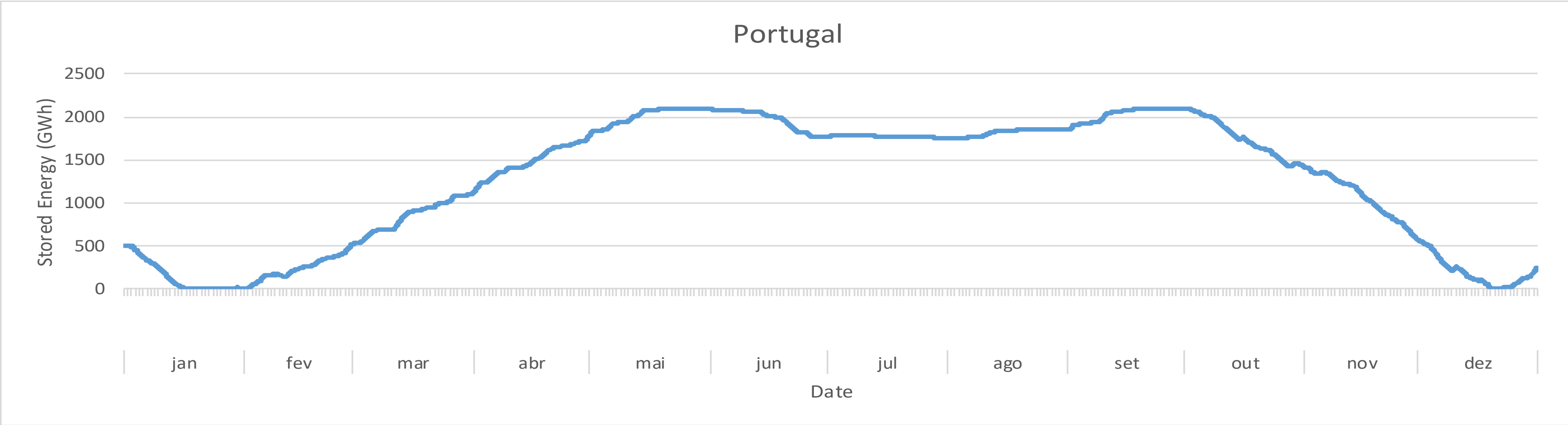
		Winter	Spring	Summer	Autumn
Italy	Min PP/AP	0,82	0,80	0,80	0,85
	Max PP/AP	0,84	0,82	0,82	0,86
	Min PG/AP	1,16	1,13	1,13	1,20
	Max PG/AP	1,20	1,18	1,17	1,24
Portugal	Min PP/AP	0,73	0,89	0,76	0,73
	Max PP/AP	0,76	0,94	0,81	0,77
	Min PG/AP	1,06	1,31	1,12	1,07
	Max PG/AP	1,12	1,38	1,19	1,13

Observing Table 31, the new ratios are closer to 1, indicating there are no seasons in which the system has a greater predisposition for pumping or generating energy. In Italy, all seasons present the same ratios, thus there is no preferable season to pump or generate.

The new operational strategy continues to have a higher ratio in the Spring in Portugal, leading to the conclusion that is the ideal season to stock energy.


Italy
Stored Energy (GWh)
800
700
600
500
400
300
200
100
0
jan
fev
mar
abr
mai
jun
jul
ago
set
out
nov
dez
Date


Italy
Power (MW)
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
Cost of electricity (€/MWh)
250
200
150
100
50
0
jan
fev
mar
abr
mai
jun
jul
ago
set
out
nov
dez
Date
Power (MW)
Cost of electricity (€/MWh)



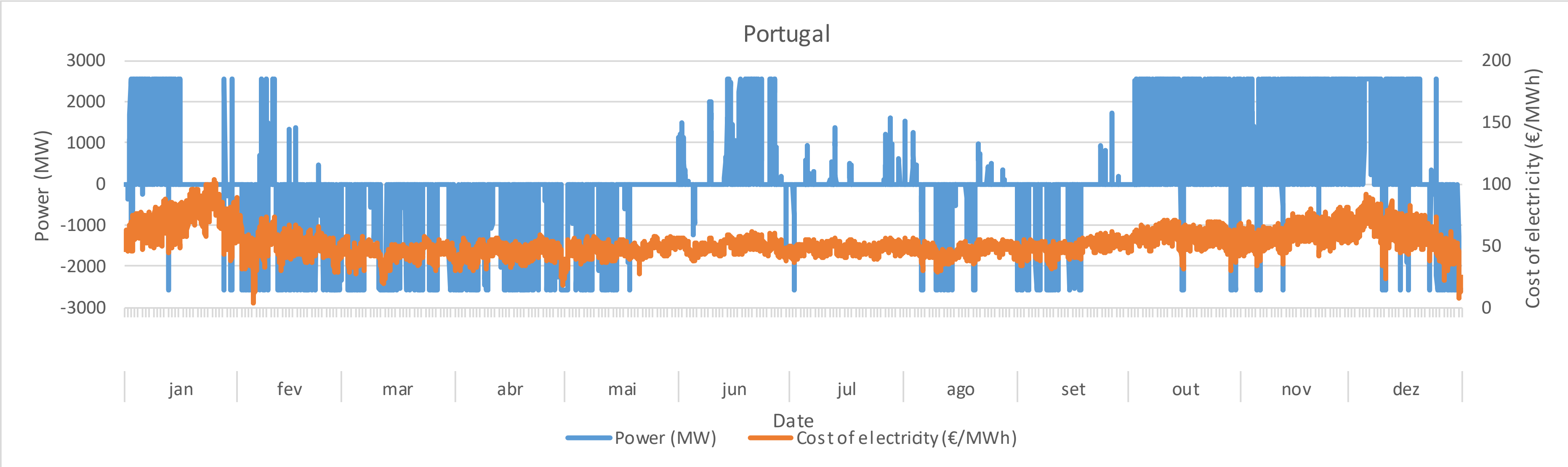


Figure 63 Stored energy and exchanged power at nominal capacity (positive if generated, negative if pumped), and cost of electricity for Operational Strategy 3.b

Once again, the energy stored (Figure 63) from optimal strategy 3.b presents great similarities with the operational strategy 2, for Italy. The implementation of the linear power equations with variable coefficients in Italy shows a behavior where the machinery works mainly at full capacity.

Portugal's new PHS stored energy curve maintains the same behavior as the operational strategy 2, maintaining the same 2 peaks of stored energy. Moreover, the PHS during the months from July until September have higher hours of operations when compared to operational strategy 2. We also observe that the system mainly works at nominal capacity.

Table 32 Revenues for Operational Strategy 3.b (thousands of €)

Profits	Italy	Portugal
Jan	51365	37475
Feb	-24087	-18047
Mar	47107	-21344
Apr	21205	-24436
May	14433	-11604
Jun	1904	18171
Jul	27085	1264
Aug	56896	-2742
Sep	-19684	-8920
Oct	19384	45266
Nov	73414	59164
Dec	-18446	37598
Tot (million €)	250,03	111,85

The Portuguese PHS in the operational strategy 3.b presents profit losses in the same months as operational strategy 2. The operational strategy 3.b still uses the Winter to generate a great part of the profit. The current operation presents a reduction of 7 million € compared to operational strategy 2.

Under this linear analysis the Italian PHS system presents an annual profit with 250,03 million of €, approaching the profit value of operational strategy 2.

Looking at the Figure 64 and comparing the 2 cases, a reduction in the number of working hours for the turbines and pumps can be seen. Moreover, the operational strategy 3.b works mainly full at nominal capacity, with a very steep decrease in the power generated in both countries. The Italian PHS pumps work nearly 200 hours more than the Portuguese's at full capacity. Once again, the Figure 64 presents a very similar behavior as the Figure 59.

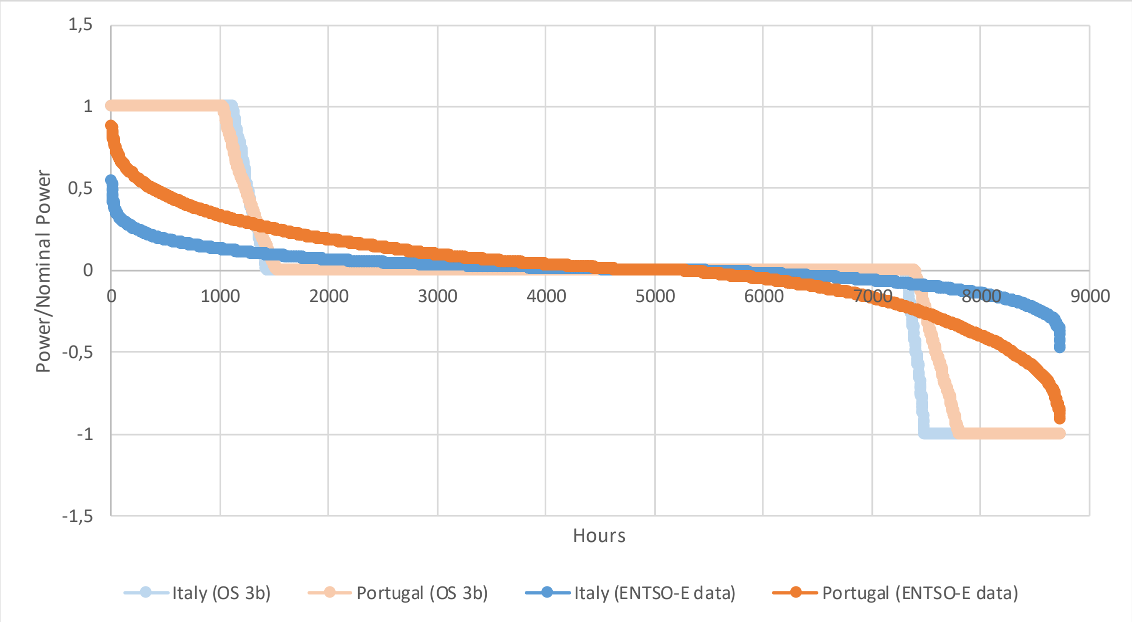


Figure 64 Operation Strategy 3.b and ENTSO-E historical data: a: power/ nominal power ratio by working hours for Italy and Portugal

At the end of the year, Italy would require discharge 463,21 GWh and presenting a possible revenue of 30,16 million €, while Portugal needed to charge the PHS with 256,52 GWh and a cost of 16,70 million of €.

6.5 Comparison of the Operational Scenarios

The present chapter expresses the results from operational strategies. As observed from Table 33 Summary table of the main characteristics of each operational strategy in both countries, the operational strategy 2: Operation at full pump and turbine power with limitation by price threshold is the strategy which allows to obtain higher profits from 2017 for both countries. Individually, this strategy allows the Italy PHSs to discharge and charge extremely rapidly their reservoirs. This behavior allows to explore more the system. Portugal's PHSs present a similar behavior in all operational strategies since during the Spring the PHSs pump energy to preserve it for the Autumn and Winter, where the energy prices are higher, and it is more advisable to generate energy. Nevertheless, it is also Portugal's operational strategy 2, the strategy with highest annual profit.

The Table 33 also shows that the operational strategy 2 presents the lowest values of working hours for the turbines and pumps. This concludes that the systems of both countries do not necessarily need to work many hours, but to find an ideal operational strategy

Table 33 Summary table of the main characteristics of each operational strategy in both countries

		Italy	Portugal
Yearly profit (millions €)	Operational Strategy 1	57,71	56,65
	Operational Strategy 2	290,30	118,40
	Operational Strategy 3. a	177,52	102,01
	Operational Strategy 3. b	250,03	11,85
Turbine working hours	Operational Strategy 1	2305	2517
	Operational Strategy 2	1378	1371
	Operational Strategy 3. a	1211	2439
	Operational Strategy 3. b	1423	1518
Pump working hours	Operational Strategy 1	2128	1336
	Operational Strategy 2	1448	1249
	Operational Strategy 3. a	1903	1766
	Operational Strategy 3. b	1425	1347

Conclusion

This thesis work focuses on the importance of the Pumped Hydroelectric Storage and on how it can contribute to the energy market. The objective of the thesis is to analyze the Italian and Portuguese PHS current behavior and to apply different operational strategies to understand their possible economic margin of profit during a year. A statistical analysis of the present PHSs behavior, for Italy and Portugal, complements the study.

Initially, a literature review for the future energy demand is compiled. The literature review compares world and Europe future energy demand according to the estimation from International Energy Agency and USA Department of Energy, exploring also the future developments of the energy sources which supply the demand. Furthermore, it analyzes Italy's and Portugal's energy demand and the transition from the present energy supply in order to fulfill European Union Directives.

The next step is a review of the Energy Storage Systems including a classification depending on the form of energy under which electricity is stored and an assessment of the main characteristics and functionalities. More into detail, the Pumped Hydroelectric Storage main characteristics, pros and cons were studied. The most recent PHS innovation systems were analyzed, such as the hybrid battery-PHS plant to supply the ancillary services and the integrated wind/solar-PHS plants in islands. Moreover, the chapter defines a list of the Pumped Hydroelectric Storages functioning in 2017 in Portugal and Italy.

The last part of literature review analyzes the 4 electrical markets of Italy, Portugal, Australia and U.S.A. The U.S.A have a regulated or de-regulated energy market depending on the state. As for Italy, Portugal and Australia, they all have liberalized energy markets. The 3 liberalized energy markets have day ahead market, future market and ancillary services and all have independent entities ensuring the functionating and trading of the services. In particular, the Australian regulatory entity required to create upper and lower limits to the day ahead price to regulate the energy market.

The datasets from ENTSO-E express the energy generated and energy pumped from PHSs in Italy and Portugal in every hour and the dataset from GME and REN provide the electricity prices for Italy and Portugal, respectively, which permitted the statistical analysis for all datasets. Using the datasets information for the year 2017 as reference, energy generated, and energy pumped equations were identified for both countries which could represent the historical data. These energy equations were created based on multiple linear regressions. According to the PHSs' actual behavior in both countries, there is not a PHS good exploitation strategy and for this reason the systems present a low profit.

After that, simulations are performed in order to maximize the economic profile of the PHSs in each country through the application of various operational strategies. The simulations use the Italian and Portuguese prices from the day ahead market. Each simulation identifies the price thresholds to define an operational strategy, where above a certain price the PHSs generated energy (Min PG) and below a certain price the PHSs accept energy (Max PP).

Then 3 operational strategies were conceived:

- Operational strategy 1: Optimization of the present scenario through a multiple linear equation limited by a price threshold;
- Operational strategy 2: Optimization as an ideal system working with an on/off mode of the total installed capacity, with limitation by price;
- Operational strategy 3: Optimization with a linear variation from zero to full use of the installed capacity, with a gradual growth.

The results show that operational strategy 2 is the strategy with higher profit, being nearly 290 million € for the Italian PHSs and 120 million € for the Portuguese PHS. Italy's situation shows that if there is small energy storage capacity for a very high installed capacity, the system can fully charge and discharge in a very short period in order to maximize their profit. Observing Portugal, the energy storage capacity is much higher, and it is preferable to have a long-term goal to exploit the PHS. The results also show that the PHSs tend to store energy during spring, when prices are lower, whereas they generate energy during winter, when the electricity prices are higher.

Recommended future developments of the work suggest adopting a monthly threshold in the analysis instead of the seasonal approach implemented here, to increase the time resolution on each operational strategy. Another possible element which can improve the analyses on the price thresholds would be to increase the number of years of study. The literature reviews suggest that the overall efficiency variates from 70 to 85%. For the present work the overall efficiency used was 72% which is a conservative approach, this value could also be object of discussion in next investigations. Furthermore, this thesis focusses on the day ahead market, but the PHSs could also participate on the ancillary services for direct remuneration from the renewable energy sources balance or even in the capacity market to ensure that the PHS is able to delivery energy when the electrical grid needs it.

Acronyms

PHS – Pumped Hydroelectric Storage

CAES – Compressed Air Energy Storage

TES – Thermal Energy Storage

SMES – Superconducting Magnetic Energy Storage

BES - Battery Energy Storage

EDP – Energias de Portugal

REN – Rede Energética Nacional

NEM – National Electrical Market

WEM – Wholesale Energy market

GME- Gestore Mercati Energetici

PEM FC - Proton Exchange Membrane Fuel Cells

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