Wind-Hydro Hybrid Park

António Pedro de Matos Eliseu

Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

Supervisor: Prof. Rui Manuel Gameiro de Castro

Examination Committee

Chairperson: Maria Eduarda De Sampaio Pinto de Almeida Pedro

Supervisor: Prof. Rui Manuel Gameiro de Castro

Member of the Committee: Prof. Célia Maria Santos Cardoso de Jesus

November 2018

Declaration

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

Abstract

Since the beginning of the 21st century, a significant growth in research and implementation of new renewable energy sources has occurred, amongst which is wind power. However, the integration of this technology in the electrical grid creates power imbalances originated by the high variability and unpredictability regarding wind’s speed and direction.

Pump-hydro-storage plants allow water to be stored in upper reservoirs, through the operation of pumps, when a certain power is not necessary and, later, used the water stored to generate power when a demand exists. Therefore, the coupling of pump-hydro-storage plants with wind power arise as a solution to overcome the inherent problems that wind power possesses, by allowing the balancing of certain power deviations.

The case-study is an example of an infrastructure of this kind and a study is conducted concerning the optimization between these two technologies, in a hypothetical operation scenario in Portugal. This study is divided in two sections. The first attempts to maximize the market profit during an operation day and incorporates a day-ahead optimization and an operational day strategy. The second contains an analysis regarding the feasibility of the installation to generate a constant target power during a complete operation day.

The results obtained for the first section illustrate two distinct modes of operation for maximizing the profit, depending on the value for electricity market prices. As for the second section, it was concluded that the optimal target value for a constant output power is between 6 MW to 7 MW.

Keywords: wind power, pump-hydro-storage plant, optimization, maximizing profit, constant power.

Resumo

Desde o princípio do século XXI, um aumento significativo no estudo e implementação de novas formas de energia renovável tem ocorrido, entre elas a energia eólica. No entanto, a integração desta tecnologia na rede elétrica origina desequilíbrios de potência criados pela variabilidade e difícil previsão da velocidade e direção do vento.

Centrais hídricas com capacidade de armazenamento permitem guardar água em reservatórios superiores, através de bombas, quando uma determinada potência não é necessária e utilizar o volume de água armazenado para produzir energia quando a procura assim o exige. Portanto, a combinação da energia eólica com centrais hídricas deste tipo é uma solução para ultrapassar os problemas inerentes da tecnologia eólica, através do balanceamento de desvios na potência.

O caso para análise é uma infraestrutura deste tipo e um estudo é efetuado no que diz respeito à otimização da coordenação entre as duas tecnologias, num cenário de operação em Portugal. O estudo está dividido em duas secções. A primeira tem como objetivo maximizar o lucro da instalação e incorpora uma otimização para o dia seguinte e a estratégia para o dia de operação. A segunda engloba uma análise quanto à possibilidade da instalação gerar uma potência constante durante um dia completo de operação.

Para a primeira secção, os resultados traduzem dois modos distintos de operação para maximizar o lucro consoante os preços do mercado de eletricidade. Quanto à segunda, foi concluído que a gama ótima para o valor de potência constante é entre 6 MW e 7 MW.

Palavras-chave: energia eólica, centrais hídricas com bombagem, otimização, maximização do lucro, potência constante.

Acknowledgments

First, I would like to express my gratitude to my supervisor, professor Rui Castro, for the help and confidence provided during this endeavor, always available with an open door to support me. Without his guidance, this dissertation would certainly not be possible.

To my family. Especially my parents, not only for the effort that allowed me to reach this far in my academic studies, but, most importantly, the education given to me as a person. Also, my older sister Ana and my older brother João… whatever.

To the friends that I made while studying in Instituto Superior Técnico. This dissertation is the culmination of a five year period that without your invaluable friendship, support and laughter would be impossible to achieve. Special thanks to Telmo Felgueira, not only for the countless laboratories together, but also for the great help provided during the coding of the artificial neural network algorithm.

To my Alentejo friends. Your friendship and unforgettable moments are absolutely priceless.

Finally, to the friends that I got to make during Erasmus. That was a memorable experience which I will always cherish.

To all, thank you.

António Eliseu

“We live on an island surrounded by a sea of ignorance. As our island of knowledge grows, so does the shore of our ignorance”

John Archibald Wheeler

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

Abbreviations

ANN	Artificial Neural Network
ARMA	Autoregressive Moving Average
DA	Day-Ahead Market
EU	European Union
ID	Intraday Market
LP	Linear Programming
MIBEL	Iberian Electricity Market
MILP	Mixed Integer Linear Programming
NAR	Autoregressive Neural Network
NWP	Numerical Weather Prediction
ODS	Operational Day Strategy
OMIE	Operador del Mercado Ibérico de Energia
PHS	Pump-Hydro-Storage
PV	Photovoltaic
SMA	Simple Moving Average

Symbols

$\boldsymbol{A}$ Inequality constraint matrix

$\boldsymbol{A_{eq}}$ Equality constraint matrix

$\boldsymbol{b}$ Inequality constraint vector

$\boldsymbol{b_{eq}}$ Equality constraint vector

$\boldsymbol{c_{hydro}}$ Operational costs for hydro generation

$\boldsymbol{c_{pump}}$ Operational costs for pumping

$\boldsymbol{dev_i}$ Market imbalance costs in hour i

$\boldsymbol{E_i}$ Energy stored in upper reservoir during day-ahead optimization, in hour i

$\boldsymbol{E_{i\_real}}$ Energy stored in upper reservoir during operational day strategy, in hour i

$\boldsymbol{E_p}$ Potential energy stored in upper reservoir

$\boldsymbol{f}$ Coefficient vector

$\boldsymbol{g}$ Acceleration due to the gravitational force

$\boldsymbol{H}$ Hydro power plant fall head

$\boldsymbol{i}$ Operation hour

$\boldsymbol{lb}$ Upper bound vector

$\boldsymbol{m}$ Mass of water stored in upper reservoir

$\boldsymbol{P}$ Available power stored in upper reservoir

$\boldsymbol{P_{demand}}$ Constant target power value

$\boldsymbol{P_{Gi}}$ Power delivered to the grid during day-ahead optimization, in hour i

$\boldsymbol{P_{Gi\_real}}$ Power delivered to the grid during the operational day strategy, in hour i

$\boldsymbol{p_i}$ Spot market price during day-ahead optimization, in hour i

$\boldsymbol{p_{i\_real}}$ Spot market price during operational day strategy, in hour i

$\boldsymbol{P_i^+}$ Auxiliary variable for linearization of objective function during operational day strategy

$\boldsymbol{P_i^-}$ Auxiliary variable for linearization of objective function during operational day strategy

$\boldsymbol{P_{Hi}}$ Hydro power produced in hour i

$\boldsymbol{P_{Hi\_real}}$ Hydro power produced during operational day strategy in hour i

P_{Wi} Wind power produced by the park in hour i

P_{Wi_real} Wind power produced by the park during the operational day strategy, in hour i

P_{wind} Active power generated by a single wind turbine

P_{WGi} Wind power delivered to the grid during day-ahead optimization, in hour i

P_{WGi_real} Wind power delivered to the grid during operational day strategy, in hour i

P_{WPi} Wind power used for the pumping during day-ahead optimization, in hour i

P_{WPi_real} Wind power used for the pumping during operational day strategy, in hour i

Q Water flow

Q_i^{gen} Water flow used for hydro generation in hour i

Q_i^{pump} Water flow used for pumping in hour i

R_i^{lower} Water volume stored in lower reservoir in hour i

R_i^{upper} Water volume stored in upper reservoir in hour i

u Wind speed

ub Lower bound vector

η_{gen} Efficiency of generation process

η_{pump} Efficiency of pumping process

ρ Water density

1. Introduction

1.1. General Context and Motivation

The current-day power systems have been developed with large and centralized power plants in mind and, until the last decade, the electrical grid was largely dependent on conventional fossil-fuels to operate the power plants. Mankind was unaware of the consequences the abusive and unconscious consumption of those conventional sources of energy throughout the years would have in future generations. However, the growing concern over the environmental impact and sustainability of those energy sources, allied with political and economic interests in countries all over the world, have led to a shift in paradigm and an increased focus in the energy production through renewable energy sources.

In 2007, the EU proposed the 2020 Energy and Climate Package which aimed to reduce greenhouse gas emissions by 20%, taking 1990's emissions as reference, while seemingly increasing the share of renewable energy to at least 20% of the total consumption [1]. With the measures implemented at European level alongside national initiatives by the governments of some of the countries, the EU is on track to reach the goals planned [2]. Nevertheless, worldwide greenhouse gas emissions are rising, especially due to emerging superpowers such as China or India. China is responsible for 25% of the world's emissions with a 1.7% increase in 2017 [3]. Moreover, in the EU, although the targets for 2020 will most likely be reached, the goals proposed in the 2030 Energy and Climate Package, which intended to expand the previous goals by decreasing emissions by 40% and increasing the renewable energies share by 40% [4], and the Energy and Climate Package for 2050, which again expand to 60% the emissions and 60% the share of renewable energies [5], seem unachievable at the moment with the current actions in place. Figure 1.1 presents the greenhouse gas emissions evolution since 1990 to 2016 and the current projections for the future.

A conclusion can be reached that there is still a great margin for improvement if the goal is the worldwide reduction of greenhouse gas emissions. For instance, in late 2017, China approved a plan to greatly reduce these emissions with the implementation of a trading scheme where power plants will give an allowance to emit a certain amount of CO_2 [6], but the eventual success of this measure remains to be seen. The obvious choice is to invest in the research and development of renewable energy sources.

Figure 1.2 highlights the world's global renewable power capacity, from 2007 to 2017. It is possible to observe a significant growth in this period, where the total power installed more than doubled in ten years, going from 1000 GW in 2007 to 2195 GW in 2017. Hydropower is still the overwhelming leading technology, nevertheless, in the past years, other renewable energy sources such as wind power and photovoltaic cells (PV) had a much higher growth rate.

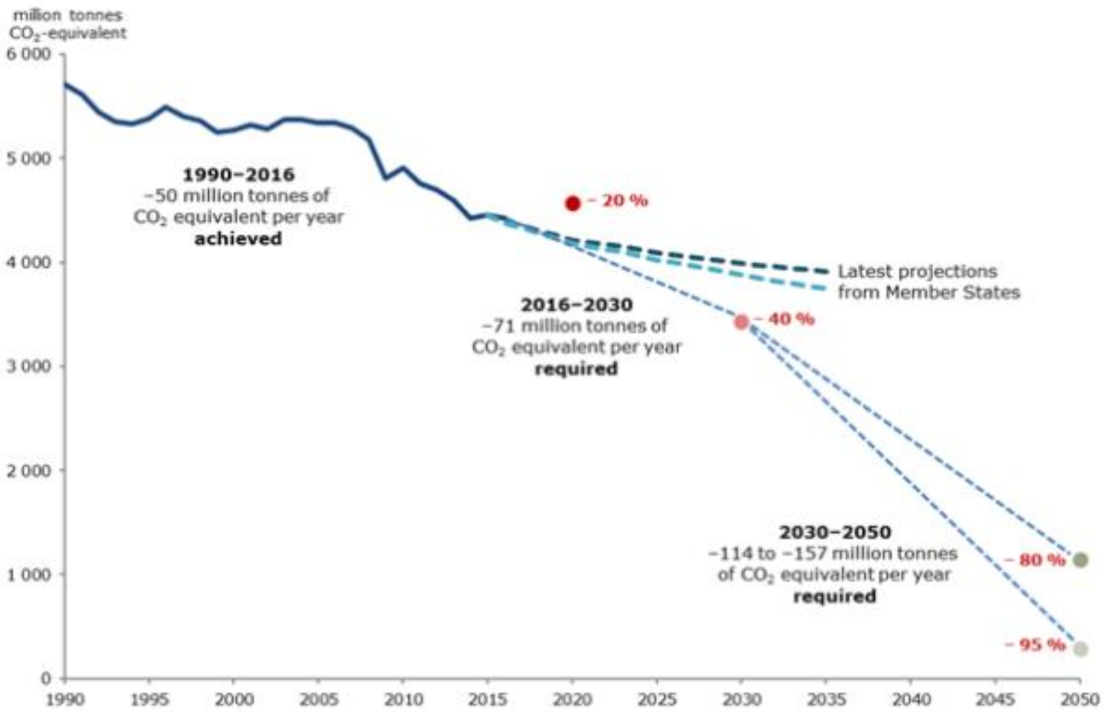

Figure 1.1 - Greenhouse gases emissions from 1990 to 2016 and projections until 2050 [2]

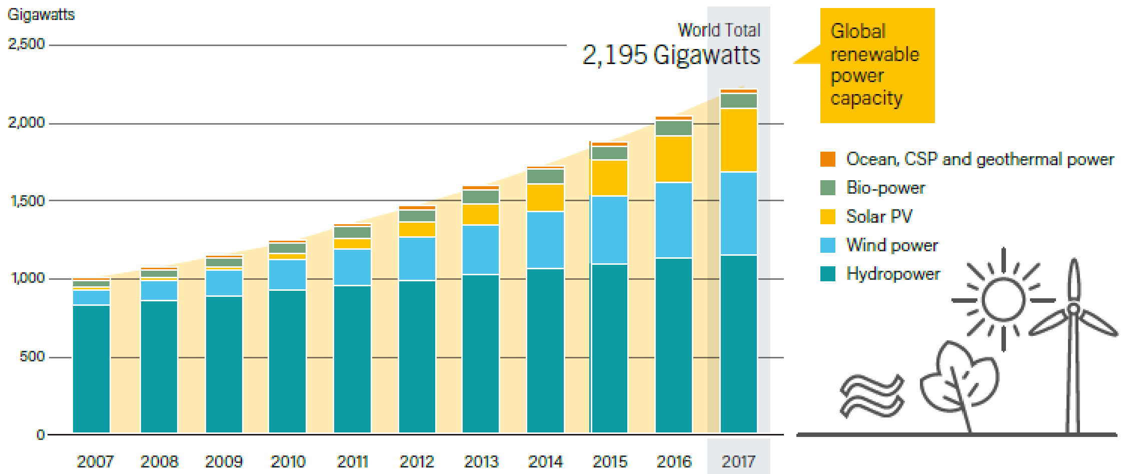

Figure 1.2 – World's renewable power capacity from 2007 to 2017 [7]

The European market has always been in the forefront concerning generating power through renewable energy sources. Figure 1.3 shows, in Europe, the annual installed capacity and renewable share. One can see that in 2000 the renewable share was less than 20% of new power installations and by 2007 it reached 50%. From 2011 forward, this share as always been higher than 70% with annual power installed between 20 and 35 GW. Since 2000, 60% of the installed capacity has been renewables, with the greater share being wind power with 33%. This is due to the fact that wind power production is an optimized and mature technology.

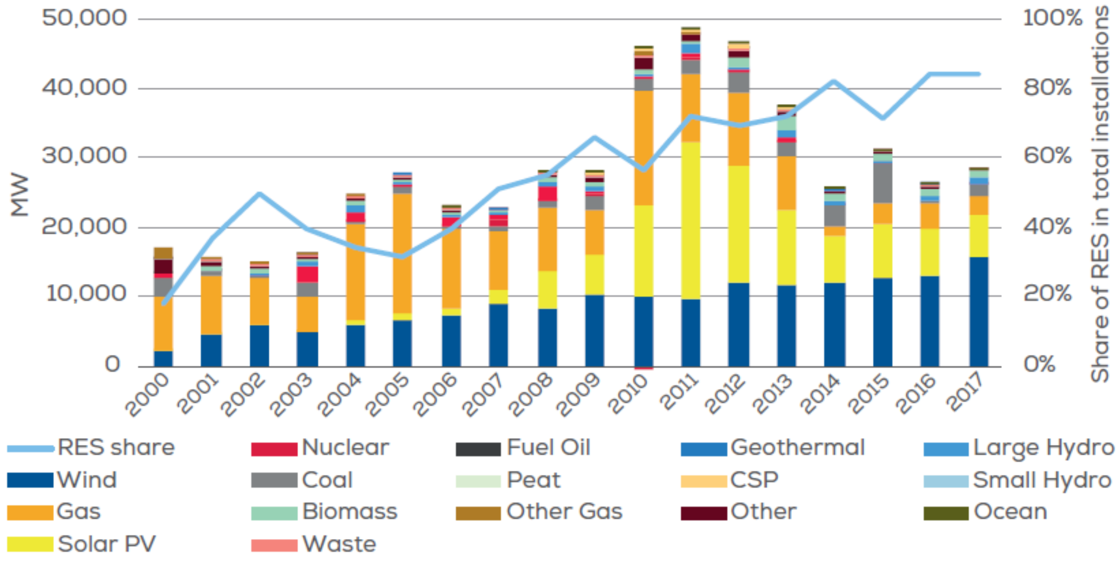

Figure 1.3 - Annual installed capacity and renewable share, in Europe [8]

One of the main disadvantages of wind power generation is related to the inconsistency in wind's speed and direction which makes the predictability of the power generated to be a difficult task, especially for more than a few hours. There are several solutions to attenuate this power uncertainty. One of them is the coordination between wind power plants and other generation facilities such as hydro plants or conventional thermal plants. Another solution is storing the surplus of wind power generated to then later compensate the eventual power discrepancy. Combining wind power plants with pump-hydro-storage plants (PHS) is the most common application of storing that energy, since PHS is a mature and well-developed technology.

In fact, the EU believes that the ability to store energy will be one of the primary answers to reduce the carbon dioxide emissions originated from the electricity power system. Energy storage gives the possibility of balancing the variation in the power generated from renewable sources, improving the flexibility, efficiency and the penetration of renewable energy sources in the electrical grid [9].

Since the beginning of the century, Germany demonstrated a high investment towards renewable energy. Figure 1.4 illustrates the share of installed wind power in different European regions and countries. One can observe that Germany has led the way in this regard. Many innovative projects have originated from Germany following this strong investment. The case study present in this thesis is such a case, a wind power plant combined with a PHS with a revolutionary design approach [10]. This project, intended to be fully connected to the grid by the end of 2018, aims to move Germany into reaching their targets of generating at least 65% of its energy through renewable energy sources by 2030 [11].

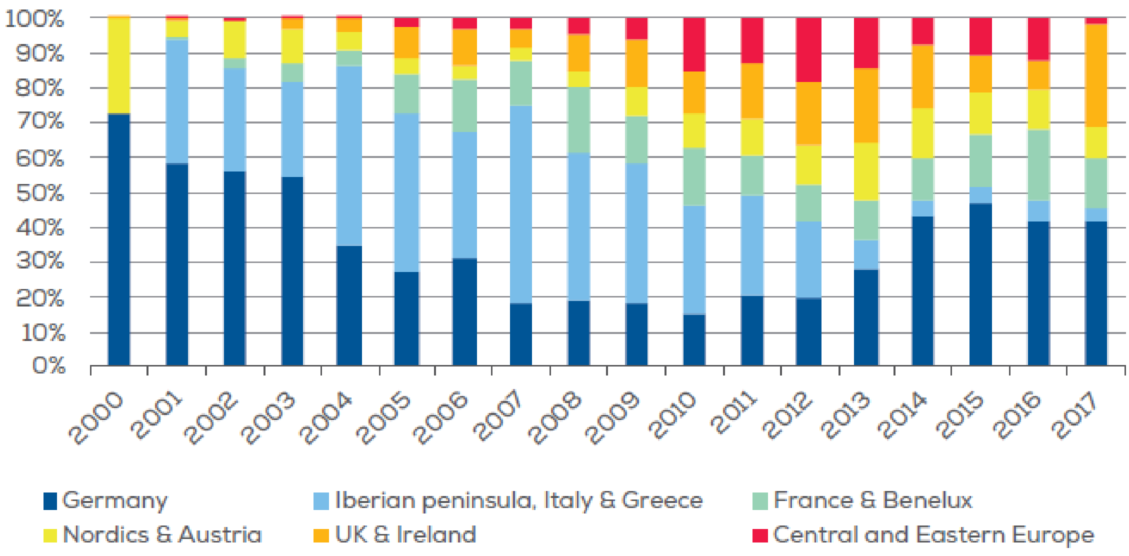

Figure 1.4 - Share of installed wind power capacity in different European regions [8]

1.2. Literature Review

Several studies regarding wind-hydro coordination have been performed, especially in the past decade. In the following section, a description of different works related to this topic is presented, including the major contributions to this master thesis.

Wind-hydro coordination optimization can be divided in either deterministic or stochastic studies. In the deterministic approach, optimization is conducted with well-known initial conditions and data, with no randomness involved. Wind forecasting is usually achieved through point forecasting where the expected wind value is obtained for a certain number of time intervals regarding a given time-horizon. For the stochastic studies, wind forecasting is usually elaborated in a probabilistic manner where wind value predictions have an uncertainty and associated error involved since the uncertainty and unpredictability of the variables is an inherent feature of a stochastic model.

Wind-hydro coordination studies can also be segmented into two different problems. The first attempts to optimize the installation's operation with the goal of maximizing the market profit. The second problem covers the possibility of a wind-hydro system to distribute a constant power to the grid with the goal of overcoming wind power forecast deviations. A more detailed look into each approach is provided next, along with previous literature that had a major contribution towards the study elaborated in this dissertation.

1.2.1. Maximizing Overall Profit

Regarding the optimization of the market operation, the studies between the coupling of wind power plants and pump storage plants can be divided in two parts:

- **Day-ahead optimization**: In this case, optimization for the energy bids to be made in the day-ahead market is done. Wind and price forecasts for the operational day are taken into consideration. The usual operation of a pump storage plant is for water to be pumped when prices are low and, when prices rise, use that stored energy to generate power and increase the profit of the installation. The graph in Figure 1.5 illustrates the described normal operation of a PHS plant, where, in hour i, P_{hi} is the power generated by the hydro unit, P_{pi} is the power used in the pumping operation, E_i is the energy stored in the upper reservoir of the plant and c_i is the spot market prices.

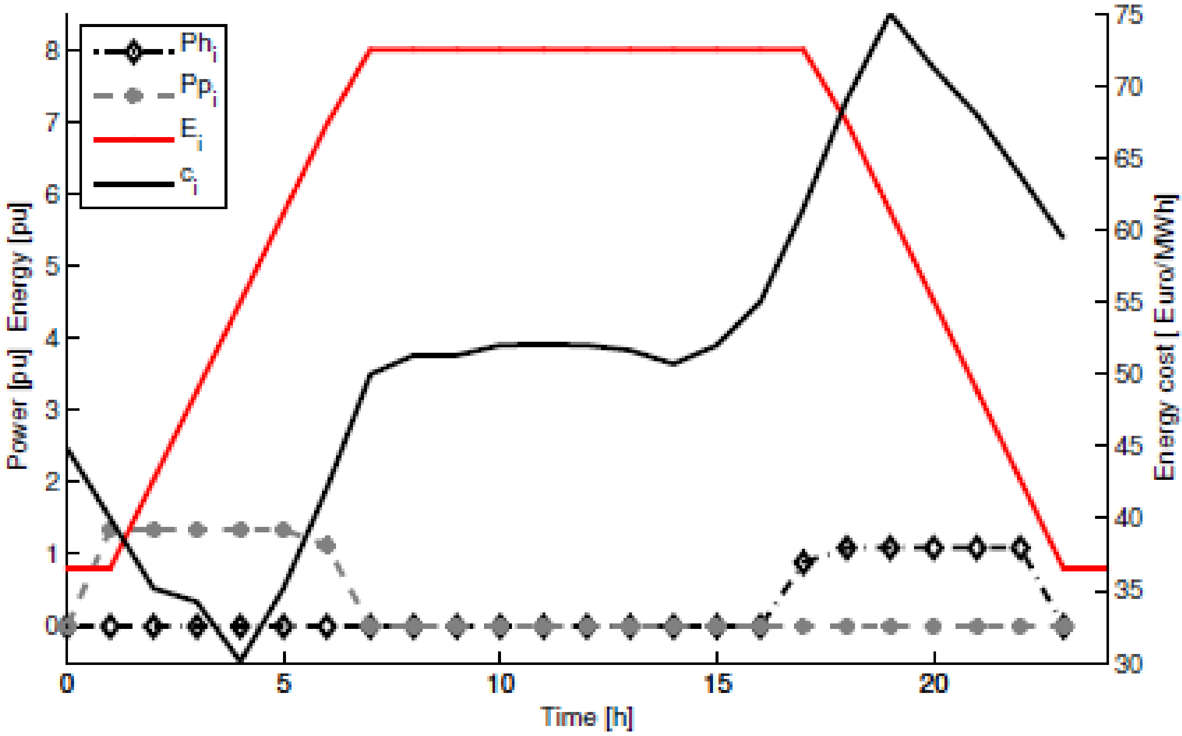

Figure 1.5 - Normal operation of PHS plant [12]

- **Operational strategy**: The operational strategy attempts to minimize the difference between the power bids obtained in the day-ahead optimization and the actual power generated. Is usually performed by storing energy when wind power is higher than what was initially predicted and generating power when wind power was smaller than what was initially forecasted.

The following studies comprise the background for this thesis work:

1. *Duque et al.* [12] proposes an optimized operation with the goal of reducing imbalance costs. Wind power prediction is achieved with an uncertainty forecast, which is taken into account in the optimization problem. The results concluded that the operation would be profitable for the wind farm and the PHS plant.
2. In *Castronuovo and Peças* [13], optimal operation and hydro storage sizing of a wind-hydro power plant in Portugal is presented. The storage was set at 20% of the nominal wind farm capacity and, for a value of 11 MW, the inclusion of the pump storage plant under optimal control traduced to an increased annually averaged profit of 12%.

3. In the work of *P. Cruz et al.* [14], a Mixed Integer Linear Programming (MILP) algorithm is proposed to optimize the day-ahead planning of an installation with hourly discretization. Two cases are analysed depending on the initial stored energy in the reservoir and it is concluded that a higher stored energy presents a higher profit.
4. A stochastic model is proposed by *Castronuovo and Peças* [15] where the daily operation planning is optimized using linear programming with hourly discretization. The model is based on Monte Carlo simulations to create wind scenarios composed by the wind power average value and the standard deviation.
5. In *Castronuovo et al.* [16] section 3.1, a day-ahead scheduling is conducted using a statistical wind forecasting solved through linear programming. In section 3.2, an operational strategy analysis is presented based on ratios between the day-ahead planning and the operational day real values. With those ratios, new points of operation can be obtained.
6. *Pousinho et al.* [17] is divided in two sections. The first focuses in short-term hydro scheduling where the optimal operation planning algorithm is proposed and the second the development of strategies for wind producers, due to wind power and electricity price uncertainties. Both algorithms implemented are solved with a linear programming approach.
7. *Bessa et al.* [18] starts by introducing a day-ahead optimization algorithm and later presents three possible strategies to be followed during the operational day. The first strategy attempts to follow the plan from the day-ahead optimization. The second tries to match the forecasted wind power consumed with the hydro and pump operations. The third focus in minimizing the penalties for power imbalances.

1.2.2. Constant Output Power

Due to the ability of hydro power plants to rapidly alter their operating point, they arise as a valid solution to improve the penetration of wind power in the grid, by maintaining the balance between generation and demand, especially when equipped with pumping systems. This pumping operation allows the storage of excess wind power, in the form of water, on the upper reservoirs of the power plant.

However, concerning the topic of wind-hydro coordination, the majority of the literature focus on the optimization of the market operation, maximizing the overall profit during an operational day. Not many studies are found researching the complete balancing of the generated wind power through the usage of PHS plants. This dissertation provides such a study and, regarding this topic, the major contributors are:

1. *Pedro Mendes et al.* [19], where a model is utilized to analyze the ability of coordinating two PHS plants with the installed wind power capacity in Portugal. The goal was to maintain constant, throughout the all year, the output power at a given target value and it was concluded that the feasibility of continuously reaching the target power, in the complete time frame, depends greatly on the installed capacity values, the storage capacity of the reservoirs, as well as the target value itself.

2. In *Papaefthymiou et al.* [20] it is discussed the operation of a Hybrid Power Station in the island of Ikaria, Greece. This station is composed by a wind farm, two small hydro power plants and a pumping power plant. An operation policy is proposed and a yearly simulation of the system is elaborated with the aim of extrapolating the benefits of such a station in an isolated grid scenario.

1.3. Research and Objectives

Wind power is a highly variable and unpredictable resource of energy. Wind power varies following wind speed variations that can occur very rapidly. The high volatility of wind power production makes its integration in an electrical power system a highly important topic of discussion. The conjugation of wind power with PHS plants improves the penetration of wind power in the electrical grid.

This dissertation aims to optimize the coordination between a wind farm and a pump storage power plant, in the context of the Portuguese power system. With this purpose in mind, this dissertation is divided in two major problems:

- Maximizing the overall profit of the park in a market operational day.
- Predicting the ability of the park providing a certain constant output power, for every day of the year.

In the first part, the day-ahead optimization algorithm is presented where the electrical energy bids to be placed for the following operation day, in the electrical market, are defined. Based on a real wind speed scenario and MIBEL energy prices, wind speed and price forecasting are calculated, for a real day, using an artificial neural network (ANN) approach. With the wind speed and price predictions, the optimization algorithm returns the daily power dispatch that maximizes the profit for that given day.

Following that power dispatch, the strategy to be conducted during the operation day is provided, where inherent deviations between the real wind speed and energy price values and the predictions made in the day-ahead planning, dictate that the original electrical energy bids cannot be completely achieved. The strategy takes into account the wind speed and energy prices deviations, in addition to power imbalance costs, and updates the original day-ahead planning bids with regards to these deviations.

In the second part, several simulations are performed, where an algorithm is used to analyse the ability of the park to output a given constant power during the 24 hours of an operation day. The simulations are conducted for different constant power values and in order to conclude the feasibility of providing a certain target power for each day of the year, they are run with different initial water volumes in the reservoirs and for a total of 500 wind speed scenarios. Each wind speed scenario is predicted based on a real wind speed time series, for a random day of a year, using the same ANN approach.

The main objectives behind the elaboration of this research are:

- Study the integration and operation of a similar type of wind-hydro system in the portuguese power system and conclude about the market’s profitability for the two described problems.

- Conduct an investigation regarding the combination of the day-ahead optimization plan with the operational day strategy.
- Conclude the feasibility of a similar installation delivering a constant output power to the grid through the coordination between wind turbines and a PHS plant, overcoming wind power deviations that occur in the forecasting process.

1.4. Document Structure

This dissertation is divided in 5 chapters.

Chapter 1 provides the research objective and motivations, introducing the essential context and background behind the research proposed. It contains the scope and major contributions to this thesis with a literature review. Is accompanied by the structure of the dissertation.

Chapter 2 includes the theoretical background necessary for the elaboration of this study, delving into the major characteristics of wind and hydropower, as well as, the model used for both technologies. It also gives a review for the MIBEL market operation and insight into the forecasting algorithms utilized.

Chapter 3 is divided in three sections. The first introduces the case study characteristics and schematic, along with the assumptions considered. The second presents the wind/hydro optimization algorithm for both the day-ahead and operational strategy. The third part focus on the algorithm to study the probability of the installation to provide a constant output power to the grid, in all 24 hours of any given day of the year.

In Chapter 4 the results are provided, including a simulation breakdown for the implementation of both algorithms described in chapter 3, along with the overall results and respective analysis.

Chapter 5 includes the major conclusions taken from the elaboration of this dissertation. An overview of the possible future work regarding this topic is also described.

2. Theoretical Background

2.1. Wind Power

Wind power has been present in human civilizations for a long time. Earlier on, farmers would use windmills to grind and pump water and sailors would navigate the seas using the wind breeze. Since the development of electric power, new ways of producing energy have been researched and talked about and wind power found new applications on this field. Throughout the years, wind power technology has continued to grow, especially in the last decade with new talks regarding global warming and cleaner sources of energy.

In this chapter, an overview of the current situation wind power has globally and in Portugal is provided, as well as, the characteristics and model used throughout this study.

2.1.1. General Situation

Global View

Since the beginning of this century, countries all over the world are investing on the research and development of new sources of producing energy, mainly through renewable energy sources. Among the different alternatives, wind power is the one with the highest growth rate, with a continued investment in new installations. At the present moment, in large markets like Germany or the United Kingdom, these new installations are driven by policy and regulatory changes, but with the drop of prices for wind power, both onshore and offshore, this technology is quickly becoming mature and competitive throughout the globe. In recent years, the installed capacity in smaller markets has increased, especially in the year 2017. In Figure 2.1, the wind power global capacity plus annual additions are presented from 2007 to 2017. One can observe the continued growth in this ten-year span, especially in the last four years, where the annual additional power installed was always superior to 50 GW, reaching the peak in 2015 with 64 GW.

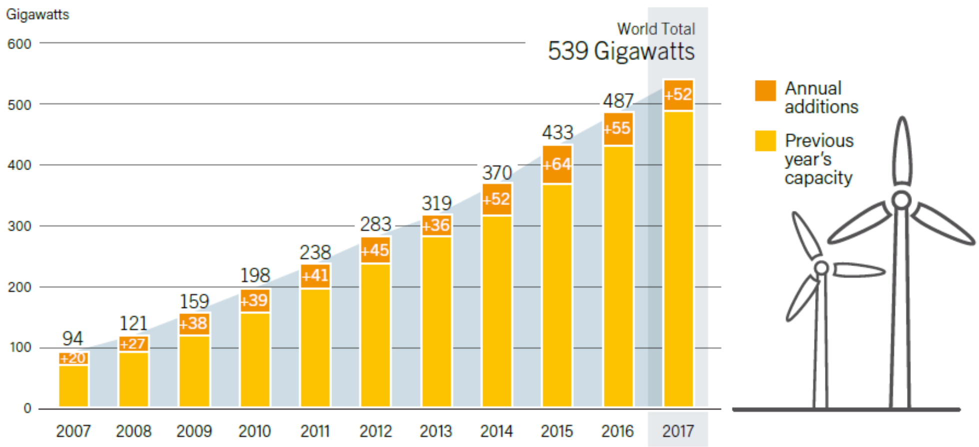

Figure 2.1 - Wind power global capacity and annual additions from 2007 to 2017 [7]

In 2017, Asia remained for the nine-consecutive year, the leading market in new installed capacity. China was the country with the highest annual installed capacity with an extra 19.7 GW added to the previous year capacity of 168.7 GW. The United States and Germany were the second and third leading countries in the annual capacity installed with 7.0 GW and 6.1 GW, respectively, less than half of China's value. By the end of 2017, China reached a total installed capacity of 188.4 GW, naturally retaining the number one spot for total capacity worldwide. Figure 2.2 illustrates, in the top 10 countries, the wind power and annual additions installed, for the year 2017.

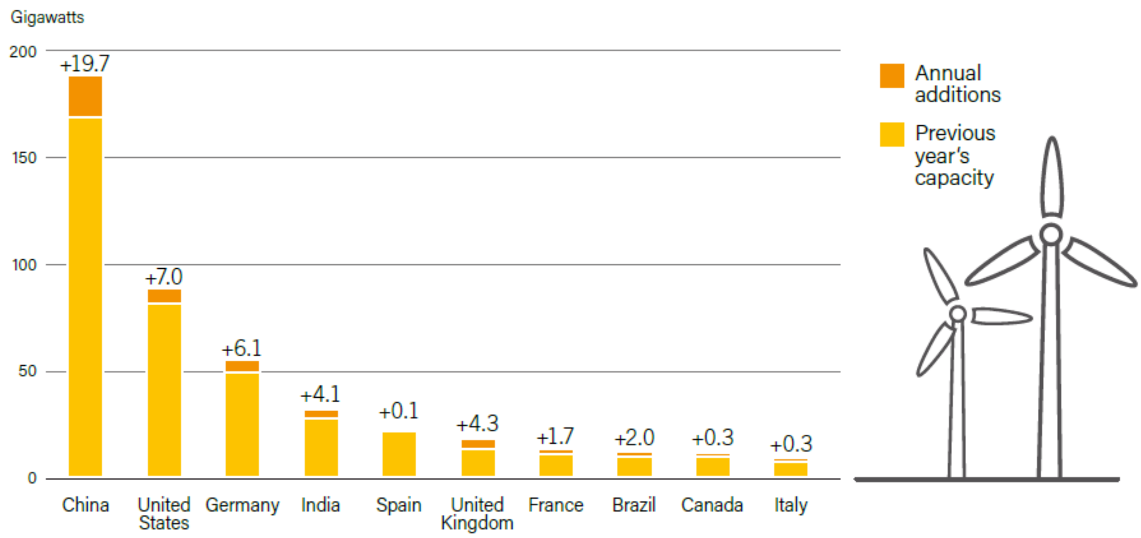

Figure 2.2 - Top 10 countries with the highest wind power capacity and annual additions installed, in 2017 [7]

Offshore wind power is an evolving technology with serious benefits when compared to onshore solutions. In the sea, wind speed is higher and more constant, with less influence from friction and topography. However, a higher investment cost is needed due to the engineering challenges associated with this kind of projects. Fixation of the wind turbines and the transmission of the generated power to the mainland grid are amongst them. Despite onshore wind power remaining the overwhelming majority in the global installed capacity with more than 96%, a total of 4.3 GW of offshore wind power was installed in 2017, increasing the total offshore capacity by 30%. In Figure 2.3 the offshore wind power global capacity by region, in the last decade, is presented.

Intermittency and irregular wind speed are the major disadvantages regarding wind power generation. Availability of regular and intense wind is a key feature when considering a given area for a wind park project. However, despite this major constraint, some countries have reached a high wind power penetration in the power system, making this energy source a key factor in the power produced for those given countries. Figure 2.4 gives the share of electricity demand met by wind power, for countries with over 10%, in the year 2016.

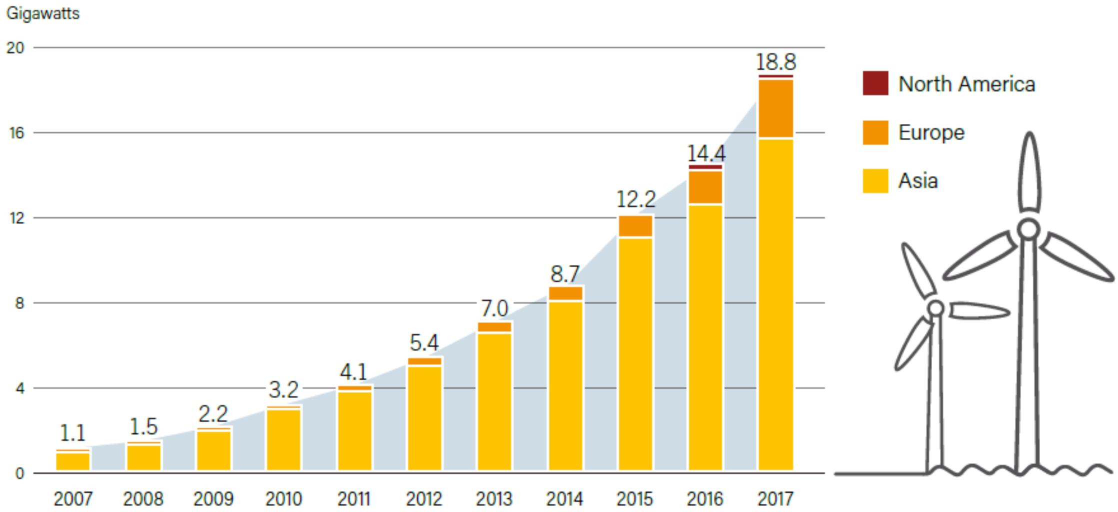

Figure 2.3 - Offshore wind power capacity evolution from 2007 to 2017 [7]

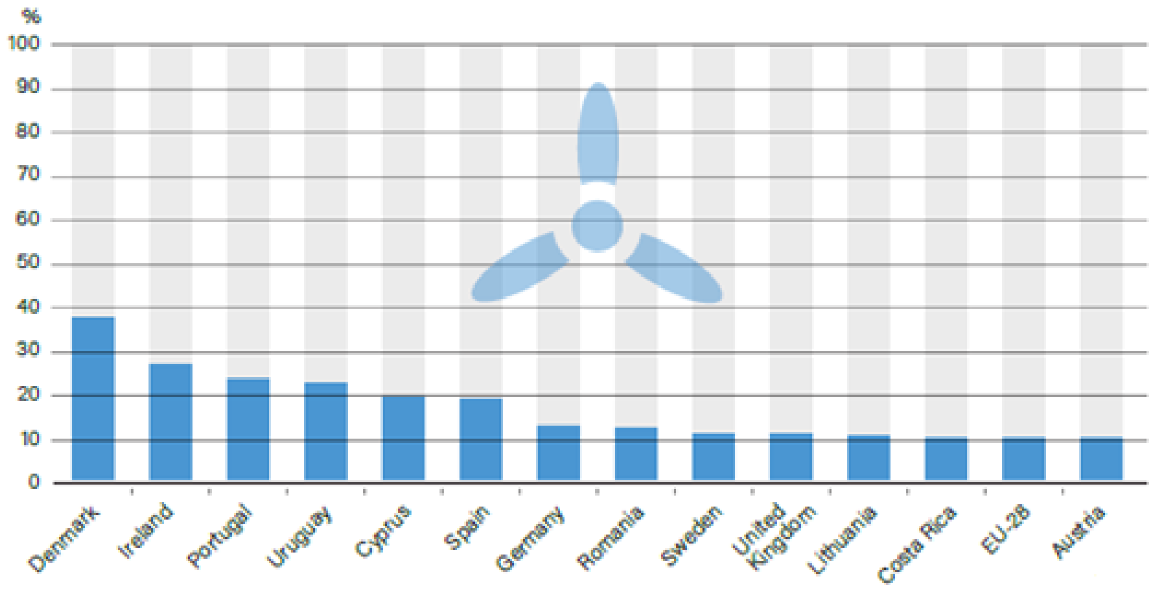

Figure 2.4 - Share of electricity demand met by wind power, per country, in 2016 [21]

In Portugal

Wind power was first introduced in Portugal in the mid-eighties and, since that moment, the installed capacity has grown at a fast rate. The main reason behind the investment in the technology was the growing concerns with environmental impacts and the awareness of the advantages behind wind power production. Most of the wind turbines present in the Portuguese territory were installed between 2005 and 2012. Table 2.1 shows the evolution the technology had from 2009 to March 2018. The data for 2018 are provisory, therefore table's values for this year correspond to an evolution between April 2017 and March 2018. One can see a continued growth in the wind turbines and wind parks installed until 2016, where the peak power capacity was reached with 5313 MW. From this point on, no more investment was made regarding the construction of new wind turbines and parks, which indicates that the Portuguese territory is reaching its full potential in terms of possible locations suitable for viable wind park projects. Since 2013, wind power accounted for a total of around 12 TWh per year. In terms of the percentage of wind power in the total renewable production, between 2009 and 2018, the values range from 31.9% to 50.5%. These variations are mainly caused by the different hydro power generated each year, which greatly affects the total renewable production.

Table 2.1 - Evolution of wind power from 2009 to March 2018 [22]

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Power Production (Gwh)	7577	9182	9162	10260	12015	12111	11608	12474	12253	12990
% in Total Renewable Power	39.8	31.9	37.1	50.2	39.3	37.3	45.5	37.3	50.1	50.5
Power Installed (MW)	3564	3914	4378	4531	4731	4953	5034	5313	5313	5313
Number of Parks	215	225	236	240	244	245	255	257	257	257
Number of Wind Turbines	1966	2130	2354	2426	2476	2565	2604	2743	2743	2743

All the investment made towards the research and implementation of this technology in portuguese soil made Portugal one of the countries with the highest wind power penetration in the electrical grid worldwide. This is observable in Figure 2.4 where Portugal appears between Uruguay and Ireland has the third country with the highest share of power demand met by wind power with a value of about 25%. Leading the way is Denmark with an almost 40% share.

2.1.2. The Wind Resource

The sun’s radiation is absorbed differently by the earth’s surface with areas around the equator consistently having a higher temperature than polar zones. Air in higher temperature areas begins to rise due to the fact that it is less dense and creates low atmospheric pressure, while air in low temperature areas sink creating higher atmospheric pressure. This phenomenon is called convection. Wind is the flow of air from a high-pressure area to a low-pressure area due to convection currents.

Geographical Characteristics

During preliminary project stages of a wind farm, before the construction of the installation in a certain area, studies must be conducted in order to evaluate the wind potential in that area. These studies include several recordings of wind speed data, obtained in previous years, for that designated area. Nevertheless, an initial estimate can be made resorting to maps that translate the annual mean wind speed and the power density (W/m^2) in a respective area. For the European continent, one such map is presented in Figure 2.5 and Figure 2.6, for the wind speed and power density respectively. These figures were adapted from the Global Wind Atlas maps, an organization that maps the wind resource throughout the whole planet. One can observe that the highest wind potentials are situated in the north of the United Kingdom, in Norway and throughout the northern and western coast lines of the continent.

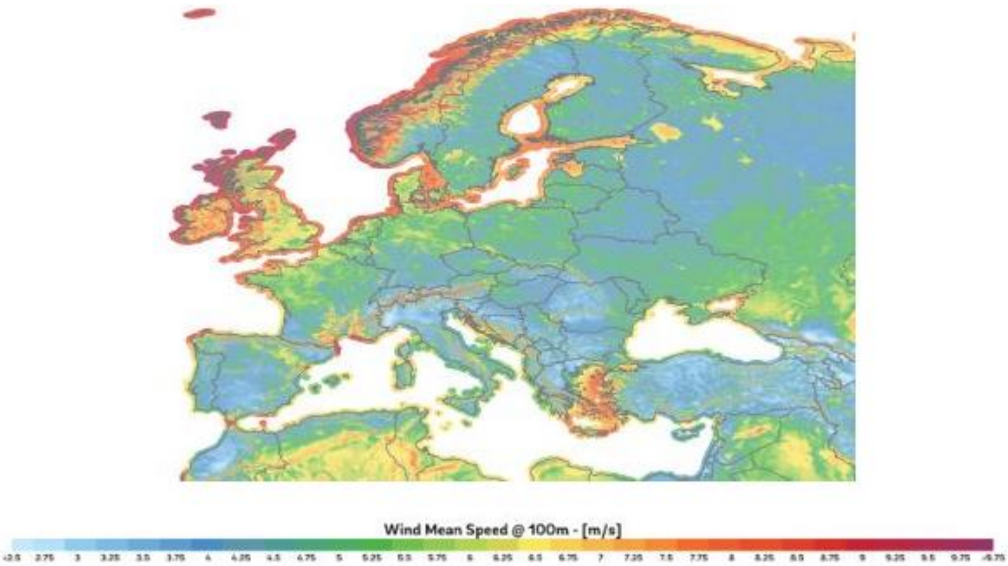

Figure 2.5 – Europe’s annual wind mean speed in 2017 (adapted from [23])

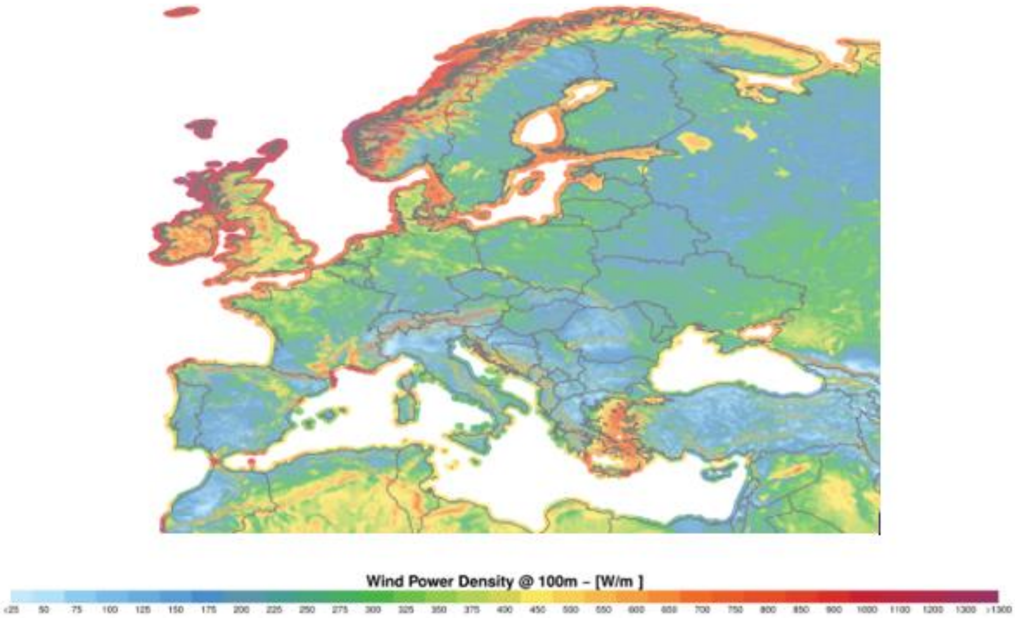

Figure 2.6 – Europe’s annual wind power density in 2017 (adapted from [23])

Portugal has a wind potential between low and intermediate values, with the biggest potentials in offshore areas and in some regions in the north of the country. A more detailed view of the annual mean speed and power density in the portuguese territory can be observed in Figure 2.7 and Figure 2.8, respectively [24].

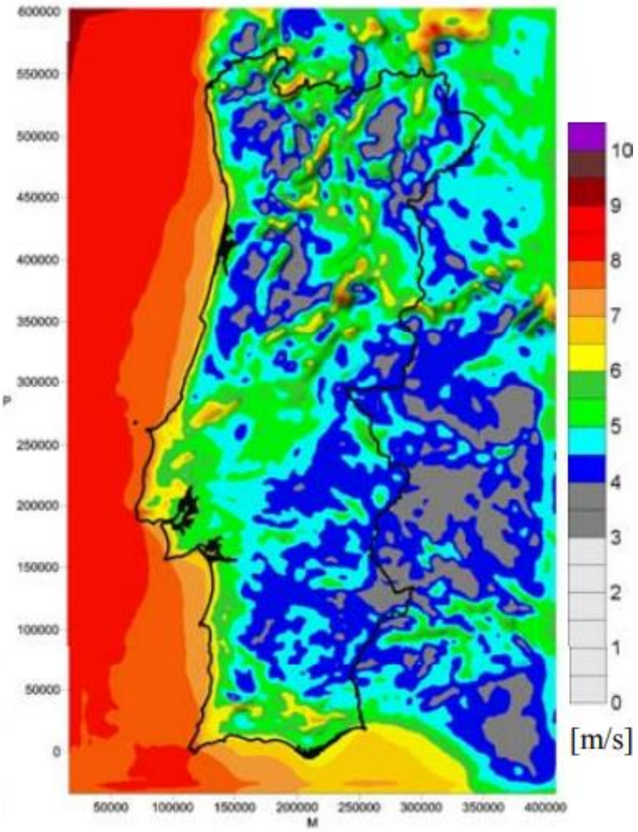

Figure 2.7 - Portugal's annual wind speed

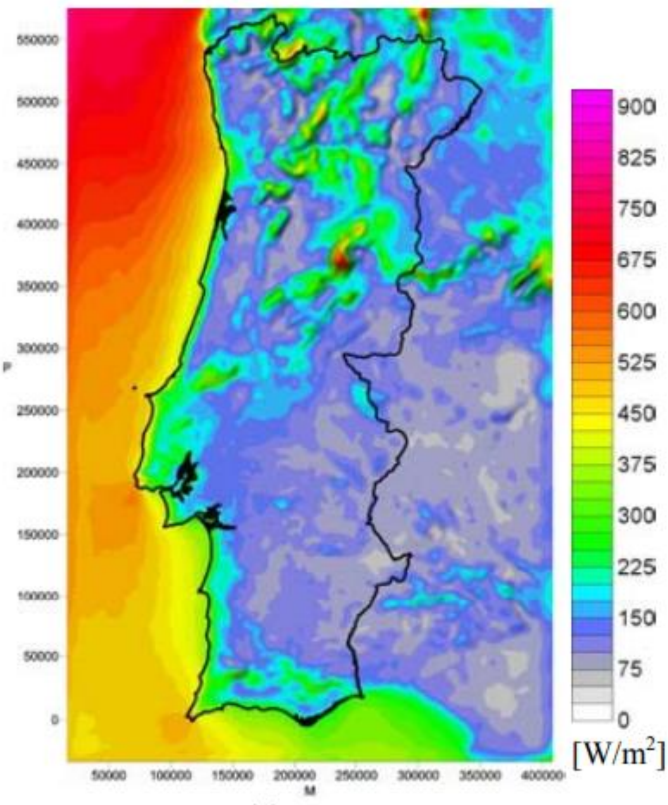

Figure 2.8 - Portugal's annual wind power density

Temporal Characteristics

Wind speed can fluctuate its intensity and direction in both short and long term time periods. Short terms variations encompass variations that may occur in few seconds or minutes and are frequently caused by turbulence. Turbulence is associated with the fluid’s motion which makes it a variable difficult to describe. Most methods to describe turbulence resort to statistical techniques. Daily and seasonal wind speed changes are considered long term variations and normally can follow a certain pattern.

Since a wind turbine possess a certain inertia to its system, one can ignore the turbulence effect and consider only wind speed hourly averages in studies about energy production.

Wind Prediction

Wind forecasting is crucial for wind parks and network operators since an accurate wind prediction can ensure a higher margin of profit while trading in electricity markets. The growth of wind power technology worldwide goes hand in hand with an improvement in wind power forecasting methods, thus major research has been elaborated about this topic. Wind forecasting is essentially divided into two major categories: a physical approach and a statistical approach.

Physical methods, often called Numerical Weather Prediction (NWP) methods, make use of mathematical models to predict atmospheric conditions based on the current weather state. The mathematical models include equations that describe the fluid’s motion and several meteorological variables can be predicted such as wind’s speed and direction, temperature and pressure [25].

Statistical methods rely heavily on historical wind speed data, although it can also include components from NWP models. The possibility to make predictions into future values of a certain variable, only considering the previous records of this given variable is the biggest advantage of these types of methods when comparing to the physical approach. The process can normally be divided into a training phase and a prediction phase.

During the training phase, which will normally be an iterative process, the model interprets the historical data, performing adjustments in the variables of the model with the aim of minimizing the error between the historical data and the model’s output data. With the already trained model, the process advances to the prediction phase where a forecast into the variable’s future values is conducted.

There are a number of different statistical methods that can be selected, such as the Autoregressive Moving Average (ARMA) or the Simple Moving Average (SMA) technique, nevertheless, in this dissertation, an artificial neural network (ANN) approach is used.

Artificial neural networks are systems that simulate the human brain, replicating the way humans learn and react to problems. An ANN consist of several artificial nodes, called neurons, that are usually organized in three different layers: the input layer, the hidden layer and the output layer. The neuros are intertwined between each other and each connection, which is called an edge, has a certain weight associated with it. These weights will increase or decrease with each iteration and are adjusted based on a learning process. The structure of an ANN is represented in Figure 2.9.

The majority of ANN’s can essentiality be divided in two types: feedforward networks and recursive networks. In feedforward networks information flows only on one direction, from the input layer to the output layer. As for recursive networks, information can flow in more than one direction and these types of networks tend to be more complex.

The training process of an ANN for wind forecasting is achieved through finding certain seasonalities in the historical data that is provided to the network. This seasonalities can be yearly, monthly, weekly or daily trends and connections that are found on the data. The data is usually divided into three different sets: the training set which establishes the weights between the nodes of the network, the validation set to accurately tune the weights found previously and a test set which perform a final evaluation of the output generated. An ANN can be viewed as a “black box” system, dependent on its inputs and outputs, without any knowledge of the internal work that is actually conducted.

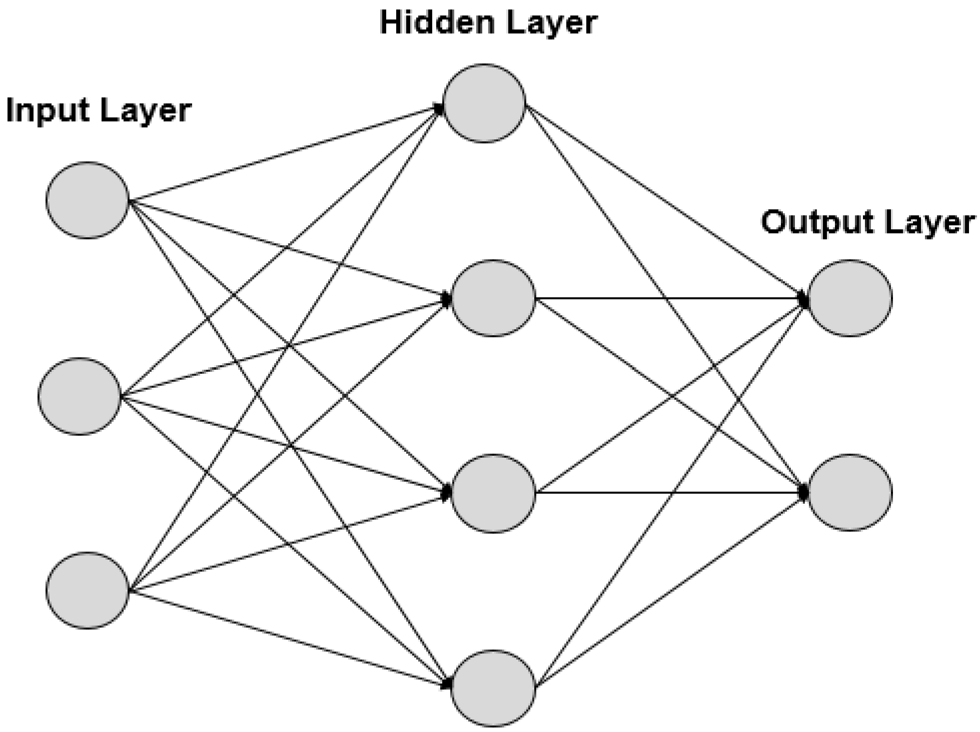

Figure 2.9 - Artificial neural network structure

In this dissertation, a closed-loop feedforward ANN is used to elaborate a hourly wind speed forecasting for a given day of the year, based on a historical yearly wind speed time series. This is implemented using the *Neural Networks Toolbox* present in the *MATLAB®* software.

The network is created using the *narnet* function which generates a nonlinear autoregressive neural network (NAR) [26]. A NAR network is able to predict the future values of a time series from that series past values. Mathematically, this can be translated by (2.1).

$$y(t) = f(y(t-1)\ldots y(t-n)) \tag{2.1}$$

The network is created with the default number of neurons in the hidden layer, 10. The data is organized in an input series and a target series and using the *preparets* function is prepared for training the network. Following this process, the network is ready to be trained using the *train* function and an one step ahead prediction is achieved. However, a 24 step ahead prediction needs to be made in order to forecast the day's 24 hours wind speed values. For that reason, the NAR network created needs to be transformed into a close loop network with the function *closeloop* and the final states of the open-loop network become the initial states of the close-loop network.

2.1.3. Wind Turbine Model

Wind speed is the major factor that influences the power output originated from a wind turbine. With higher wind speeds the turbine is able to operate at the nominal power or very close to this value, maximizing the power output. Nevertheless, a wind turbine does not generate power for every wind speed. A wind turbine power curve describes, for a given wind turbine, what is the power generated for a certain wind speed. In Figure 2.10, a power curve is showed for a V90-3.0 MW wind turbine developed by Vestas.

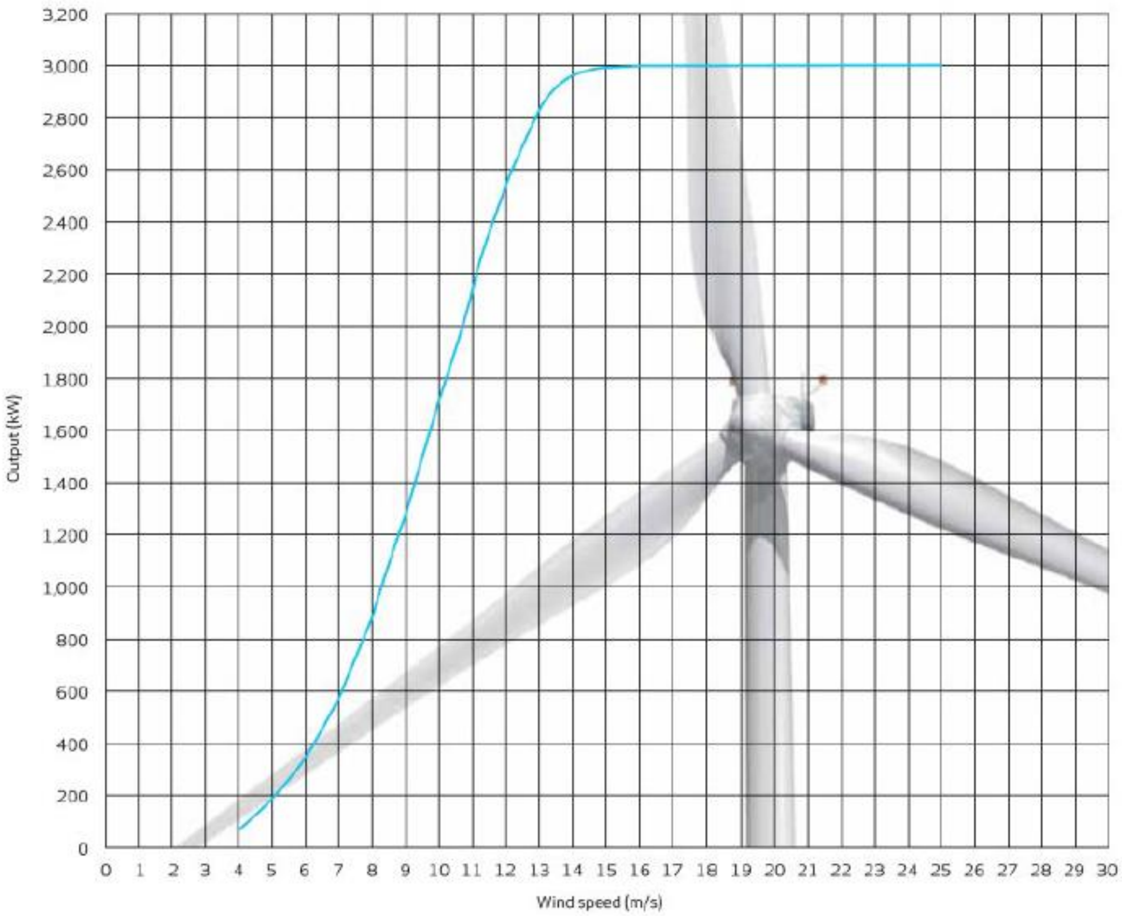

Figure 2.10 – Example of wind turbine power curve for Vestas V90-3.0 MW [27]

One can identify 4 regions in a wind turbine power curve:

1. When the windspeed is smaller than the so-called cut-in speed it is not viable to generate power given the low efficiency of the process, thus the output power is zero.
2. The second region is set between the cut-in speed and the nominal wind speed. This region is where most of the operation occurs
3. The third region is set between the nominal wind speed and the cut-out speed. In this region the power generated is constant and equal to the nominal power.
4. For values above the cut-out speed the turbine is stopped to prevent any physical damage to the equipment, hence the output power is zero.

The Vestas V126-3.45 is the model that best mirrored the characteristics of the case-study's wind turbines. In order to attain the power curve equation for this model, the power curve provided in a wind turbine datasheet [28] is approximated in the region between the cut-in and rated speed, using the *Curve Fitting Toolbox* of the *MATLAB*® software. The resulting power curve graph can be viewed in Figure 2.11 and is described by equation (2.2).

$$
P_{Wind}(u) = \begin{cases} 0, & \mathrm{u} < 3 \\ a \times \exp\left[-\left(\dfrac{u-b}{c} \right)^2 \right], & 3 \le u < 10.2 \\ 3.45, & 10.2 \le u < 22.5 \\ 0, & \mathrm{u} > 22.5 \end{cases} \quad [MW] \tag{2.2}
$$

$$
\begin{aligned} with \quad & a = 3.569 \\ & b = 11 \\ & c = 4.137 \end{aligned}
$$

Where: P_{wind} is the output power of the wind turbine; u is the wind speed in m/s;

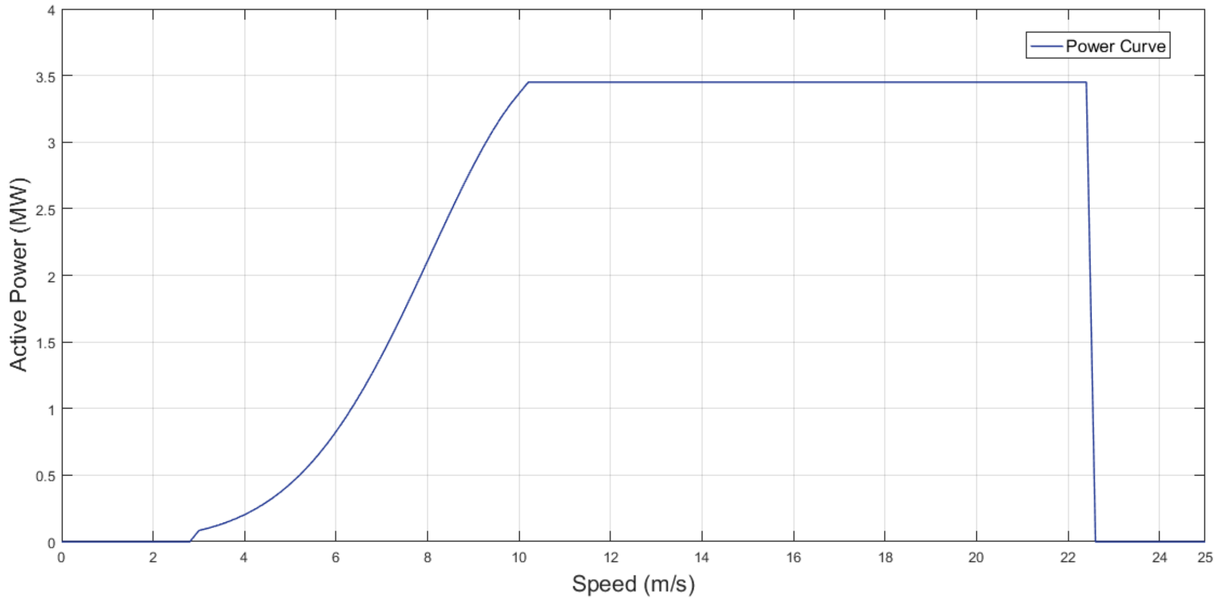

Figure 2.11 – Power curve for Vestas V126-3.45

With equation (2.2) it is now possible to obtain the wind power generated by each of the park's turbines, for any given wind speed scenario.

2.2. Hydropower

Since ancient periods of history, hydropower has been used in watermills for a vast number of applications, from irrigation to the operation of mechanical systems. In the late 19th century, the first hydropower projects were implemented with the intention of producing electric power. From that point on, this technology became a vital form of energy production and has grown into a completely mature and fully developed source of energy implemented everywhere around the world.

In this chapter, an overview of the present situation the hydropower technology has globally and in Portugal is provided. Due to the nature of this study, a more in depth look into the evolution and nature of PHS is presented, as well as, the model used while developing this study.

2.2.1. General Situation

Global View

Like it was mentioned, at the end of the 19th century, hydropower started to be adopted as a viable form for generating electric power. It was the first renewable source of energy implemented in societies and since that time, it has evolved into a totally developed source of energy. Hydropower plants also have the ability to go from zero power to maximum output power in a small period of time, making these power plants an essential back-up in electrical grids.

Given the long period of time since the introduction of hydropower and the important characteristics associated with this technology, it is the most used renewable energy source worldwide, by a large margin. Figure 2.12 highlights the global power capacity for renewables in the last ten years. Although one can observe that different types of renewables have a much higher growth rate in the same period, like wind power or solar PV, hydropower still accounts for around 50% of the total renewable power capacity. In 2017, the total hydropower capacity is estimated to be around 1114 GW, with another 1081 GW provided by all the other renewable sources, accounting to a total of 2195 GW.

Despite the power capacity growth rate being inferior to other renewable sources, the installed power capacity continues to get higher each year. In 2017, an estimated 19 GW were added to the overall global capacity. China remained the leader for new hydropower commissioned, being responsible for approximately 40% of new installations with 7.3 GW. At the end of the year, China's total capacity was 312.7 GW, generating 1190 TWh during those twelve months. Figure 2.13 shows the top 10 countries with the highest power commissioned, in 2017. Although China was the perennial leader, hydropower development across the Asian market was also strong in other regions, with countries like India and Vietnam completing new plant projects. Brazil came behind China as the second country with the highest commissioned power, continuing to explore the great hydropower possibility present in the territory, reaching a total of 3.4 GW added, passing the 100 GW mark for the total capacity.

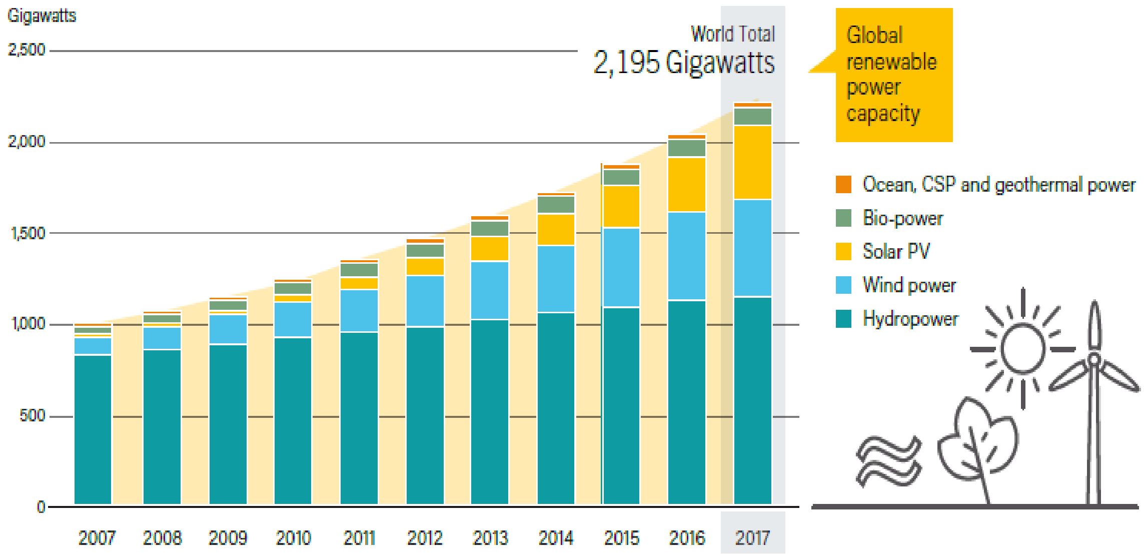

Figure 2.12 – World's renewable power capacity, from 2007 to 2017 [7]

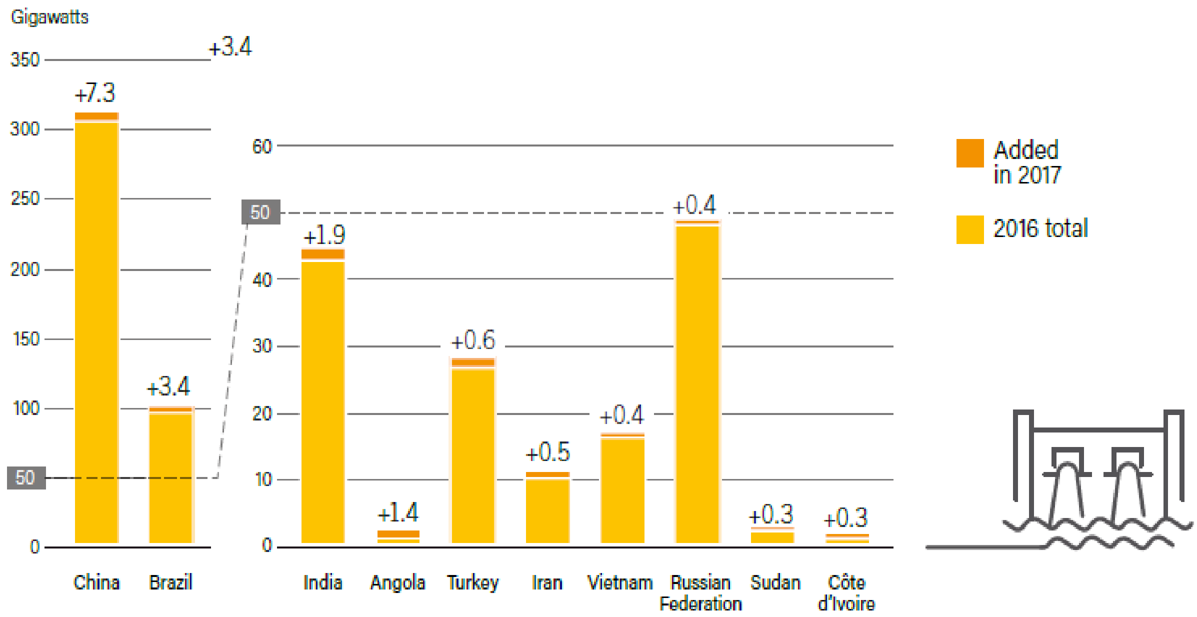

Figure 2.13 – Top 10 countries in the world with the highest installed capacity, in 2017 [7]

Figure 2.14 shows the global capacity share for hydropower in the top 10 leading countries and the rest of the world. One can see that China is, as expected, far ahead all the other countries, with a total share of 28%. With the same trend as the annual added capacity, Brazil comes behind China in the second place, totalling a share of 9%. Despite the recent expansion being relatively modest, the United States and Canada are still the third and fourth country with the highest share, accounting for 7%. Russia, India, Norway, Turkey, Japan and France all combine for a 17% share and all the remaining countries all responsible for the last 31%.

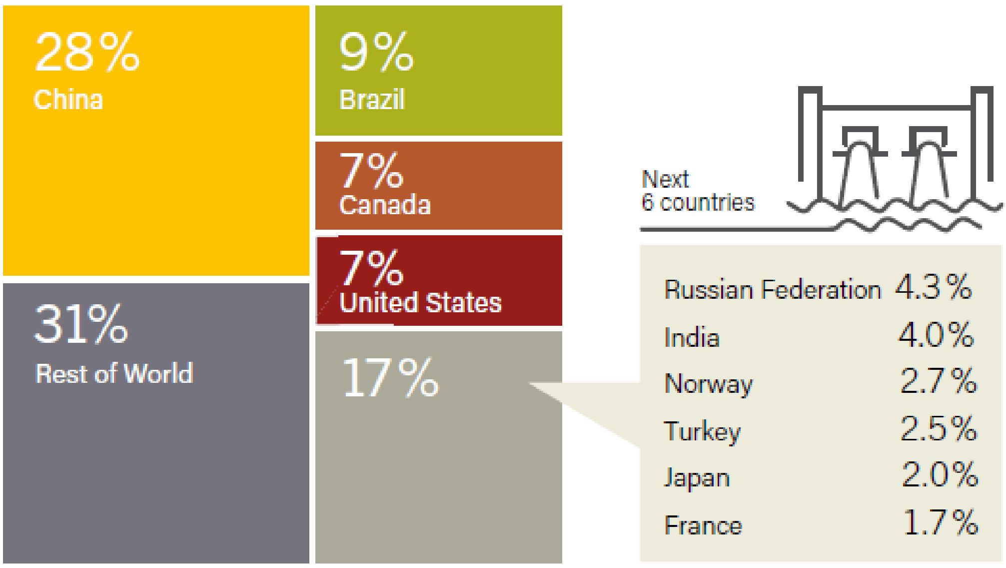

Figure 2.14 – Top 10 leading countries worldwide with the highest share in the global capacity, in 2017 [7]

In the last chapter, discussion regarding wind power concluded that the technology is mainly present in the so-called developed countries with, of course, the exception of China and India. Concerning hydropower, that is not the case. Hydropower is present in developing countries, both in terms of the annual added capacity and the total installed power. It is a sign of the importance this technology has in making a better and more robust power system, through the special characteristics it possesses.

In Portugal

Hydropower was first introduced on portuguese soil in the late 19th century with the construction of small hydro plants that would have just a few hundreds kW of power. Nevertheless, it was in the mid-20th century that the country underwent a big expansion, building hydropower plants of bigger proportions with storage capabilities. The growth continued through the seventies and eighties. It was during this thirty years' time span that the bulk of hydropower plants were constructed in Portugal.

In more recent years, to combat the dependency of fossil fuels and reduce greenhouse gases emissions, Portugal has been investing in renewable energy sources. New projects were developed for new hydro facilities and to upgrade the older power plants, increasing their capacity and infrastructure. Table 2.2 illustrates the installed power capacity and the power produced via hydropower plants, between 2009 and March 2018. The data for 2018 are provisory, therefore the table's values for this year correspond to an evolution between April 2017 and March 2018. Regarding the power capacity, one can observe an incremental growth, especially in the years 2011, 2015 and 2016, which culminated in a total power capacity of 7109 MW in 2018, more 2226 MW when comparing to the 4883 MW in 2009. One can also observe the variation in the power produced in each year with values between 6660 MW to 16609 MW. The main reason for this big discrepancy each year is the fact that the power generated in hydro plants depends mostly on the water available in the rivers. Therefore, in years with a high level of precipitation there is, naturally, a higher power output in comparison to a dry year. This last point is also clear when analysing the percentage of hydro power in the total renewable generation with values as low as 31.3% and as high as 57.5%.

Table 2.2 - Installed power capacity and power produced via hydropower plants, from 2009 to March 2018 [22]

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Power Production (GWh)	9009	16547	12114	6660	14868	16412	9800	16909	7492	8405
% in Total Renewable Power	47.4	57.5	49.0	32.3	48.6	50.6	38.4	50.6	31.3	32.7
Power Installed (MW)	4883	4896	5330	5537	5533	5570	6053	6838	7099	7109

2.2.2. Pump-Hydro-Storage Plants

The ability to store natural inflows has been an essential feature of hydroelectric systems, exploited for more than a century at this point. Nevertheless, reservoirs can also be utilized to store water inflows originated during low demand periods, giving the opportunity to use the stored energy during high demand moments. At the beginning of the 21^{st} century, almost every hydropower plant is equipped with pumping mechanics that provided the chance to store energy in an upper reservoir.

PHS is still the only technique that allow for large energy storage which is widely utilized in today's power systems. In PHS plants, water is pumped from a lower reservoir to an upper reservoir during off-peak energy periods. During peak demand the water is discharged, and a hydraulic turbine generates power. The main concept is pumping water from a low-level reservoir to an upper-level reservoir and thus storing energy in the form of hydraulic potential energy. As soon as the water goes through the turbine in the generating process, it returns to the lower reservoir. The efficiency of this process is around 80% and one of the biggest advantages regarding this technology is the long lifetime of these power plants. The main disadvantages are related to the scarcity of places suitable for these kinds of facilities and sometimes the environmental impact that can originated from the flooded region surrounding the plant.

A PHS usually is comprised by an upper reservoir, water tubes, a hydraulic pump/turbine, a motor/generator and a lower reservoir. This is illustrated schematically in Figure 2.15.

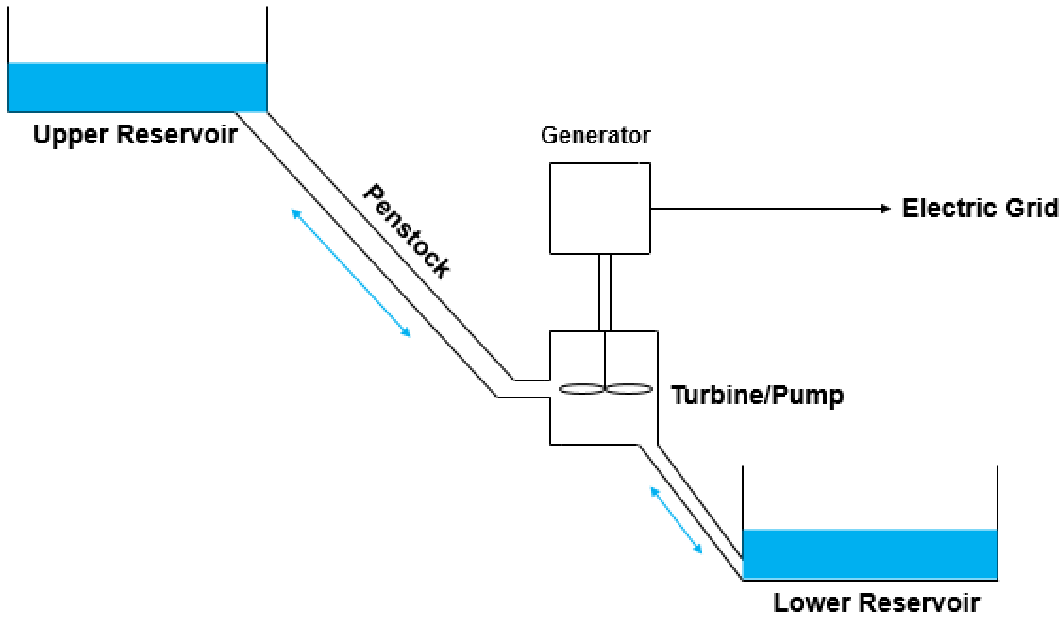

Figure 2.15 - Schematic structure of typical pump-hydro-storage power plant

Pumped storage hydropower is the dominant source of large scale storage systems, accounting for around 96% of the planet's storage capacity. In 2017 alone, pumped storage capacity rose by 3 GW accounting for a total of an estimated 153 GW installed worldwide [7]. New capacity was mainly installed in China, Portugal and Switzerland. China led the way with a total of 1.8 GW, by the end of 2017, with plans to continue expanding the capacity in the coming years. In Portugal, Frades II and Foz Tua both entered service, with an added power of 780 MW and 263 MW, respectively. These two pumped storage plants proved to be key for Portugal to stabilize electricity prices and secure electricity supply in 2017, a year of severe drought in the country.

2.2.3. Hydropower Model

Energy production through a hydropower plant is dependent on the conversion of different types of energy. The volume of water stored in the upper reservoir has a certain potential energy, E_p, associated dependent on its mass, m, on the height, H, which in this case is the fall head of the power plant, and on the acceleration due to the gravitational force, g, according to equation (2.3).

$$E_p = mgH \tag{2.3}$$

The potential energy given by equation can naturally be manipulated to obtain the available power stored in the reservoir. Dividing both members of the equation by a period of time results in equation (2.4), where energy as changed to power, P, and the mass to the rate of fluid flow, $\dot{m}$.

$$P = \dot{m}gH \tag{2.4}$$

As the water falls down the waterways from the upper reservoir, the potential energy is converted is kinetic energy. When eventually this water flow hits the hydraulic turbine blades, the turbine rotor will spin and coupled with the generator, electric power will be produced. The amount of power can be regulated based on the intake valve that affects the water flow.

The rate of fluid flow can also be expressed in relation to the product between the water volume per second, the so-called water flow, Q, and the water density, ρ, as it is shown by equation (2.5).

$$P = \rho \times Q \times g \times H \tag{2.5}$$

As in any hydraulic system, there are losses during the operation, such as frictional losses and viscous drag, plus the turbine does not have an efficiency of 100%. When mechanical power originated by the turbine rotor rotational movement is converted in electric power by the generator, this process is also not 100% efficient, existing losses inherent to the generator and the rotor movement. All these losses present in the overall generation process are represented by η_{gen}. One can now reach equation (2.6) that traduces the estimated output power of the hydropower plant. For this equation, the water density, ρ, was multiplied by the acceleration due to the gravitational force, g, to get the water specific weight equal to 9810.

$$P = 9.810 \times Q \times H \times \eta_{gen} \ [kW] \tag{2.6}$$

If instead of generation, the PHS is in the pumping operation, the expression that estimates the power consumed in the process is given by equation (2.7). For this scenario, the efficiency, η_{pump}, represents losses in the hydraulic circuit, drive pumps and electric motor.

$$P = \frac{9.810 \times Q \times H}{\eta_{pump}} \ [kW] \tag{2.7}$$

2.3. The Iberian Electricity Market

The Iberian Electricity Market, known by the acronym MIBEL, is the electricity market of Portugal and Spain. The market is divided in two major categories: the futures market where producers ensure the generation of energy and the buying agents ensure the acquisition of that energy with the intent of distributing to final clients, which may occur at later date, and the spot market where ancillary services and energy blocks are negotiated and traded with an immediate physical delivery of those goods. For the purposes of this thesis, the focus will be on the spot market, which is comprised of the day-ahead market (DA) and the intraday market (ID). In Figure 2.16 one can observe the structure of the market.

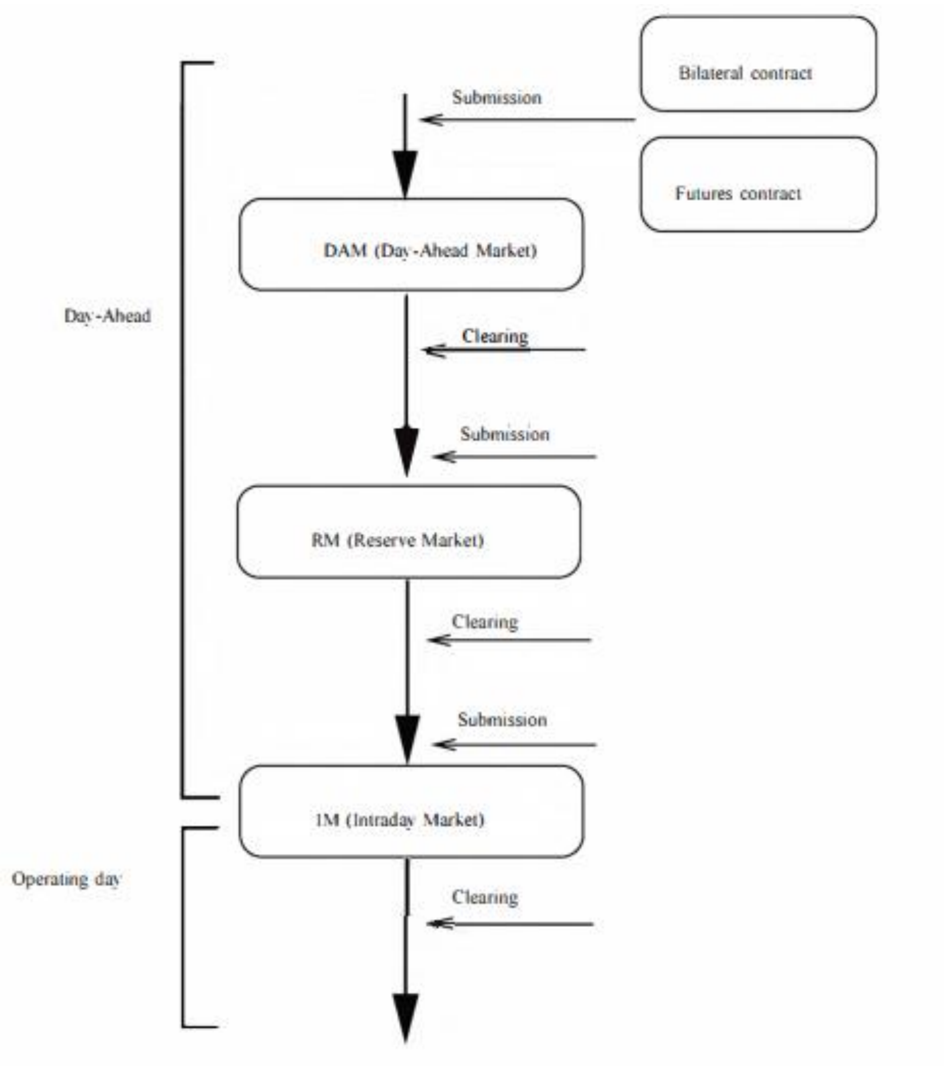

Figure 2.16 – Structure of MIBEL [29]

2.3.1. Day-Ahead Market

The DA energy market is a platform to trade electricity which is delivered in the day that follows the negotiation. In other words, the DA market operates in day D with the intention of trading energy for day D+1, forming the price bids to be made for all the 24 hours of that day. At the current moment, it is the most important segment of MIBEL, being responsible for most of the energy transactions.

Agents with generation units submit selling bids and agents with load units submit buying bids. The supplier's bid reflects the minimum price that this respective agent is willing to receive for the quantity that he is selling and, for the buyer, the bid represents the maximum price that he is willing to pay for that amount of energy. The selling bids are organized in an ascending price order (supply curve) and the buying bids in descending price order (demand curve). The market clearing price is the smaller price which ensures that the supply meets the demand and, graphically, is the intersection of the supply and demand curves. This organization of the DA market signifies that every selling or buying agent bids are made at the market clearing price, independently of the initial bids that were made.

2.3.2. Intraday Market

The ID market was conceived to be an adjustment market and the difference between the DA and the ID market is that the former operates in day D and the latter in day D+1. Due to transmission lines congestion problems, power outages and forecasting errors the contracted energy in the DA market and the actual energy that is generated in D+1 may differ, for that reason the main goal of the ID market is minimize that energy imbalance. Supply agents can submit buying bids and demand side agents can submit selling bids, allowing these agents to correct their DA market positions.

2.3.3. Spot Market Prices Prediction

The spot market prices are one of the input data for the DA algorithm and it highly influences the energy bids that are placed on the market pool. For this reason, when performing the DA optimization algorithm in day D, an accurate forecast of the market prices of day D+1 is recommended in order to reach a close approximation of the market prices for that day. If the spot market prices forecasted and the actual market prices differ significantly, the scheduled plan obtain resorting to the DA algorithm is no longer optimal in the operational day. Hence, similar to what was performed regarding wind speed forecasting, an algorithm for correctly predicting the spot market prices needs to be conducted.

Artificial neural networks were proposed for the wind speed forecasting issue, as explained in 2.1.2. One of the key features mentioned was the fact that ANN's operate as a "black box", meaning that an ANN can function completely independent of the input data. Consequently, an ANN approach can also be utilized for the spot market prices issue and the algorithm already in place for the wind forecasting problem can be used without any alterations.

3. Wind-Hydro Coordination

This chapter describes the characteristics of the system considered for the case-study and the methodologies used for the wind-hydro coordination. The methodologies are segmented in two separate sections. The first aims at maximizing the wind-hydro park's profit in a market operation. The two algorithms proposed for maximizing the profit are detailed. Secondly, the ability of the wind-hydro park to output a constant target power is studied and the method used is explained.

3.1. Case-Study Definition

The case-study that was considered is based on a pilot project currently being developed in Gaildorf, a small town close to Stuttgart, in Germany [30]. The intention behind this dissertation is to study the possible application of a similar project in Portugal.

The pilot project includes a wind farm with a total power capacity of 13.6 MW, with 4 wind turbines of 3.4 MW each. The wind turbines have a hub height of approximately 180m. The wind farm is combined with a pump-hydro-storage power plant with a total capacity of 16 MW and an electrical storage capacity of 70 MWh. The base of each wind turbine constitutes an upper water reservoir that, according to [10], have a volume storage capacity of 10.6 million gallons which equates to 40000 m^3 (1 gallon = 0.00378 m^3) or, in terms of electrical storage capacity, a fourth of the total capacity, which is 17.5 MWh. Thus, the total storage capacity of the four upper reservoirs is 160000 m^3 or 70 MWh, with each individual reservoir having a storage capacity of 40000 m^3 or 17.5 MWh. The lower reservoir has also a total storage capacity of 160000 m^3 or 70 MWh. The upper reservoirs are connected to the PHS plant via a penstock with a fall height of 200m. The total volume of water present in the system is 160000 m^3. An illustration of the case-study is showed in Figure 3.1.

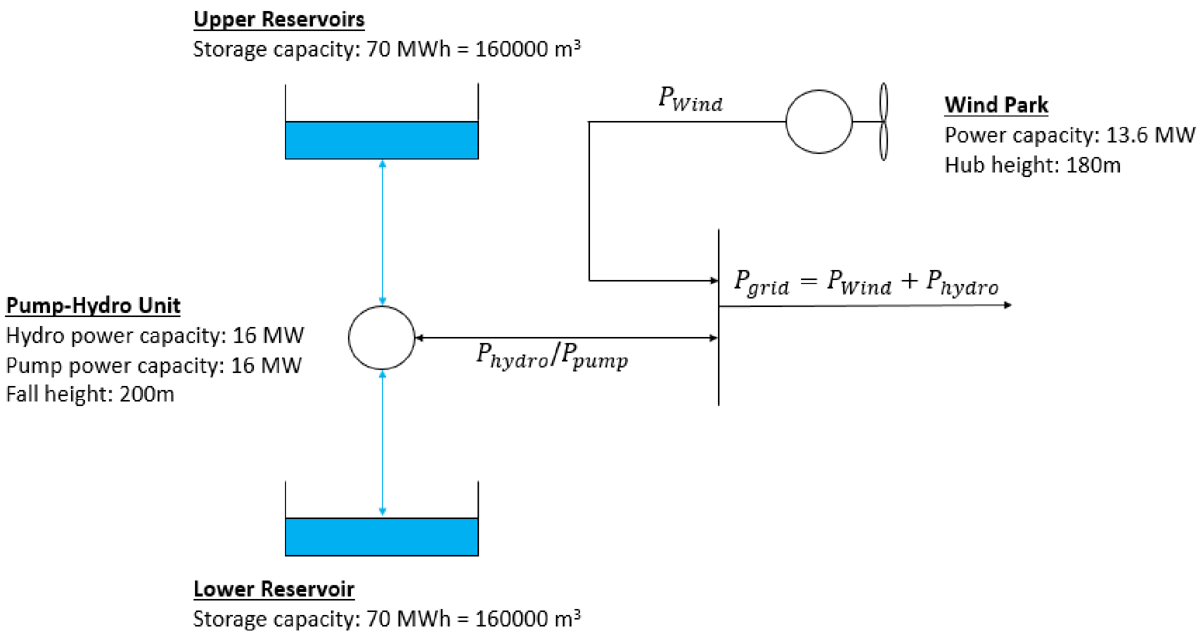

Figure 3.1 - Case-study schematic

Three historical data are used as inputs for the two methodologies to be studied: a spot market prices and imbalance prices time series for the Iberian Electricity Market and a wind speed time series. All the time series comprise of hourly values for the respective variables. The spot market prices were obtained, from 10th of May 2017 to 10th of May 2018, in *Operador del Mercado Ibérico de Energia* (OMIE) [31]. The imbalance prices were attained from REN (Redes Energéticas Nacionais) [32].

While simulating the park's operation an effort was made with the intent of simulating the system in a realistic manner. However, certain assumptions were made regarding the system that are listed afterwards:

- The wind turbines and the hydropower unit can directly supply the power into the grid. Power flow losses in the transmission lines are neglected, as well as possible congestion problems that may occur.
- All 4 upper reservoirs have the same total storage capacity, therefore, to simplify the number of variables, it is assumed that those 4 reservoirs constitute one single reservoir. The single upper reservoir will then have a storage capacity of 160000 m^3 or 70 MWh, which is equal to the lower reservoir.
- Since the historical wind speed time series had a relatively high annual average speed (approximately 8.5 m/s), it was assumed that this data was obtained at the hub height of the wind turbines (approximately 180m), thus the application of Prandtl Law is not necessary.
- The historical wind speed data and spot market prices match one another. In other words, it is considered that the historical wind speed data is taken from 10th of May 2017 to 10th of May 2018.
- All 4 wind turbines receive the same amount of wind and generate the same amount of energy, although in reality the turbines are in slightly different geographical places.
- It was assumed that the efficiency for the hydro generation was 80% and for the pumping operation 70% and the possibility of pumping and generating in the same hour is possible.
- The market price for positive and negative imbalances is equal.
- The system's total water volume remains equal to 160000 m^3 and hydrological data is disregarded.
- As mentioned in Chapter 2, it was presumed that the Vestas V126-3.45 was the model that best depicted the characteristics of the park's 4 wind turbines. Thus, the power capacity of the wind park in the case-study is 13.8 MW and not 13.6 MW.
- Internal operational costs regarding hydro generation and the pumping operation were considered, based on values from *Castronuovo and Peças* [15]. For the hydro generation the cost is 1 €/MWh and for the pumping operation 1.5 €/MWh.

3.2. Maximizing Market Profit

In a wind-hydro park, the PHS plant allows energy to be stored and used at a later time. One of the reasons behind this characteristic is to increase the park's operator profit while submitting selling bids in the market pool. In order to maximize this situation, two optimization problems need to be solved: a day-ahead optimization problem and an operational day problem.

3.2.1. Day-Ahead Optimization Algorithm

Day-ahead optimization consists in storing the wind energy that is generated during low market price periods to then sell that energy at a later time, when the prices are higher, improving the overall profit. The DA optimization problem is based in the wind power forecasted, the spot market prices predicted and the water stored in the reservoirs for day D+1. With this input data, the optimization problem is solved, returning the hourly discretized plan to be followed that ensures the maximization of the profit in the DA market. The hourly plan includes, for each hour, the quantity of wind energy to be sold directly to the grid, the quantity of wind energy to be used in the pumping operation and quantity of hydro energy to be delivered to the grid.

Mathematically, this optimization problem can be summarized by equations (3.1) to (3.12):

$$Max \sum_{i=1}^{24} \left[P_{Gi}.p_i - c_{hydro}.P_{Hi} - c_{pump}.P_{WPi} \right] \tag{3.1}$$

subject to

$$P_{Gi} = P_{WGi} + P_{Hi} \tag{3.2}$$

$$P_G^{\min} \leq P_{Gi} \leq P_G^{\max} \tag{3.3}$$

$$P_{Wi} = P_{WGi} + P_{WPi} \tag{3.4}$$

$$P_W^{\min} \leq P_{Wi} \leq P_W^{\max} \tag{3.5}$$

$$P_{WP}^{\min} \leq P_{WPi} \leq P_{WPi}^{\max} \tag{3.6}$$

$$E_i = E_{i-1} + \eta_{pump}.P_{WPi} - \frac{P_{Hi}}{\eta_{hydro}} \tag{3.7}$$

$$E_{\min} \leq E_i \leq E^{\max} \tag{3.8}$$

$$E_1 = E_{initial} \tag{3.9}$$

$$E_{24} \geq E_{final} \tag{3.10}$$

$$P_H^{\min} \leq P_{Hi} \leq P_H^{\max} \tag{3.11}$$

$$P_{Hi} \leq \eta_{hydro}.\left[E_i + \eta_{pump}.P_{WPi}\right] \tag{3.12}$$

Where: p_i is the spot market price predicted in hour i; P_{Gi} is the power delivered to the grid by plant in hour i; P_{Wi} is the active wind power generated by the turbines, in hour i, by the wind speed forecasted; P_{WGi} is the wind power that is delivered to the grid in hour i; P_{WPi} is the amount of wind power that is used for the pumping operation in hour i; P_{Hi} is the hydro power produced during hour i; c_{pump} are the internal operational costs associated with the pumping operation; c_{hydro} are the internal operational costs associated with the hydro power generation; E_i is the energy stored in the reservoirs in hour i;

The objective function represented by (3.1) aims to maximize the market profit of the plant incorporating the operational costs of both the hydro power generation and the pumping operation. The total active power delivered to the network in each hour is given by (3.2) and is the addition of the fraction of wind power sent to the grid and the hydro power generated. The minimum, P_G^{min}, and maximum power, P_G^{max}, which the wind-hydro plant is able to generate is defined in (3.3). In (3.4), the total wind power which is generated by the plant's turbines in each hour is divided in the fraction that is sent to the grid and the fraction that is used for the pumping operation. Both (3.5) and (3.6) translate the physical constraints for the wind turbines of the plant, defining the minimum, P_{WG}^{min}, and maximum wind power, P_{WG}^{max}, that is possible to be delivered to the grid and the minimum, P_{WP}^{min}, and maximum wind power, P_{WP}^{max}, that is possible to transmit for the pumping operation, respectively. The balance of energy stored in the reservoirs, in hour i, is obtained by (3.7), where to the previous hour stored energy, E_{i-1}, is added the energy corresponding to the pumped water and subtracted the energy corresponding to the water used for the hydro power generation. In (3.8), both the maximum, E^{max}, and minimum, E_{min}, limits of the energy that is possible to store in the reservoirs is defined. Expressions (3.9) and (3.10) provide the initial energy stored in the reservoirs, $E_{initial}$, and the planned final energy after the day-ahead scheduling, E_{final}, respectively. The initial energy is necessary for the application of (3.7) and the final energy is specified so that a consistent scheduling scheme for the reservoirs is achieved. The minimum, P_H^{min}, and maximum power, P_H^{max}, that the hydraulic turbines are physically able to generate is defined in (3.11). Also, in (3.12), it is defined that the hydropower produced cannot be superior to the amount of energy available in the reservoir, in addition to the water pumped in the same hour. Both (3.11) and (3.12) translate the minimum and maximum values that P_{Hi} can achieve.

In the context of the case-study, all variables' numeric minimum limits are equal to zero. The maximum limit is the following, for each variable: P_G^{max} equal to 29.8 MW; P_{WG}^{max} and P_{WP}^{max} are equal to 13.8 MW; E^{max} is 70 MWh; P_H^{max} equal to 16 MW.

It is important to remind that the total wind power generated, P_{Wi}, is obtained resorting to the wind turbine power curve defined by (2.2), with the wind speed forecasting being achieved through an artificial neural network approach.

Recurring to a linear programming (LP) algorithm the optimization problem is solved. The algorithm used is the *linprog* function present in the *MATLAB® Optimization Toolbox*, which solves problems that respect the following formulation expressed in (3.13) [33].

$$Min\ f^T.x\ \ subject\,to \begin{cases} A.x \le b \\ A_{eq}.x = b_{eq} \\ lb \le x \le ub \end{cases} \tag{3.13}$$

Where: f is a coefficient vector; x is the decision vector; A and b represent the linear inequality constraints of the decision vector; A_{eq} and b_{eq} the linear equality constraints of the decision vector; lb and ub the lower and upper bounds of the decision vector, respectively.

For this particular problem, the decision vector is a 120x1 vector which contains all the variables of the problem and is given by (3.14).

$$x = \left[P_{Gi}\ P_{WGi}\ P_{Hi}\ P_{WPi}\ E_i \right]^T \quad i = 1,...,24 \tag{3.14}$$

By multiplying the decision vector with the coefficient vector, it is possible to obtain the objective function. In this case, the coefficient vector stated in (3.15).

$$f = \left[p_i\,|0| - c_{hydro}\,| - c_{pump}\,|0 \right] \quad i = 1,...,24 \tag{3.15}$$

Equations (3.10) and (3.12) are the two inequality constraints for this problem. Matrix A, which is an incidence matrix (compose of 1, 0 and -1 values), has a dimension 25x120 and vector b, with dimension 25x1, is translated in (3.16).

$$b = \left[0\,E_{final} \right]^T \tag{3.16}$$

Equations (3.2), (3.4) and (3.7) represent the equality constraints and matrix A_{eq} and vector b_{eq} translate these relationships. In this case, matrix A_{eq} (which is an incidence matrix just like A), has a dimension 72x120 and vector b_{eq}, with dimension 72x1, is defined by (3.17).

$$b_{eq} = [0|P_{Wi}\,|E_{initial}\ \ 0]^T \quad i = 1,...,24 \tag{3.17}$$

As for the variable's lower and upper bounds, it is defined by expressions (3.3), (3.5), (3.6), (3.8) and (3.11), which is traduced by the vectors of equation (3.18) and (3.19), both with dimensions 1x120.

$$lb = \left[P_G^{\min}\,|P_W^{\min}\,|P_H^{\min}\,|P_{WP}^{\min}\,|E_{\min} \right] \tag{3.18}$$

$$ub = \left[P_G^{\max}\,|P_W^{\max}\,|P_H^{\max}\,|P_{WP}^{\max}\,|E^{\max} \right] \tag{3.19}$$

The *linprog* function solves minimization problems, therefore, in order to actually maximize the objective function, one must minimize $-f^T.x$, which is equal to maximizing $f^T.x$.

3.2.2. Operational Day Strategy

The high variability of wind speed leads to a high unpredictability regarding the wind power forecasted. Hence, an imbalance originates between the selling bids obtain via the DA optimization and the actual power generated in the operational day. The higher the deviation between the contracted power and the real power generated, the higher the regulation costs are in order to balance the situation. Thus, the operational day strategy (ODS) objective is to minimize these deviations, increasing the overall profit of the park.

The input data for the ODS consists of the actual operational day spot market prices, the real hourly values of the wind speed and water stored inside the reservoirs, as well as, the DA selling bids. With this data, a new hourly optimization problem is solved that returns, for each hour, the selling bids to be submitted in the ID market pool that maximize the wind-hydro plant profit.

Mathematically, the major difference between the ODS and the DA problem is the fact that the objective function needs a new term that encompasses the regulation costs associated with the deviations. In this case, the optimization problem can be summarized in equation (3.20) to (3.31):

$$Max \sum_{i=1}^{24} \left[P_{Gi\_real}.p_{i\_real} - c_{hydro}.P_{Hi\_real} - c_{pump}.P_{WPi\_real} - dev_i.| P_{Gi} - P_{Gi\_real} | \right] \tag{3.20}$$

subject to

$$P_{Gi\_real} = P_{WGi\_real} + P_{Hi\_real} \tag{3.21}$$

$$P_G^{\min} \le P_{Gi\_real} \le P_G^{\max} \tag{3.22}$$

$$P_{Wi\_real} = P_{WGi\_real} + P_{WPi\_real} \tag{3.23}$$

$$P_W^{\min} \le P_{Wi\_real} \le P_W^{\max} \tag{3.24}$$

$$P_{WP}^{\min} \le P_{WPi\_real} \le P_{WP}^{\max} \tag{3.25}$$

$$E_{i\_real} = E_{i-1\_real} + \eta_{pump}.P_{WPi\_real} - \frac{P_{Hi\_real}}{\eta_{hydro}} \tag{3.26}$$

$$E_{\min} \le E_{i\_real} \le E^{\max} \tag{3.27}$$

$$E_{1\_real} = E_{initial} \tag{3.28}$$

$$E_{24\_real} \ge E_{final} \tag{3.29}$$

$$P_H^{\min} \le P_{Hi\_real} \le P_H^{\max} \tag{3.30}$$

$$P_{Hi\_real} \leq \eta_{hydro} . \left[E_{i\_real} + \eta_{pump} . P_{WPi\_real} \right] \tag{3.31}$$

Where: P_{Gi_real} is the actual power delivered to the grid in hour i; p_{i_real} is the real spot market prices in hour i; P_{Wi_real} is the actual active wind power generated by the turbines, in hour i, by the wind speed forecasted; P_{WGi_real} is the real wind power that is delivered to the grid in hour i; P_{WPi_real} is the real amount of wind power that is used for the pumping operation in hour i; P_{Hi_real} is the real hydro power produced during hour i; E_{i_real} is the actual energy that is stored in the reservoirs in hour i;

The objective function is expressed by (3.20) and the first three terms, similar to the DA optimization problem, represent the maximizing of the market profit while also incorporating the operational costs of both the hydro power generation and the pumping operation. The novelty is in the fourth term where the deviations' penalties are defined. The deviation between P_{Gi} and P_{Gi_real} can be either positive or negative and, for that reason, it is expressed by the absolute value of these two variables. The deviation costs in each hour are given by dev_i. The revenue is then given by the multiplication of the absolute value and the deviation costs. The problem constraints represented by equations (3.21) to (3.31) are similar to the problem constraints defined for the DA optimization in equations (3.2) to (3.12).

Analogous to the DA situation, the actual wind power that is generated, P_{Wi_real}, is obtained using the wind turbine power curve expressed in (2.2). Although, in this case, the real values for the wind speed for that given day are utilized. Similarly, the minimum and maximum limits for each variable remain the same.

The absolute value present in the objective function introduces a nonlinearity, therefore it is necessary to reformulate the problem as a linear problem by performing a linearization of the objective function. Considering a general problem expressed in (3.32) and (3.33).

$$Max \;\; f^T x - |x| \tag{3.32}$$

subject to

$$x_{\min} \leq x \leq x^{\max} \tag{3.33}$$

Where: f is the coefficient vector for the linear term; x is the decision vector; x_{min} and x^{max} are the lower and upper bounds of the decision variables, respectively.

The equivalent linear problem is expressed in equation (3.34) to (3.37).

$$Max \; f^T x - (x^+ + x^-) \tag{3.34}$$

$$x_{\min} \leq x \leq x^{\max} \tag{3.35}$$

$$x = x^+ + x^- \tag{3.36}$$

$$x^+ \geq 0, x^- \geq 0 \tag{3.37}$$

Thus, applying this linearization to the problem in question, the objective function in (3.20) is reformulated and stated by (3.38) to (3.41).

$$Max \sum_{i=1}^{24}\left[P_{Gi\_real}.p_{i\_real} - c_{hydro}.P_{Hi\_real} - c_{pump}.P_{WPi\_real} - dev_i.(P_i^+ + P_i^-)\right] \quad (3.38)$$

subject to

$$P_{Gi\_real} - P_{Gi} - P_i^+ - P_i^- = 0 \quad (3.39)$$

$$0 \le P_i^+ \le P_{\max}^+ \quad (3.40)$$

$$0 \le P_i^- \le P_{\max}^- \quad (3.41)$$

The constraints (3.39) to (3.41) are added and the ones expressed by (3.21) to (3.31) remain the same. With the two added variables the decision vector changes its dimension to 168x1 and is now defined by (3.42).

$$x = \left[P_{Gi\_real}\ P_{WGi\_real}\ P_{Hi\_real}\ P_{WPi\_real}\ E_{i\_real}\ P_i^+\ P_i^-\right]^T \quad i = 1,...,24 \quad (3.42)$$

Equation (3.43) states the coefficient vector.

$$f = \left[p_{i\_real}\,|0|-c_{hydro}|-c_{pump}\,|0|-p_{i\_real}.dev|-p_{i\_real}.dev\right] \quad i = 1,...,24 \quad (3.43)$$

There are no added inequality constraints so, for that reason, matrix A and vector b remain equal. However, equation (3.39) introduces a new equality constraint and matrix A_{eq} changes its dimension to 96x168 and vector b_{eq}, with dimension 96x1, is stated in (3.44).

$$b_{eq} = \left[0|P_{Wi\_real}\,|E_{initial}\ \ 0|0\right]^T \quad i = 1,...,24 \quad (3.44)$$

Equations (3.40) is included in the lower and upper bounds vectors, changing its dimension to 1x168 for both cases. The lower and upper bounds vectors are expressed in (3.45) and (3.46), respectively:

$$lb = \left[P_G^{\min}\,|P_W^{\min}\,|P_H^{\min}\,|P_{WP}^{\min}\,|E_{\min}\,|0|0\right] \quad (3.45)$$

$$ub = \left[P_G^{\max}\,|P_W^{\max}\,|P_H^{\max}\,|P_{WP}^{\max}\,|E^{\max}\,|P_{\max}^+\,|P_{\max}^-\right] \quad (3.46)$$

3.3. Constant Power Output

One of the main characteristics of the wind resource is the high degree of unpredictability concerning its speed and direction. These variations can occur very suddenly, in a matter of seconds or minutes, or in longer periods of time, such as variations due to the changing of seasons. The electric system is constructed in a way that production must always equal demand. Thus, the high variability of wind power production creates stability problems in the whole electric system. Moreover, in the last section was explained how this variability regarding the wind forecast and the actual wind can lead wind park operators to pay regulation costs that will decrease their profit in the ID market.

In this section a model is proposed where the possibility of firming the output power production of the wind-hydro park in question is analyzed through simulating the park's operation. Each simulation results in the probability of the wind-hydro park supplying a certain constant power for a complete operational day (all the 24 hours of an operational day), given the wind speed that is available. The ability to supply a certain target output power is tested for different wind speed scenarios, as well as different volumes of water stored in the reservoirs of the power plant.

The aim for delivering a certain constant power to the grid is twofold. First, it greatly improves wind power penetration by combating grid stability issues, since it allows for a more accurate balance between production and demand in the system. Second, if the wind-hydro park operator recognizes in advance that the park is going to be able to supply a certain constant power with a very high degree of certainty (very high probability), the difference between the contracted power in the DA market and the actual power that is generated is very small or non-existing.

Structure of the Algorithm

The goal is to analyze the ability of the park to supply a constant target power for any given day of the year, therefore different wind speed scenarios need to be created for simulating different situations. In order to represent a yearly operation, 500 wind speed predictions were generated, based on the ANN algorithm already described in a previous chapter. Whereas in the DA optimization algorithm, the ANN would predict the wind speed for a pre-defined day, in this case the ANN algorithm will instead generate wind speed predictions for random days of the historical wind speed data. The reason behind this is the monthly differences in wind speed values that arise due to different seasonal times of the year. By randomly selecting a day to create a wind speed scenario, the study includes those seasonal patterns. It is important to note that the algorithm itself does not suffer any changes, only the selection of the input and target data is altered.

Wind speed variations might occur rapidly, inducing a wind production variation. Hydro power plants have the ability to quickly change the operating point, providing an ideal solution to combat these power discrepancies. Hence, the maintenance of a constant target power is achieved by combining the hydro power production with the wind power technology if the wind turbines are not able to deliver the target power to the grid. If there is a surplus of wind power in relation to the target constant power, that surplus is used to feed the pumping operation, where water is sent from the lower reservoir to the upper reservoir and that extra power is stored in the form of potential energy. However, if wind power generation is lower than the predefined target value, the hydro power unit must provide the extra power. This way, a constant balance is able to be accomplished.

Thus, the power balance between wind power and hydro power production must be equal to the demanded target value, P_{Demand}, and this is mathematically expressed in (3.47):

$$P_{Demand} = P_{Wi} + P_{Hi} \rightarrow P_{Hi} = P_{Demand} - P_{Wi} \qquad (3.47)$$

If $P_{Hi} \geq 0$, that means the total generated wind power is below the target value and remaining power needs to be supplied by the hydro power turbine. In this case, the volume of water of the upper reservoirs will decrease and, consequently, the volume of water of the lower reservoir will increase. The balance of the volume of water that is being used for this operation needs to be accounted for and is expressed by equation (3.48) to (3.50).

$$Q_i^{gen} = \frac{P_{Hi} \times 1000 \times 3600}{9.810 \times H \times \eta_{gen}} \; [m^3 / h] \tag{3.48}$$

$$R_i^{upper} = R_{i-1}^{upper} - Q_i^{gen} \; [m^3] \tag{3.49}$$

$$R_i^{lower} = R_{i-1}^{lower} + Q_i^{gen} \; [m^3] \tag{3.50}$$

If instead $P_{Hi} \leq 0$, the total generated wind power is above the target value and the surplus of wind power is used for the pumping operation. In this case, the volume of water of the upper reservoir will increase and the volume of water in the lower reservoir will decrease. Analogous to the hydro production situation, this water balance can be stated in equation (3.51) to (3.53).

$$Q_i^{pump} = \frac{|P_{Hi}| \times 1000 \times 3600 \times \eta_{pump}}{9.810 \times H} \; [m^3 / h] \tag{3.51}$$

$$R_i^{upper} = R_{i-1}^{upper} + Q_i^{pump} \; [m^3] \tag{3.52}$$

$$R_i^{lower} = R_{i-1}^{lower} - Q_i^{pump} \; [m^3] \tag{3.53}$$

Naturally, there are limitations regarding the hydro generation and the pumping operation. In particular, physical limitations regarding the upper and lower reservoirs, as well as limitations regarding the wind and hydro turbines maximum capacity. These limitations are translated by equations (3.54) to (3.57).

$$R_{\min}^{upper} \leq R_i^{upper} \leq R_{\max}^{upper} \; [m^3] \tag{3.54}$$

$$R_{\min}^{lower} \leq R_i^{lower} \leq R_{\max}^{lower} \; [m^3] \tag{3.55}$$

$$P_W^{\min} \leq P_{Wi} \leq P_W^{\max} \; [MW] \tag{3.56}$$

$$P_H^{\min} \leq P_{Hi} \leq P_H^{\max} \; [MW] \tag{3.57}$$

The minimum limits are, again, all equal to zero. The maximum limits for each variable are the following: R_{max}^{upper} and R_{max}^{lower} are equal to 160000 m^3; P_W^{max} is 13.8 MW; P_H^{max} is 16 MW.

Hydro generation is only possible if the volume of water in the upper reservoir is sufficient to generate the power deficit. If this condition is not verified the target power cannot be achieved, there is no hydro power production and the only power that is sold to the grid is originated from the wind turbines. Likewise, storing the wind power surplus in the upper reservoir via the pumping operation is only possible if the water in the lower reservoir is sufficient. However, if this condition is not met, water from the upper reservoir is released to the lower reservoir via an auxiliary channel and that same volume of water is then pumped back to the upper reservoir using the power surplus. This way the power surplus is disposed of and the target power is maintained.

Since the volume of water stored in the reservoir is key for the combine operation of the wind-hydro park, different initial volumes of water stored in the reservoirs need to be considered. Hence, 6 different initial values are simulated, starting with 20000 m^3 stored in the upper reservoir to 140000 m^3. A certain target power value is tested, for each of the 500 wind speed forecasts and each of the 6 initial volumes values. After the testing of that target value, an increment of 1 MW is imposed and that new target value is again tested for each of the 500 wind speed forecasts and 6 initial volume values. In total, target values ranging from 1 MW to 16 MW are tested. This account for a total of 48000 simulations elaborated.

4. Results

This chapter is sectioned in two parts. The first covers the results and the respective analysis for the two algorithms, the DA optimization and the ODS optimization, that comprise the maximization of the profit. In the second the results and analysis for the constant power output problem are presented.

4.1. Maximizing Market Profit

To examine the maximizing market profit problem two different simulations are going to be performed. The two simulations differ in the spot market prices, imbalance costs and the wind speed considered, which will impact the operation of the wind-hydro park. A breakdown of the results of both simulations, for the DA algorithm and the ODS algorithm, is exhibited next. It is important to note that both simulations are conducted with an initial energy stored in the upper reservoir, $E_{initial}$, equal to 35 MWh (half of the total capacity of the reservoir). It was selected the same value for the final energy stored, E_{final}, so, in both situations the initial and final energy stored in the upper reservoir is equal.

4.1.1. Day-Ahead Optimization

<u>Simulation 1</u>

The first simulation was performed using the historical data for the 10th of April 2018. This means that the DA optimization is hypothetically conducted on the 9th of April 2018. Primarily, the forecast of the spot market prices needs to be achieved. Figure 4.1 depicts a comparison between the forecasted market prices obtained via the ANN approach, as well as, the real market prices. The lowest prices predicted are reached in hours 4, 5 and 6 where the prices are below the 30 €/MWh, with a minimum of around 27 €/MWh in hour 5. As for the highest prices, they are reached in the last hours of the day, hours 22, 23 and 24, with maximum of 57 €/MWh in hour 24.

Proceeding the spot market prices forecast, one must repeat the process only this time for the wind speed values. In Figure 4.2, the result of the wind speed forecast and its real values is exhibited.

The input data required to run the DA optimization algorithm is now set and the DA wind-hydro planning can be generated. This plan can be viewed in Figure 4.3, where the power to be delivered to the grid, in each hour, by the wind-hydro park is represented, in addition to the wind power produced via the 4 wind turbines. The power to be distributed to the grid is equal to the wind power during 20 hours of the total of 24 hours of operation. The 4 hours where this is not the case are hour 4, 5, 6 and 24. In hours 4,5 and 6 the power to be sent to the grid is below the wind power produced, therefore this power is being stored through the pumping of water from the lower reservoir to the upper reservoir. These three hours correspond to the 3 hours where the market prices are predicted to be the lowest during that day. As for hour 24, this is the hour with the highest price point during the day, hence the power delivered to grid is far superior to the wind power produced, as hydropower was generated in this hour.

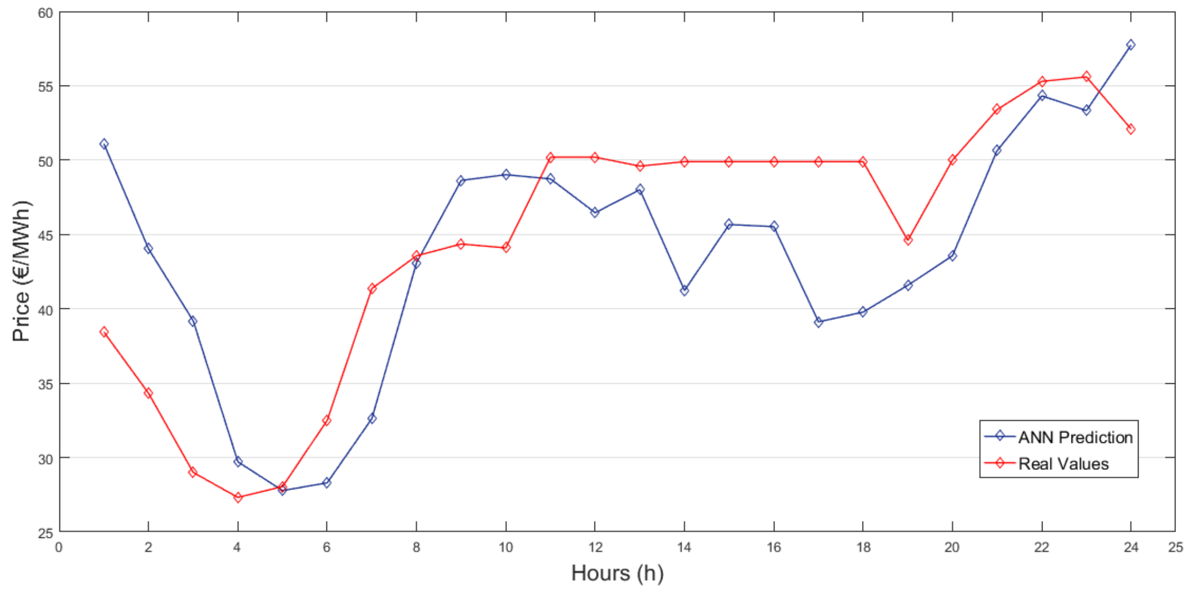

Figure 4.1 – Forecasted spot market prices and real prices on the 10th of April 2018

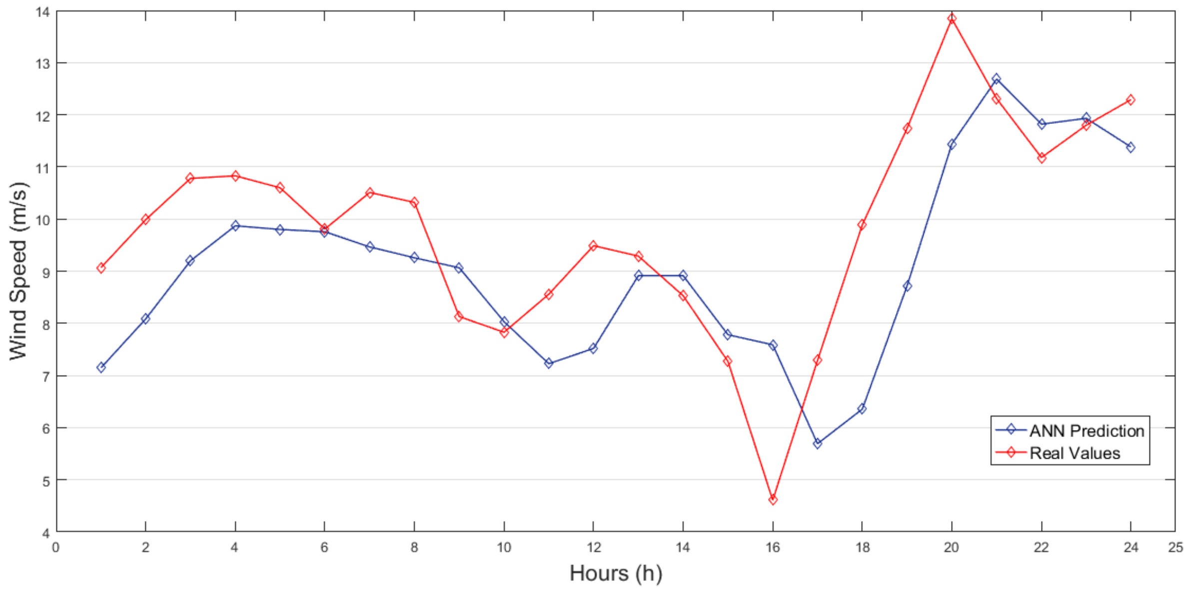

Figure 4.2 – Forecasted wind speed and real wind speed values on the 10th of April 2018

The wind-hydro schedule detailed corresponds to the operation that was already expected, namely in Figure 1.5, where power would be saved through the pumping of water during hours of low price points to then be sold at higher price points.

Figure 4.4 highlights, in greater detail, the scheduling of the hydro turbine. It is important to refer that the power produced via the hydraulic turbine, in hour 24, is its maximum capacity of 16 MW. As for Figure 4.5, the evolution of the energy stored in the upper reservoir is illustrated and one can observe that indeed in hours 4, 5 and 6 the energy levels rise and in hour 24 the levels drop to the set final value of 35 MWh.

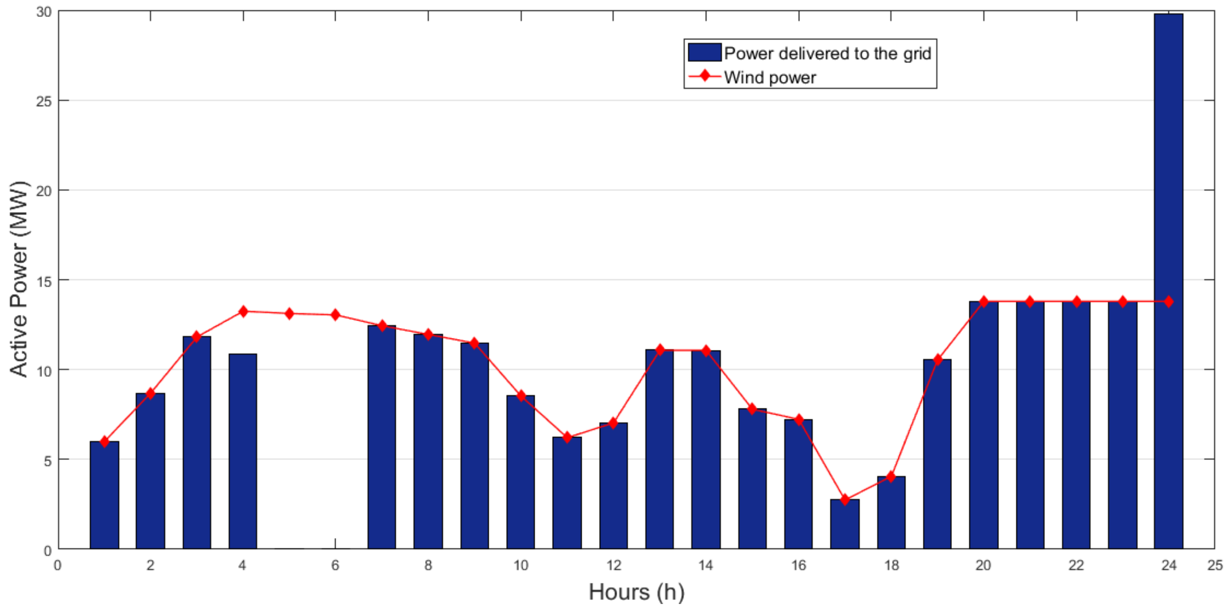

Figure 4.3 – Power bids to be placed in the day-ahead market accompanied by the wind power produced by the 4 wind turbines on the 10th of April 2018

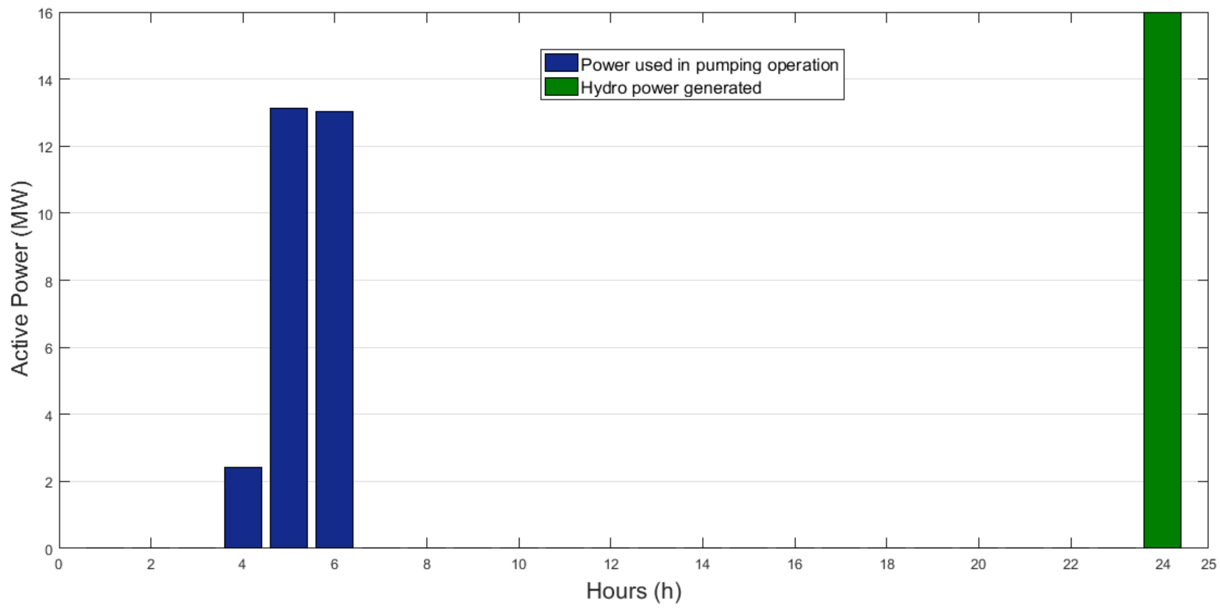

Figure 4.4 – Detailed view of the hydro turbine schedule of operation, including the hours of operation and power used in the respective operation mode

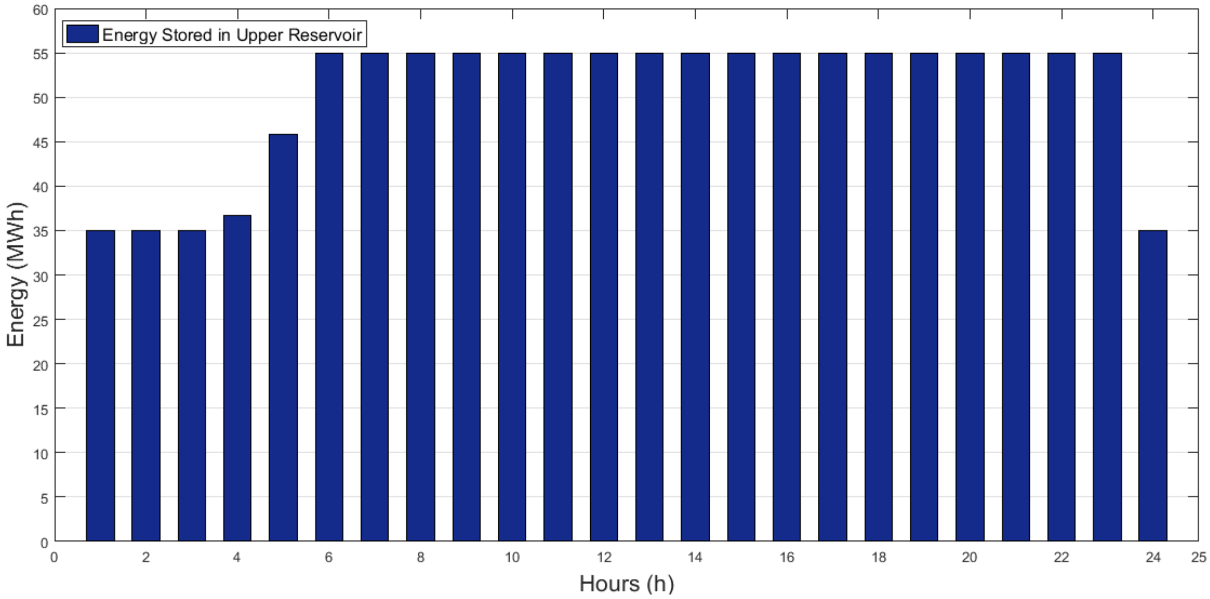

Figure 4.5 – Evolution of the energy stored in the upper reservoir

Simulation 2

The second simulation was performed using the historical data for the 10th of May 2018, which means the DA optimization is hypothetically conducted on the 9th of May 2018. Similarly to the first case, the input data comprised of the forecasted spot market prices and the wind speed needs to be obtained first. In Figure 4.6, the forecast corresponding to the spot market prices, along with the real market values is presented. The lowest prices predicted are achieved in hours 5, 6 and 7 with prices close to the 40 €/MWh mark and the highest prices are attained for hours 22, 23 and 24 with prices nearing 60 €/MWh. The minimum price is approximately 39 €/MWh in hour 6 and the maximum 60 €/MWh in hour 23.

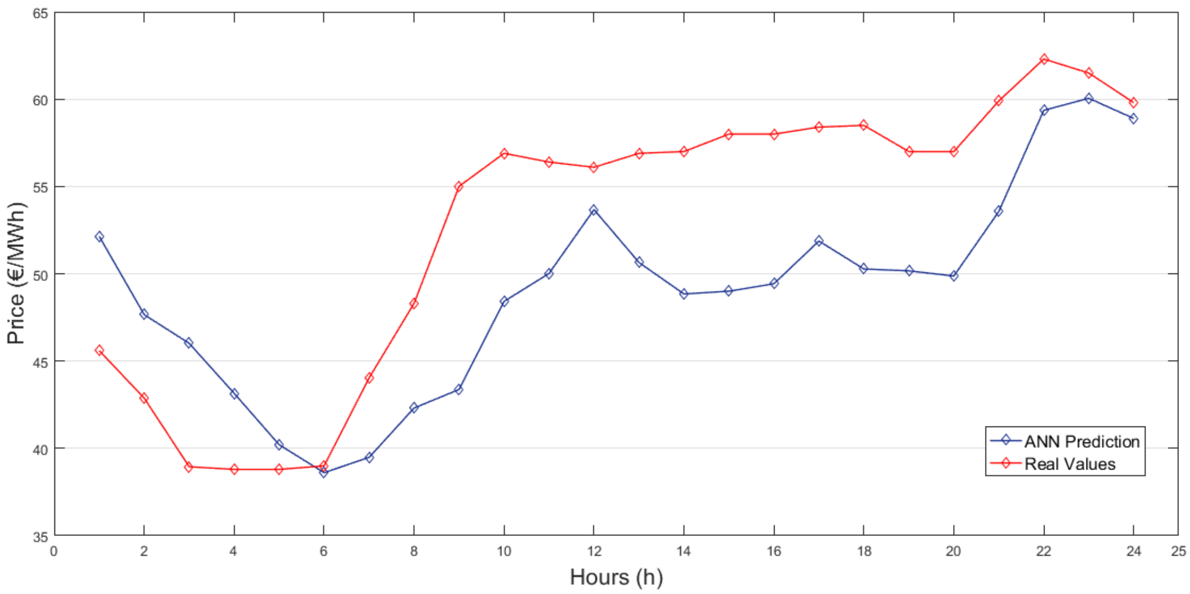

Figure 4.6 - Forecasted spot market prices and real prices on the 10th of May 2018

Figure 4.7 exhibits a comparison between the wind speed forecast values used in the algorithm and real wind speed values.

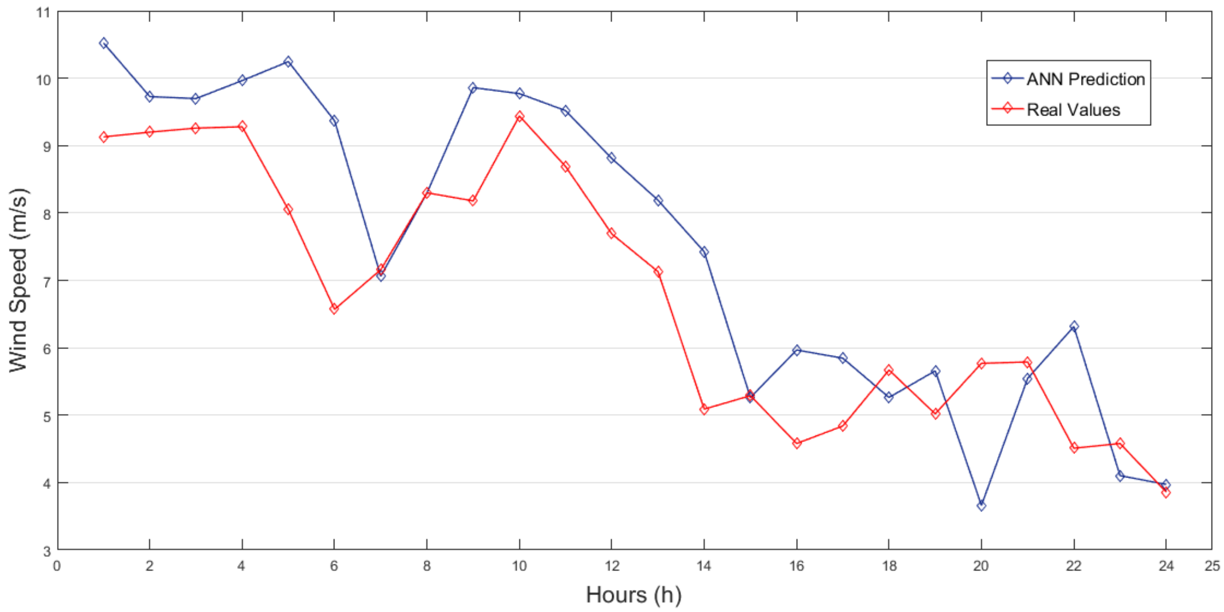

Figure 4.7 - Forecasted wind speed and real wind speed values on the 10th of May 2018

For simulation 2, the DA wind-hydro optimization plan is showed in Figure 4.8, where it is possible to see the power to be delivered to the grid in each hour of the operational day, along with the wind power produced. By examining Figure 4.8, one can spot that, in every hour of the day, the wind power produced is equal to the power to be distributed to the grid. This implies that the optimal plan of operation does not include any hydro generation or pumping operation. The reason behind this situation is the difference between the maximum and minimum market prices. In this case, the difference is approximately 20 €/MWh and the optimal plan for maximizing the profit considers that it is not viable, from a profit point of view, to store the wind power during low price points to then sell that respective power in higher price points. Instead, the optimal plan of operation considers that all the wind power should be sold as it is being produced.

The difference between low and high market prices when the pumping operation is viable is approximately the 30 €/MWh mark and simulation 1 represents one such case of operation. When the difference between low and high market prices is below this value, simulation 2 represents these situations. It is important to note that, with the historical spot market prices data used, simulation 1 would occur in approximately 10% of the days and simulation 2 in 90% of the days, since in the majority of the days the market prices never reach a difference of 30 €/MWh between low and high prices.

Since there is no hydro generation and pumping operation in simulation 2, the stored energy in the upper reservoirs remains with the set initial value of 35 MWh throughout the 24 hours of operation. As a final remark, it is important to address the fact that simulation 2 does not include any hydro operation because the final stored energy is set to be equal as the initial stored energy. If the final stored energy happened to be set to a value higher than the initial stored energy, the pumping operation would occur in low price points to meet that value. Similarly, if the final stored energy happened to be set to a value lower than the initial stored energy, hydro generation would occur in high price points to meet that value.

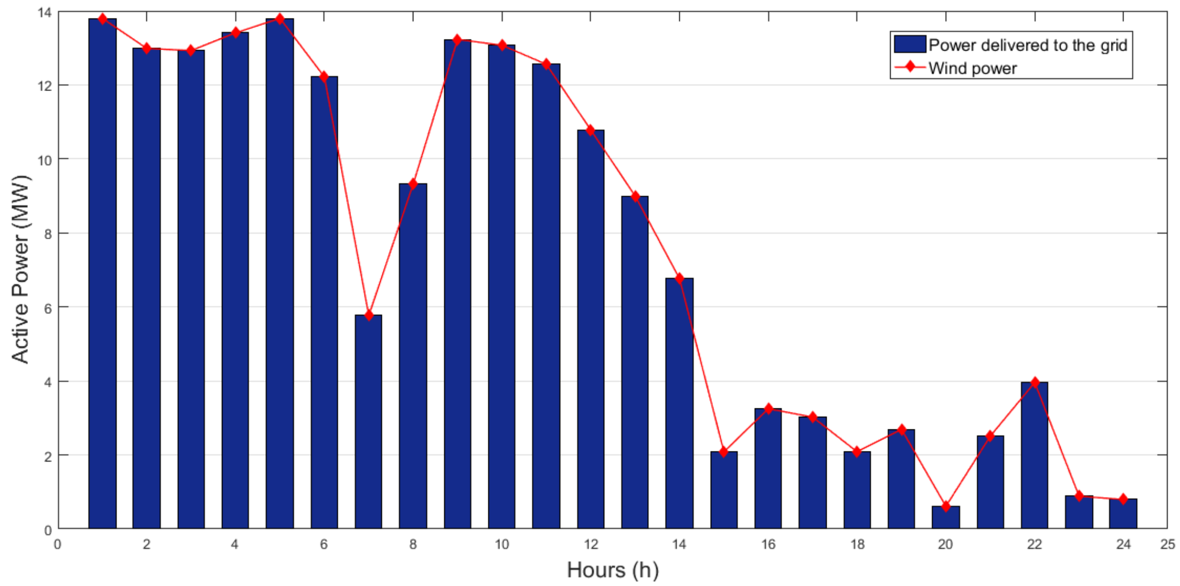

Figure 4.8 - Power bids to be placed in the day-ahead market accompanied by the wind power produced by the 4 wind turbines on the 10th of May 2018

4.1.2. Operational Day Strategy Algorithm

Simulation 1

Following the DA strategy for the 10th of April 2018, the ODS strategy attempts to minimize the imbalance between the contracted power and the actual produced power, maximizing the profit. Figure 4.9 shows the spot market prices, in addition to the imbalance prices. Normally, the market prices are superior to the imbalance prices and, in this case, that is true for all hours except hour 1 where the imbalance price is almost 50 €/MWh.

The ODS strategy followed that maximizes the profit is presented in Figure 4.10, where it is shown the wind power produced, the power that is distributed to the grid, along with the contracted power obtained from the DA plan. An increase in both pumping and hydro generation occurs, in relation to the DA plan, in order to balance the deviations between the contracted power and the power sent to the grid. Since the objective function for the ODS algorithm is non-linear and dependent on a number of factors, such as the spot market prices, imbalance prices, wind speed and the DA contracted power, an analysis of the ODS is more nuanced and not straightforward. However, one can still draw some conclusions and tendencies in the results. When the imbalance prices are high, the power delivered to the grid tends to be equal to the contracted power to minimize the deviation costs. Also, like the DA plan for simulation 1, in hours where the market prices are low there is a tendency of pumping operation in those hours and in hours where the market prices are high hydro generation tends to occur.

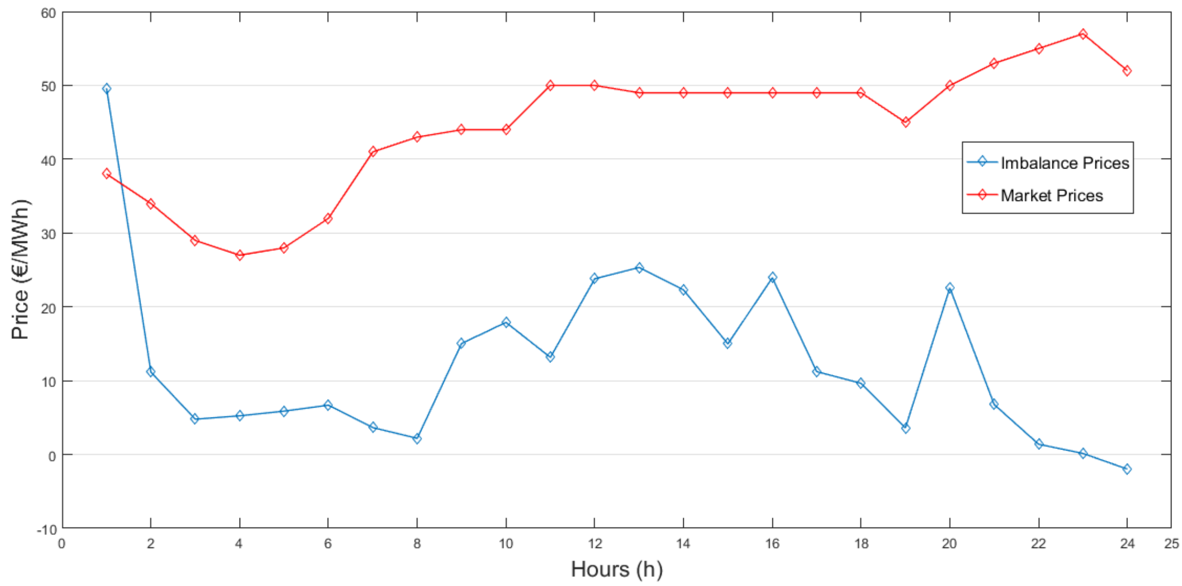

Figure 4.9 – Spot market prices and imbalance prices on the 10th of April 2018

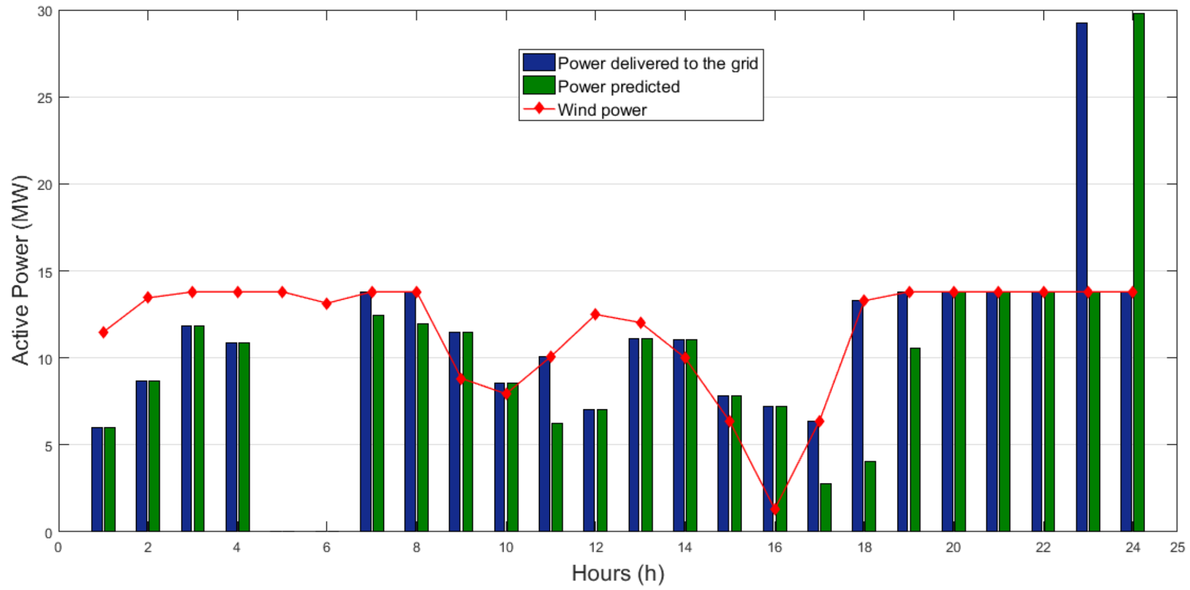

Figure 4.10 – Wind power produced, power delivered to the grid during the ODS, along with the power bids placed in the DA market on the 10th of April 2018

Figure 4.11 illustrates, in more detail, the schedule followed by the hydro turbine representing the power used in the operation of the pumps, along with the power produced in each hour. The evolution of the energy stored in the upper reservoir during the operational day is highlighted in Figure 4.12, where it is possible to confirm the final value of energy is, indeed, the set final value of 35 MWh.

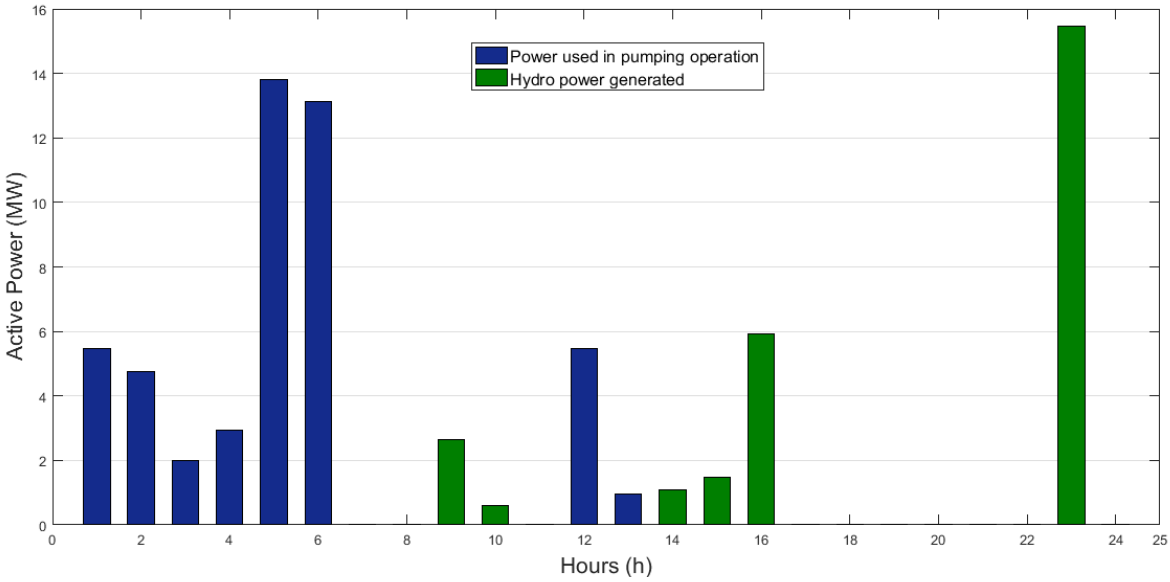

Figure 4.11 - Detailed view of the hydro turbine operation, including the hours and power used in the respective operation mode

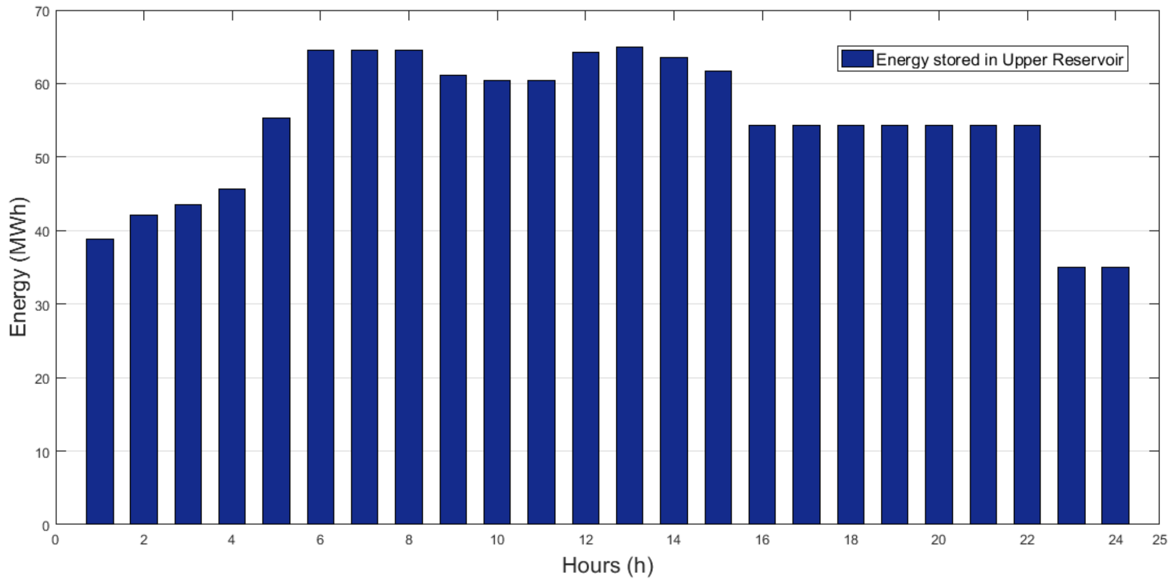

Figure 4.12 – Evolution of the energy stored in the upper reservoir during the operation day

Simulation 2

Similarly to simulation 1, with the DA strategy for the 10th of May 2018, the ODS can be obtained. In Figure 4.13 it is presented the spot market prices and imbalance prices for that respective day. The highest imbalance costs are close or above the 30 €/MWh margin and the lowest imbalance cost is approximately -12 €/MWh in hour 8.

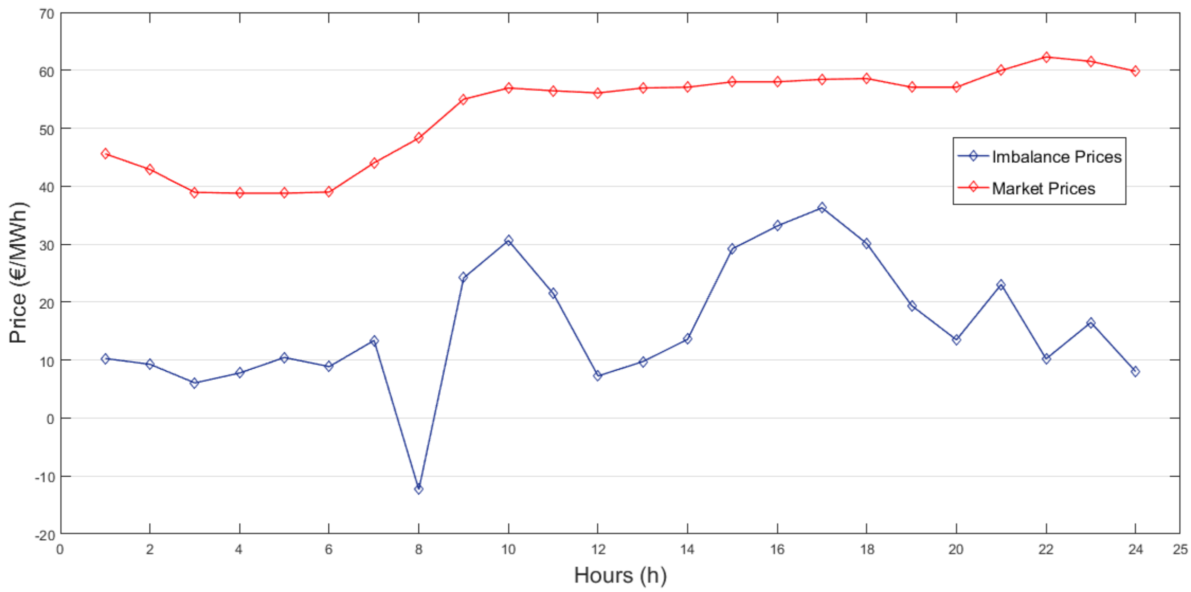

Figure 4.13 – Spot market prices and imbalance prices on 10th of May 2018

The ODS can be viewed in Figure 4.14 where, similarly to simulation 1, it is showed the wind power generated by the 4 wind turbines in conjunction with the power delivered to the grid and the DA contracted power. In the DA analysis of simulation 2 there was no hydro generation or pumping operation and it was mentioned the reason behind this situation. Nevertheless, in the ODS, this is no longer verified and the hydro turbine schedule has a total of 9 hours of operation. The power delivered to the grid still tends to follow the wind power produced in the majority of the hours, even when market prices are higher like in the DA simulation. Also, as expected, when the imbalance prices are high the power distributed to the grid tends to be equal to the power originally contracted. Hours 10, 16 and 17, where the imbalance prices are the highest during the day, highlight this point since wind power was below the forecasted value and, consequently, hydro generation was needed to minimize the deviations costs.

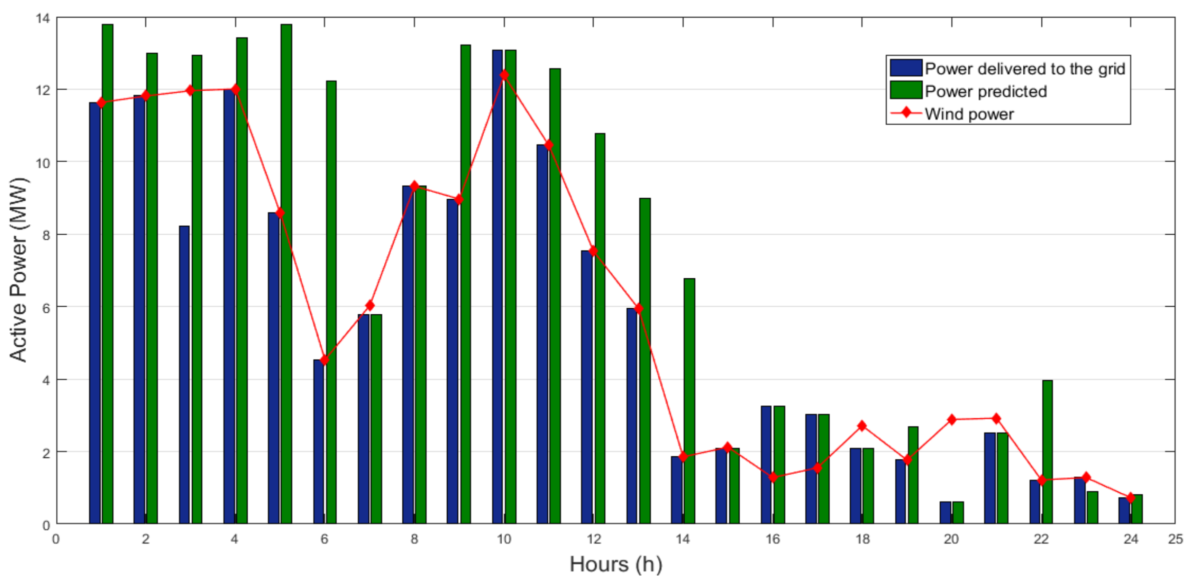

Figure 4.14- Wind power produced, power delivered to the grid during the ODS, along with the power bids placed in the DA market on the 10th of May 2018

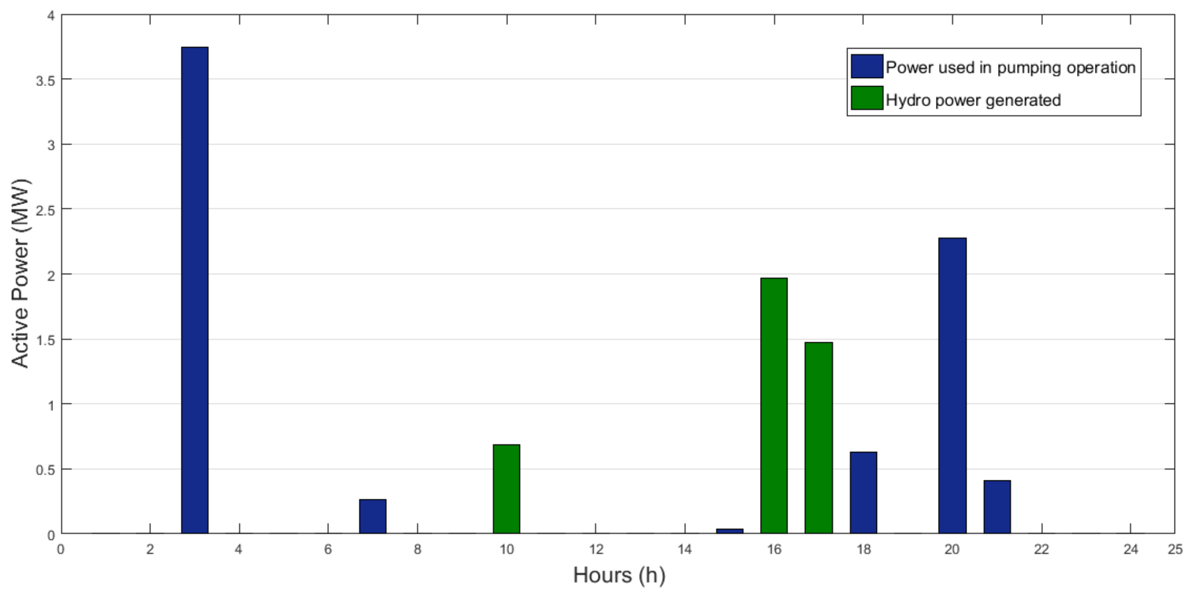

Figure 4.15 - Detailed view of the hydro turbine operation, including the hours and power used in the respective operation mode

The operation schedule followed by the hydro turbine is depicted in Figure 4.15 and it is possible to confirm the 3 hydro generation hours are, indeed, hours 10, 16 and 17. As for the evolution of the energy stored in the upper reservoir, it is presented in Figure 4.16. It is possible to view that the energy level is always close to the set initial value of 35 MWh, since small power amounts are being used in both the hydro generation and pumping operation. This is due to the fact that the hydro turbine is used for minimizing the deviation costs.

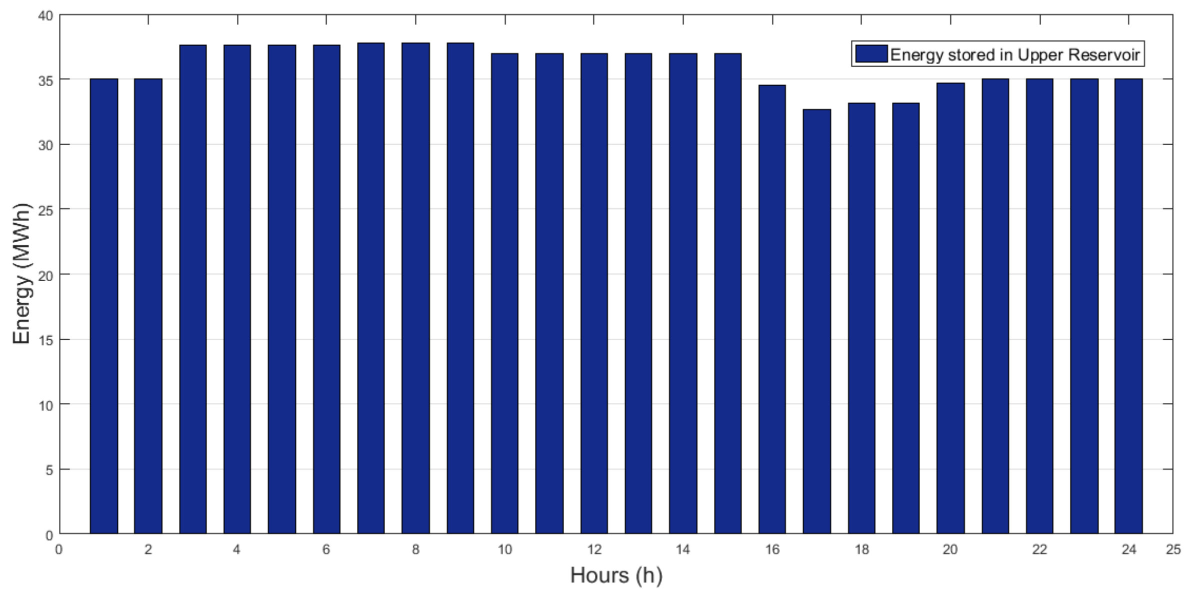

Figure 4.16 – Evolution of the energy stored in the upper reservoir during the operation day

4.1.3. Discussion

Looking at the objective function for the ODS defined by (3.20), in order to produce the highest possible profit the first term, which constitutes the power delivered to the grid, must be maximized and the fourth term, which constitutes the power imbalances, must be minimized. Thus, the ODS comprises the balance between the maximization of the first term and minimization of the fourth term.

The operational day 10th of April 2018, is studied in simulation 1 for both the DA problem and the ODS. The DA results constitute the typical wind-hydro operation where the pumping operation occurs in low market price points and hydro generation in high market price points. The same principle is followed in the ODS, where hydro generation and the pumping operation occur with the goal of increasing the power delivered to the grid in higher market price points, maximizing the profit. For this situation, one can say that the maximization of the first term is the predominant aspect for maximizing the profit of the installation and this maximization is conducted through the operation of the hydro turbine.

As for simulation 2, it studies the operational day 10th of May 2018 for both the DA problem and the ODS. However, due to the difference between maximum and minimum market prices forecasted, the DA plan only includes the wind power produced and no generation of pumping is performed using the hydro turbine. The principle behind the DA optimization is also followed in the ODS, where the power sent to the grid is, in most of the hours, equal to the power produced via the 4 wind turbines. It is to balance certain power deviations that the hydro turbine is used. Therefore, for this situation, one can conclude that the minimization of the fourth term is the predominant aspect while maximizing the profit of the wind-hydro park and this minimization is conducted through the operation of the hydro turbine.

For the two operational days considered, the profit estimated via the DA algorithm and the actual profit given by the ODS are presented in Table 4.1. The profits are showed for 3 distinct final energy values for the upper reservoir: 35 MWh, the value set in the previous simulations, 17.5 MWh and 52.5 MWh. The initial value remains 35 MWh.

On the 10th of April the DA estimation for the profit is inferior to the actual profit in the ODS and the opposite occurs for the 10th of May. This is caused by the deviations between the forecasted values and the real values. Also, the lower the final energy value the higher the profit in both the DA optimization and the ODS since a lower final energy value means a higher possibility for hydro generation.

Table 4.1 – Estimated profit for the day-ahead contracted power and installation's profit during the operational days, for different final reservoir energy values

			Profit [€]	
			10^{th} of April 2018	10^{th} of May 2018
Final Energy Stored in Upper Reservoir [MWh]	**17.5**	**DA**	11581	9348
		ODS	12562	7916
	35	**DA**	10831	8522
		ODS	11810	7033
	52.5	**DA**	10043	7503
		ODS	11059	6030

4.2. Constant Power Output

For the constant output power problem 48000 simulations were performed depending on the wind speed forecasted, target power value or initial water volume in the reservoirs. Thus, in order to have a better understanding of how each simulation works, the results for two simulations are going to be introduced primarily, before delving into the overall results.

4.2.1. Simulation Breakdown

The simulations examples that are going to be described are conducted for a constant target output power of 9 MW and for two different volumes of water stored in the upper reservoir: 80000 m^3, which account to 50% of the total volume, and 20000 m^3 that corresponds to 12.5% of the total volume. The goal is to highlight, for the same wind speed and target power, two different situations that may occur.

First, the wind speed forecast for a random day of the historical wind data needs to be elaborated. In Figure 4.17, a graph for the forecasted values that are going to be used during the two simulations are showed, as well as, for a reference stand point, the real wind speed values for that random day.

Following the wind speed forecasting, the wind power that the 4 wind turbines are able to generate given that wind speed is obtained through the application of equation (2.2). Thus, Figure 4.18 illustrates the total active power that the 4 wind turbines produce and the target power value.

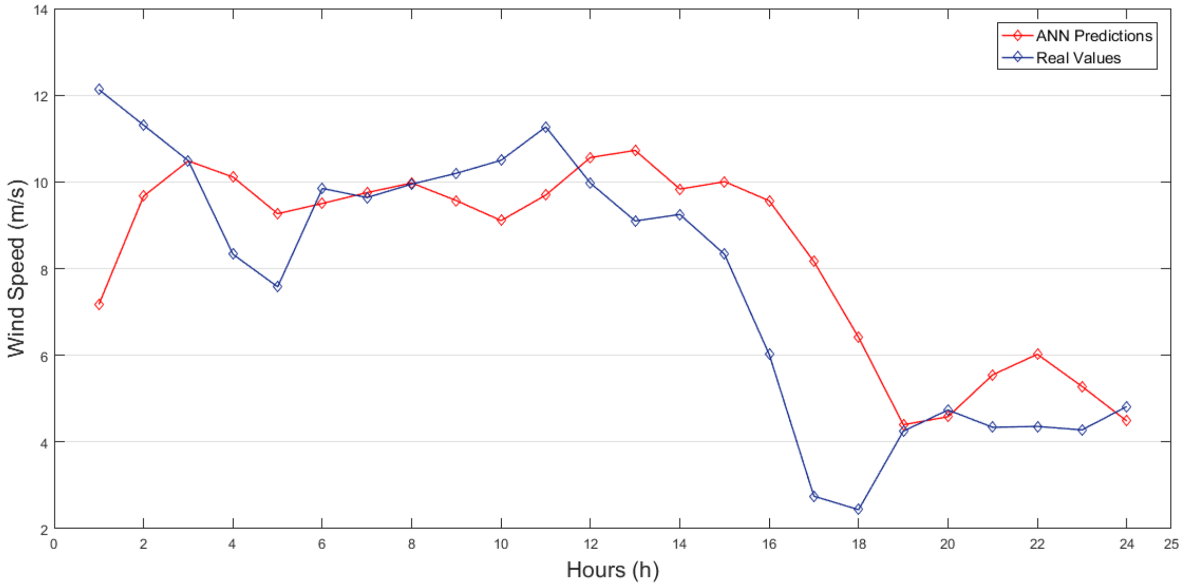

Figure 4.17 - Wind power forecasted for random day via the ANN approach and the real wind speed values for the respective day

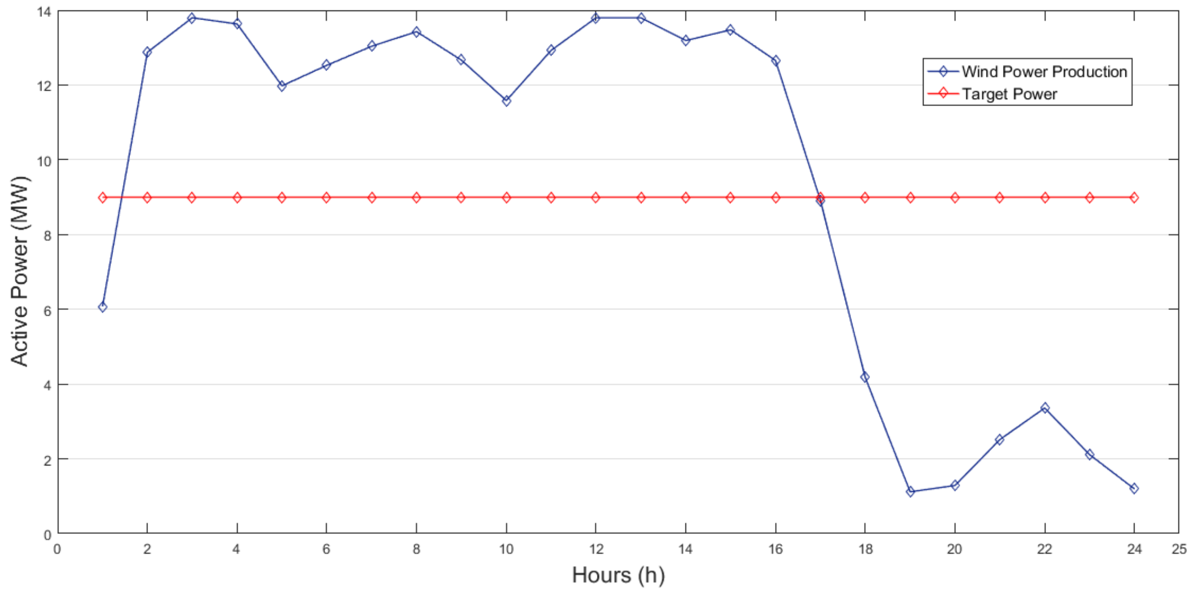

Figure 4.18 - Total active power generated by the 4 wind turbines plus the target power

It is possible to observe in Figure 4.18 that for 15 hours the total wind power produced is superior to the target power value and in the remaining 9 hours it is inferior. Hence, in this case, to maintain a firm output power there are going to be 15 hours of pumping operation and 9 hours of hydro generation. Figure 4.19 and Figure 4.20 depict, for a 50% and 12.5% initial volume of water respectively, the scheduling of the hydro turbine in order to maintain a firm output power, presenting for each hour the water flow used either in hydro production or the pumping operation.

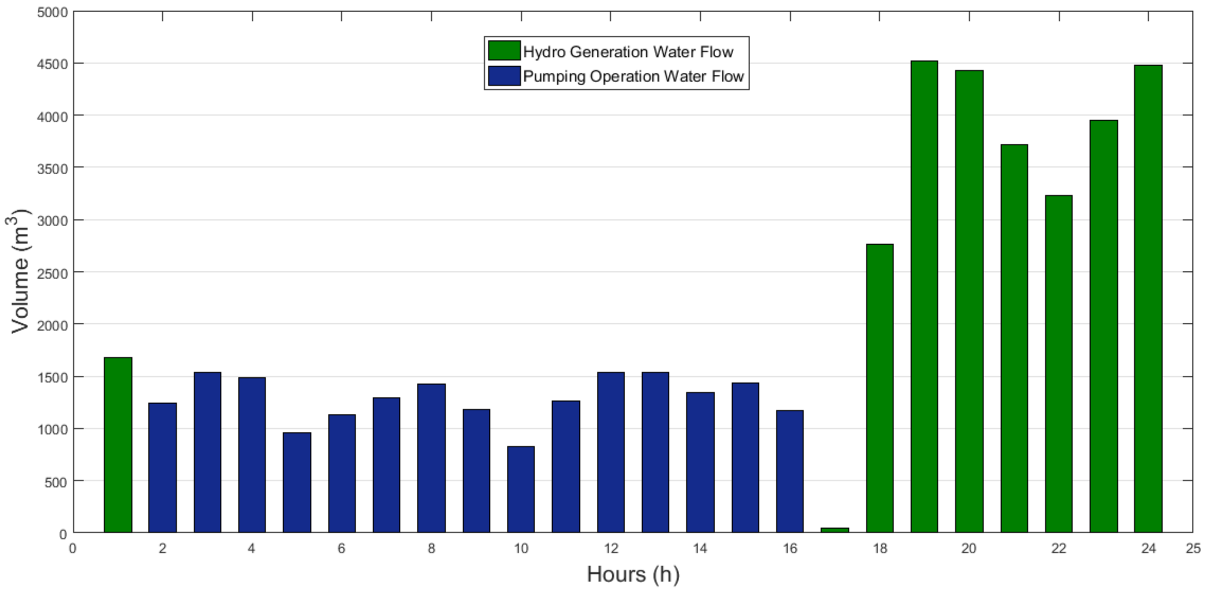

Figure 4.19 - Hydro scheduling for an initial water volume of 80000 m3

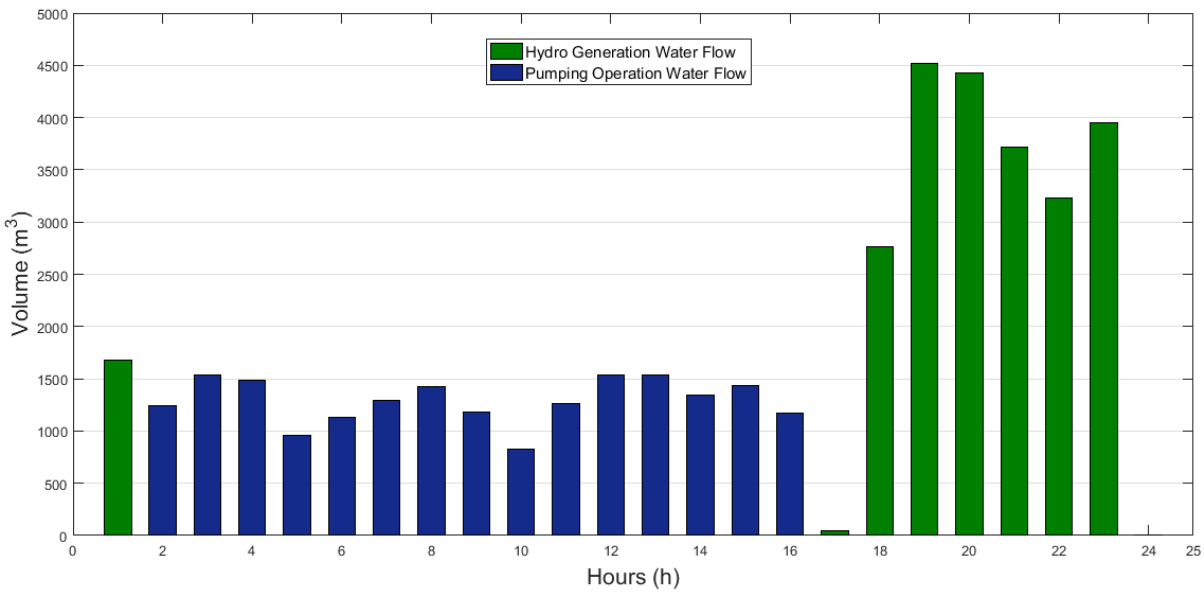

Figure 4.20 - Hydro scheduling for an initial water volume of 20000 m3

One can see, for the first case, the 15 pumping hours and 9 hours generation hours initially expected and, as a consequence, it was possible to maintain the target power. However, for the second case, it was not possible to generate the target power in the last hour of the day, hour 24, since the upper reservoir no longer had sufficient water to generate the target power. The evolution of the water volume in both the upper and lower reservoirs can be visualized, based on the water flow values for each hour, for both scenarios in Figure 4.21 and Figure 4.22. It is possible to observe that, in the second situation, in hour 23 the upper reservoir does not have water, therefore it is impossible to generate the remaining power in the following hour. The amount of water flow per hour is equal for both situations, thus the reservoir's water volume evolution is the same. Therefore, the difference between successfully maintaining a firm power in all 24 hours is highly contingent in the initial value for the water stored.

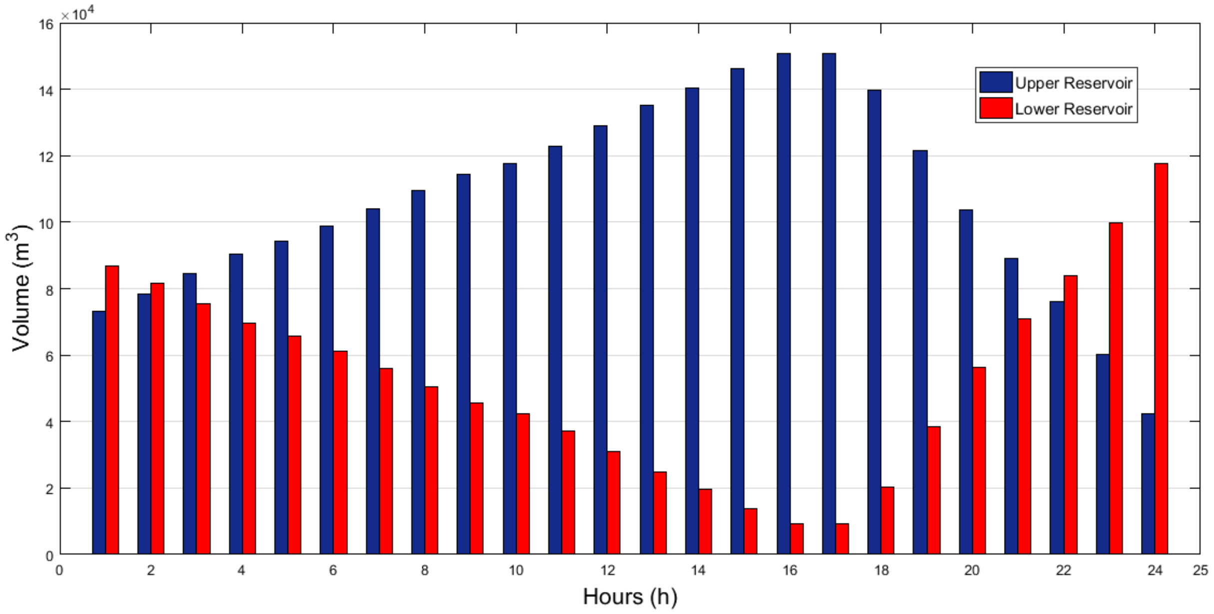

Figure 4.21 - Water volume evolution in the upper and lower reservoirs for an initial water volume of 80000 m3

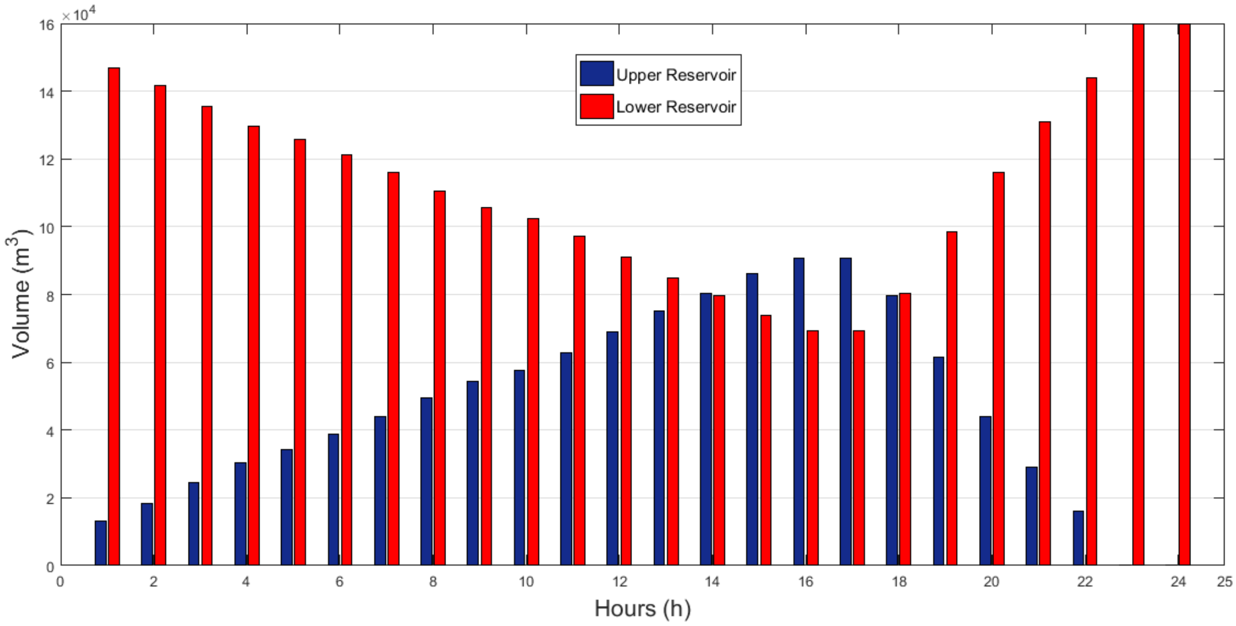

Figure 4.22 - Water volume evolution in the upper and lower reservoirs for an initial water volume of 20000 m3

4.2.2. Overall Results

After a better understanding of how the results for each simulation are obtained, the overall results for all the simulations elaborated is presented in Figure 4.23. One is able to see, for each initial water volume value, the probability of successfully maintaining a certain target output value. A probability of 100% means that the wind-hydro park can maintain a constant power output in all 500 wind speed scenarios generated and a probability of 0% means the opposite, that in the 500 wind speed scenarios is never possible to maintain a certain target power value. The probability values highlighted in Figure 4.23 are also showed in greater detail in Table 4.2.

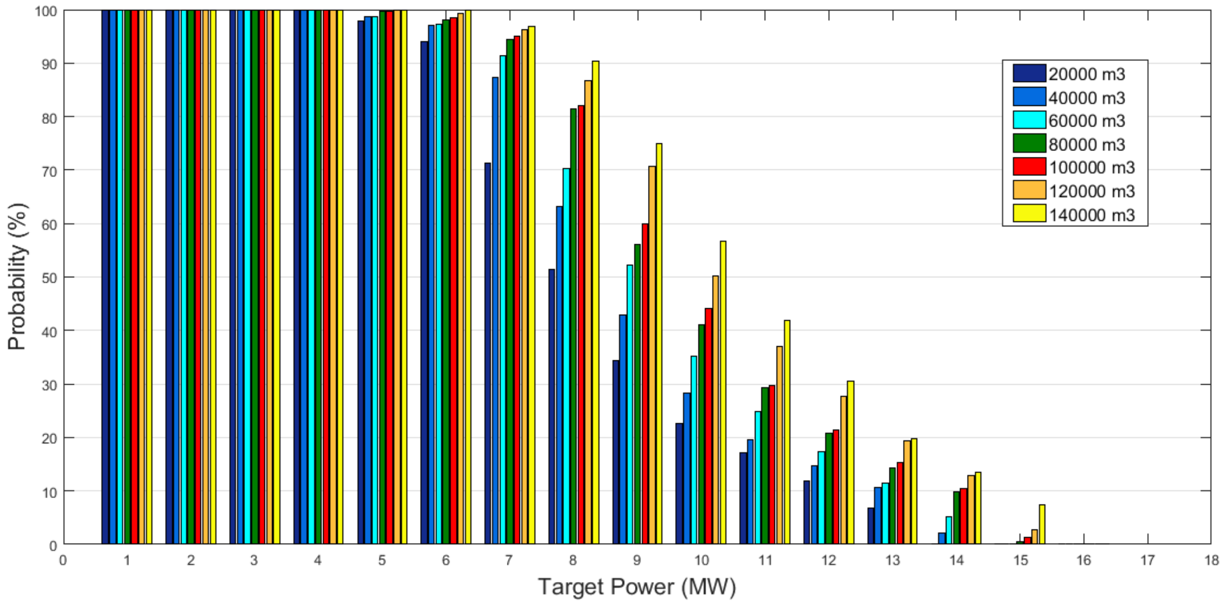

Figure 4.23 – Probability of maintaining a certain target power for different initial water volumes in upper reservoir

Table 4.2 – Detailed look of the probabilities depicted in Figure 4.23

		Target Power [MW]															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Initial Water Volume [m³]	**20000**	100	100	100	100	97.8	94	71.2	51.4	34.4	22.6	17.2	11.8	6.8	0.2	0	0
	40000	100	100	100	100	98.6	97	87.4	63.2	42.8	28.2	19.6	14.8	10,6	2.2	0	0
	60000	100	100	100	100	98.6	97.2	91.4	70.2	52.2	35.2	24.8	17.4	11.4	5.2	0	0
	80000	100	100	100	100	99.6	98	94.4	81.4	56	41	29.4	20.8	14.4	9.8	0.6	0
	100000	100	100	100	100	99.6	98.4	95	82	60	44.2	29.8	21.4	15.4	10.4	1.4	0
	120000	100	100	100	100	100	99.2	96.2	86.8	70.6	50.2	37	27.6	19.4	12.8	2.8	0
	140000	100	100	100	100	100	100	96.8	90.4	75	56.6	41.8	30.6	19.8	13.4	7.4	0

Seemingly, for a single initial water volume value, the higher the target power value the smaller the probability of success actually is. This is naturally expected, since the higher the target power value more generation hours are, most likely, required to maintain firm the output power, therefore a higher initial water volume is extremely beneficial. The same justification can be made concerning the situation of same target power value, where the highest probability of success is attained by the higher initial water volume.

Target power values close to the nominal power of the wind turbines (13.8 MW) have, as expected, a low probability of success since in most hours of the day hydro generation is necessary to produce the remaining power. Opposite to that, smaller constant power values possess a very high probability, in many cases 100%, since wind power is normally able to generate all the required power. However, the most notable aspect one can see is that the optimal range of constant power values is situated between 6 MW to 7 MW where a very high probability of success is achieved for almost every initial volume value, with the lowest being 71.2% chance of success. Thus, for the wind-hydro park in analysis, the optimal operation point is set between 6 MW and 7 MW, which is approximately half of the nominal wind power value.

The ability of the wind-hydro park to output a certain target power with high degree of probability would also eliminate imbalance costs in a market operation since it would be highly likely that the contracted power for the day-ahead market would be equal to the power produced in the operational day. Thus, a hypothetical simulation of the profits of the installation is elaborated, considering the contracted power in the DA market to be a constant target value between the optimal operation point. Table 4.3 depicts the value of the profits obtained for same operational days considered in the maximization of the profit problem.

Table 4.3 – Estimation of the installation's profit in the 10th of April 2018 and the 10th of May 2018

		Profit [€]	
		10th of April 2018	10th of May 2018
Constant Target Power [MW]	6	6396	7595
	6.5	6929	8228
	7	7462	8861

5. Conclusion

This last chapter is divided into two major sections. The first includes the important conclusions that were drawn from the results described in Chapter 5 and the second proposes some work to be performed in the future with the goal of improving the present dissertation.

5.1. Reflections

The goal behind this dissertation was to study, in Portugal, the optimization of a wind farm combined with a pump-hydro-storage power plant. The thesis was ultimately divided into the optimization of the market operation of the wind-hydro park, attempting to maximize the profit of the installation during an operational day and a study regarding the feasibility of delivering to the grid a constant target value for every day in a year.

Concerning the market maximization, a review of the literature suggested that the day-ahead strategy would follow a typical operation, in other words, energy would be saved during low spot market prices in order to increase the energy bids during high spot market prices. However, with the hypothetical implementation of the case-study in the Portuguese power system and, consequently the use of MIBEL market prices, one can draw the conclusion that the typical strategy for the day-ahead optimization comprises a small fraction of the operational days, around 10% with the historical market prices used in this dissertation. For the majority of the operational days, the remaining 90%, the day-ahead strategy would only be comprised of the wind power that is being produced in each hour, with no hydro generation or pumping operation. Nonetheless, it is important to reaffirm that this conclusion is drawn from MIBEL's spot market prices ranging from the 10th of May 2017 to the 10th of May 2018, where the difference between the minimum and maximum prices was not particularly high.

Primarily, it was expected that the key input data that would eventually shape the day-ahead strategy would be the wind speed forecasted and the initial water stored in the reservoirs. Nevertheless, spot market prices revealed to be a key contributor to the overall end result and shape of the simulations conducted.

As for the operational day strategy results, despite inherent imbalances between the wind speed and market prices forecasted and the real values for these two variables in the operational day, the maximization of the profit is performed in two distinct ways. The first, for the smaller fraction of operational days, consists in increasing the power output through hydro generation in hours with high market prices. The second, for the remaining 90% of operational days, consists in minimizing the deviations costs through the operation of the hydro turbine. Therefore, the primary goal for combining wind power with hydropower technology is, indeed, related to the minimization of the power imbalances that arise from the great unpredictability and variability of wind power. Again, this conclusion is drawn out from MIBEL's spot market prices ranging from the 10th of May 2017 to the 10th of May 2018.

With respect to the possibility of the wind-hydro park outputting a constant power, the aim was to primarily study the mitigation of stability problems that may occur in the electrical grid from the high variability of wind power. The probability of delivering a certain target output value was obtained in the results and it was concluded that, for the majority of operational days, the optimal output power would be between 6 MW to 7 MW. Also, the initial volume of water in the upper reservoir was a key feature and higher values for this variable translated into a considerably increase in the probability of a certain target power value.

An extrapolation of the revenue the two operation methodologies might have during an operational day was also elaborated. By performing a comparison between the tables that translate the profits of the park for the two distinct problems, it is possible to notice that for the 10^{th} of May the values are pretty comparable and similar with one another. Albeit, decreasing even more the final energy stored in the reservoir would signify a small advantage towards the maximization of profit algorithm. The biggest difference is related to the operational day of 10^{th} of April where the maximization of profit algorithm translates to a significant higher profit in relation to a constant power output in the optimal range. Even so, one can conclude that a constant power output operation not only improves the stability of the electrical grid, but it is also a highly profitable option when operating small scale wind-hydro parks.

5.2. Future work

The work elaborated in this dissertation has possibilities to be expanded upon and improved. With that goal in mind, a few guidelines for future work are listed:

- The use of a strategy to minimize the power imbalances costs during the operational day is not a topic highly discussed in the literature, with room to evolve. In this present work, it was assumed that positive and negative imbalance costs were equal, however that is not the case in the ID market. The consideration of both positive and negative imbalance costs would cause modifications in the objective function. The inclusion of forecasted imbalance prices in the day-ahead optimization would also be an interesting topic of research, expanding the algorithm already in place.
- The simulations for the profit maximization were performed for a single day, ignoring the previous and following operational days. A monthly optimization, for instance, would make the setting of initial and final stored energy values in the reservoir a key characteristic in the optimization process. Moreover, it would result in a more accurate understanding of the combining operation between wind and hydro power.
- Expanding the spot market prices historical data to include previous values of what was considered in this study would ensure a broader scope for some of the conclusions drawn out from the profit's maximization problem.
- The 500 wind speed predictions generated using the ANN approach translate to a reasonable conclusion into a yearly operation. However, expanding this number of predictions for different

historical wind speed data would increase the accuracy of the results obtained for the constant power output problem.

- In this dissertation, the case-study can be viewed as a closed system regarding the water volume, in other words, the water volume in the system is always equal to 160000 m^3, which also translates to 70 MWh. Thus, no hydrological data was considered while developing this study. However, most wind-hydro systems do not possess this feature since PHS plants are normally built in estuary of rivers. Conducting a similar study, by changing the case-study to a more standard system, including hydrological data would signify an alteration of the algorithms used, but could lead to more correct conclusions.

6. References

[1] Eurpean Comission, "Energy 2020 - A strategy for competitive, sustainable and secure energy," 2011.

[2] European Environment Agency, "Greenhouse gas emissions drop slightly in 2016," 7 November 2017. [Online]. Available: https://www.eea.europa.eu/highlights/greenhouse-gas-emissions-across-eu. [Accessed 10 May 2018].

[3] B. Plumer, "Greenhouse Gas emissions Rose Last Year. Here Are the Top 5 Reasons," New York Times, 22 March 2018. [Online]. Available: https://www.nytimes.com/2018/03/22/climate/global-energy-demand.html. [Accessed 26 April 2018].

[4] European Comission, "2030 Energy Strategy," [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy. [Accessed 26 April 2018].

[5] European Comission, "2050 Energy Strategy," [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy. [Accessed 26 April 2018].

[6] F. Harvey, "China aims to drastically cut greenhouse gas emissions through trading scheme," The Guardian , 19 December 2017. [Online]. Available: https://www.theguardian.com/environment/2017/dec/19/china-aims-to-drastically-cut-greenhouse-gas-emissions-through-trading-scheme. [Accessed 27 April 2018].

[7] REN21, "Renewables 2018 Global Status Report," REN21 Secretariat, ISBN 978-3-9818911-3-3, Paris, 2018.

[8] Wind Europe, "Wind in power 2017 Annual combined onshore and offshore wind energy statistics," 2018.

[9] European Comission, "Energy storage - the role of electricity," 2017.

[10] T. Grumet, "This Unique Combo Of Wind And Hydro Power Could Revolutionize Renewable Energy," General Electric, 16 October 2016. [Online]. Available: https://www.ge.com/reports/unique-combo-wind-hydro-power-revolutionize-renewable-energy/. [Accessed 27 April 2018].

[11] C. Morris, "Germany lifts 2030 renewable energy target to 65%," Renew Economy, 18 January 2018. [Online]. Available: https://reneweconomy.com.au/germany-lifts-2030-renewable-energy-target-65-12576/. [Accessed 27 April 2018].

[12] Á. J. Duque, E. D. Castronuovo, I. Sánchez and J. Usaola, "Optimal operation of a pumped-storage hydro plant that compensates the imbalances of a wind power producer," Electric Power Systems Research, 81(9):1767–1777, 2011.

[13] E. D. Castronuovo and J. A. P. Lopes, "Optimal operation and hydro storage sizing of a wind-hydro power plant," International Journal of Electrical Power & Energy, 26(10):771–778, 2004.

[14] P.Cruz, H. Pousinho, R. Melício and V. Mendes, "Optimal Operation Planning of Wind-Hydro Power Systems Using a MILP Approach," 5th Doctoral Conference on Computing, Electrical and Industrial, pp.277-286, 2014.

[15] E. Castronuovo and J. P. Lopes, "On the Optimization of the Daily Operation of a Wind-Hydro Power Plant," IEEE Transactions on Power Systems, 19(3):1599–1606, 2004.

[16] E. Castronuovo, J. Usaola, R. Bessa, M. Matos, I. Costa, L. Bremermann, J. Lugaro and G. Kariniotakis, "An Integrated Approach for Optimal Coordination of Wind Power and Hydro Pumping Storage," Wind Energy, 2013.

[17] H. Pousinho, V. Mendes and J. Catalão, "Linear Programming Applied for the Optimization of Hydro and Wind Resources," Nova Science Publishers, Inc., pp.352-272, 2012.

[18] R. Bessa, I. Costa, L. Bremermann and M. Matos, "Operational Strategies for the Optimized Coordination of Wind Farms and Hydro-Pump Units," 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion, 2012.

[19] P. Mendes, R. Castro and J. F. d. Jesus, "Wind Parks – Hydro Pumping Coordinated Operation: Application to the Portuguese System," IST/TUL, 2010.

[20] S. V. Papaefthymiou, E. G. Karamanou, S. A. Papathanassiou and M. P. Papadopoulos, "A Wind-Hydro-Pumped Storage Station Leading to High RES Penetration in the Autonomous Island System of Ikaria," IEEE Transactions on sustainable energy, vol. 1, no. 3, 2010.

[21] REN21, "Renewables 2017 Global Status Report," REN21 Secretariat,ISBN 978-3-9818107-6-9, Paris, 2017.

[22] Direção Geral de Energia e Geologia, "Renováveis estatísticas rápidas - nº 161 - março de 2018," 2018.

[23] Global Wind Atlas, "Global Wind Atlas," Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, [Online]. Available: https://globalwindatlas.info/downloads/World. [Accessed 17 August 2018].

[24] P. Costa, P. Miranda and A. Estanqueiro, "Development and Validation of the Portuguese Wind Atlas," INETI and CGUL, 2006.

[25] R. Castro, Uma Introdução às Energias Renováveis: Eólica, Fotovoltaica e Mini-Hídrica, IIST Press, 2012.

[26] Mathworks, "Shallow Neural Network Time-Series Prediction and Modeling," [Online]. Available: https://www.mathworks.com/help/nnet/gs/neural-network-time-series-prediction-and-modeling.html. [Accessed 18 August 2018].

[27] Vestas Wind Systems A/S, "V90-3.0 MW Catalogue," 2013.

[28] wind-turbine-models.com, "Vestas V126-3.45," [Online]. Available: https://en.wind-turbine-models.com/turbines/1249-vestas-v126-3.45. [Accessed 3 March 2018].

[29] C. Corchero and F.-J. Merida, "Optimal Day-Ahead Bidding in MIBEL's Multimarket Energy Production System," 7th International Conference on the European Energy Market, pages 1-6, 2010.

[30] Max Bögl, "Gaildorf pioneers electricity storage," [Online]. Available: https://www.mbrenewables.com/pilot-project/. [Accessed 25 Febuary 2018].

[31] Operador del Mercado Iberico de Energia, "Dados do Mercado - Preços e Volumes," [Online]. Available: http://www.datosdelmercado.omie.es/pt-pt/datos-mercado. [Accessed 10 May 2018].

[32] REN - Sistemas de Informação de Mercados de Energia, "Cost of Imbalances," [Online]. Available: http://www.mercado.ren.pt/EN/Electr/MarketInfo/MarketResults/Imbalances/Pages/Costs.aspx.. [Accessed 23 July 2018].

[33] Mathworks, "linprog," [Online]. Available: https://www.mathworks.com/help/optim/ug/linprog.html. [Accessed 14 May 2018].