Wind-Hydro Hybrid Park

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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 possess, 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**

I. INTRODUCTION

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 completely 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.

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.

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.

Several studies regarding wind-hydro coordination have been performed, especially in the past decade. Regarding the optimization of the market operation, the studies between the coupling of wind power plants and pump-hydro-storage plants can be divided in two parts: Day-ahead optimization and Operational strategy. *Duque et al.* [1] proposes an optimized operation with the goal of reducing imbalance costs. The results concluded that the operation would be profitable for the wind farm and the PHS plant. In *Castronuovo and Peças* [2], 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%. In the work of *P. Cruz et al.* [3], a Mixed Integer Linear Programming (MILP) algorithm is proposed to optimize the day-ahead planning of an installation with hourly discretization. A stochastic model is proposed by *Castronuovo and Peças* [4] 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. In *Castronuovo et al.* [5] 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. *Pousinho et al.* [6] 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. *Bessa et al.* [7] 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.

A few other studies focus on the coordination between wind and hydro power with the goal of maintaining the balance between generation and demand. *Pedro Mendes et al.* [8], 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. In *Papaefthymiou et al.* [9] it is discussed the operation of a Hybrid Power Station in the island of Ikaria, Greece. 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.

The present study 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, the study is divided in two major problems:

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

This document is divided in 5 sections. The first provides the scope and motivations for the research elaborated, along with a literature review. The second describes key characteristics for this study of wind power, hydro power and Iberian Electricity Market. In the third the case-study is introduced and the algorithms for the day-ahead optimization, operational strategy and the constant target output problem are presented. The fourth includes the results obtained for both problems and the fifth the major conclusions drawn from the study.

II.THEORETICAL BACKGROUND

A. WIND FORECAST

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. Wind forecasting is essentially divided into two major categories: a physical approach and a statistical approach. In this study, the focus will be on the statistical methods only, in particular on an artificial neural networks (ANN) approach.

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 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.

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). A NAR network is able to predict the future values of a time series from that series past values.

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.

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

1. When the wind speed 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 [10] 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 and is described by equation (2.1).

$$P_{Wind}(u) = \begin{cases} 0, & \mathrm{u} < 3 \\ a \times \exp\left[-\left(\dfrac{u-b}{c} \right)^2 \right], & 3 \le u < 10.2 \\ 3.45, & 10.2 \le u < 22.5 \\ 0, & \mathrm{u} > 22.5 \end{cases} \quad [MW] \tag{2.1}$$

$$\text{with} \quad a = 3.569 \quad b = 11 \quad c = 4.137$$

Where: $\mathrm{P_{wind}}$ is the output power of the wind turbine; uu is the wind speed in m/s;

C. 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. As the water falls down the waterways from the upper reservoir, the potential energy is converted in 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. 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}. The estimated output power of an hydropower plant, P, can be described by equation (2.2). For this equation, the water density was multiplied by the acceleration due to the gravitational force to get the water specific weight equal to 9.810. Variable Q is the water volume per second, the so-called water flow.

$$P = 9.810 \times Q \times H \times \eta_{gen} \; [W] \tag{2.2}$$

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 (2.3). For this scenario, the efficiency, η_{pump}, represents losses in the hydraulic circuit, drive pumps and electric motor.

$$P = \frac{9.810 \times Q \times H}{\eta_{pump}} \; [W] \tag{2.3}$$

D. 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 and the spot market. For the purposes of this study, the focus will be on the spot market, which is comprised of the day-ahead market (DA) and the intraday market (ID).

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. Agents with generation units submit selling bids and agents with load units submit buying bids.

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.

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 network approach was proposed for the wind speed forecasting issue, as explained before. 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.

III. WIND-HYDRO COORDINATION

A. CASE-STUDY

The case-study that was considered is based on a pilot project currently being developed in Germany [11].

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. The total storage capacity of the four upper reservoirs is 160000 $\mathrm{m^3}$ or 70 MWh, with each individual reservoir having a storage capacity of 40000 $\mathrm{m^3}$ or 17.5 MWh. The lower reservoir has a total storage capacity of 160000 $\mathrm{m^3}$ 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 $\mathrm{m^3}$.

Three historical data are used as inputs for the two problems 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) [12]. The imbalance prices were attained from REN (Redes Energéticas Nacionais) [13].

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:

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.
7. The market price for positive and negative imbalances is equal.
8. The system's total water volume remains equal to 160000 m^3 and hydrological data is disregarded.
9. As mentioned in section 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.
10. Internal operational costs regarding hydro generation and the pumping operation were considered, based on values from *Castronuovo and Peças* [4]. For the hydro generation the cost is 1 €/MWh and for the pumping operation 1.5 €/MWh.

B. 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.

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):

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

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

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

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

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

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

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

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

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

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

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

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

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.

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 (3.13) to (3.24):

$$Max \sum_{i=1}^{24} \left[P_{Gi\_real}.p_{i\_real} - c_{hydro}.P_{Hi\_real} - c_{pump}.P_{WPi\_real} - dev_i.\left| P_{Gi} - P_{Gi\_real} \right| \right] \quad (3.13)$$

$$\text{subject to } P_{Gi\_real} = P_{WGi\_real} + P_{Hi\_real} \quad (3.14)$$

$$P_G^{\min} \le P_{Gi\_real} \le P_G^{\max} \quad (3.15)$$

$$P_{Wi\_real} = P_{WGi\_real} + P_{WPi\_real} \quad (3.16)$$

$$P_W^{\min} \le P_{Wi\_real} \le P_W^{\max} \quad (3.17)$$

$$P_{WP}^{\min} \le P_{WPi\_real} \le P_{WP}^{\max} \quad (3.18)$$

$$E_{i\_real} = E_{i-1\_real} + \eta_{pump}.P_{WPi\_real} - \frac{P_{Hi\_real}}{\eta_{hydro}} \quad (3.19)$$

$$E_{\min} \le E_{i\_real} \le E^{\max} \quad (3.20)$$

$$E_{1\_real} = E_{initial} \quad (3.21)$$

$$E_{24\_real} \ge E_{final} \quad (3.22)$$

$$P_H^{\min} \le P_{Hi\_real} \le P_H^{\max} \quad (3.23)$$

$$P_{Hi\_real} \le \eta_{hydro}.\left[E_{i\_real} + \eta_{pump}.P_{WPi\_real} \right] \quad (3.24)$$

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 (3.13) 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 (3.14) to (3.24) are similar to the problem constraints defined for the DA optimization in equations (3.2) to (3.12).

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.

Thus, applying a linearization to the problem in question, the objective function in (3.13) is reformulated and stated by (3.25) to (3.28).

$$Max \sum_{i=1}^{24} \left[P_{Gi\_real}.p_{i\_real} - c_{hydro}.P_{Hi\_real} - c_{pump}.P_{WPi\_real} - dev_i.(P_i^+ + P_i^-) \right] \quad (3.25)$$

$$\text{subject to } P_{Gi\_real} - P_{Gi} - P_i^+ - P_i^- = 0 \quad (3.26)$$

$$0 \le P_i^+ \le P_{\max}^+ \quad (3.27)$$

$$0 \le P_i^- \le P_{\max}^- \quad (3.28)$$

The constraints (3.26) to (3.28) are added and the ones expressed by (3.14) to (3.24) remain the same.

C. CONSTANT OUTPUT POWER

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.

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 predefined 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.

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 and this is mathematically expressed in (3.29):

$$P_{Demand} = P_{Wi} + P_{Hi} \rightarrow P_{Hi} = P_{Demand} - P_{Wi} \qquad (3.29)$$

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 (3.30) to (3.32).

$$Q_i^{gen} = \frac{P_{Hi} \times 1000 \times 3600}{9.810 \times H \times \eta_{gen}} \; [m^3/h] \qquad (3.30)$$

$$R_i^{upper} = R_{i-1}^{upper} - Q_i^{gen} \; [m^3] \qquad (3.31)$$

$$R_i^{lower} = R_{i-1}^{lower} + Q_i^{gen} \; [m^3] \qquad (3.32)$$

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 (3.33) to (3.35).

$$Q_i^{pump} = \frac{|P_{Hi}| \times 1000 \times 3600 \times \eta_{pump}}{9.810 \times H} \; [m^3/h] \qquad (3.33)$$

$$R_i^{upper} = R_{i-1}^{upper} + Q_i^{pump} \; [m^3] \qquad (3.34)$$

$$R_i^{lower} = R_{i-1}^{lower} - Q_i^{pump} \; [m^3] \qquad (3.35)$$

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 (3.36) to (3.39).

$$R_{\min}^{upper} \leq R_i^{upper} \leq R_{\max}^{upper} \; [m^3] \qquad (3.36)$$

$$R_{\min}^{lower} \leq R_i^{lower} \leq R_{\max}^{lower} \; [m^3] \qquad (3.37)$$

$$P_W^{\min} \leq P_{Wi} \leq P_W^{\max} \; [MW] \qquad (3.38)$$

$$P_H^{\min} \leq P_{Hi} \leq P_H^{\max} \; [MW] \qquad (3.39)$$

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 20.000 m^3 stored in the upper reservoir to 140.000 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 accounts for a total of 48000 simulations elaborated.

IV. RESULTS

A. 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 a great deal the operation of the wind-hydro park. 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.

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. 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.

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 1, where the power to be delivered to the grid, in each hour, by the wind-hydro park is represented, in addition to the forecasted wind power produced via the 4 wind turbines and the spot market prices. 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.

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. 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 2, where it is shown the wind power produced, the power that is distributed to the grid, the contracted power obtained from the DA plan, along with the real spot market prices and imbalance prices in that day. 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.

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. 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.

For simulation 2, the DA wind-hydro optimization plan is showed in Figure 3, where it is possible to see the power to be delivered to the grid in each hour of the operational day, along with the forecasted wind power and spot market prices. By examining Figure 3, 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.

Similarly to simulation 1, with the DA strategy for the 10th of May 2018, the ODS can be obtained. The highest imbalance costs are close or above the 30 €/MWh margin and the lowest imbalance cost is approximately -12 €/MWh in hour 8.

The ODS can be viewed in Figure 4 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, the DA contracted power and the spot market and imbalance prices for that day. 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 imba-

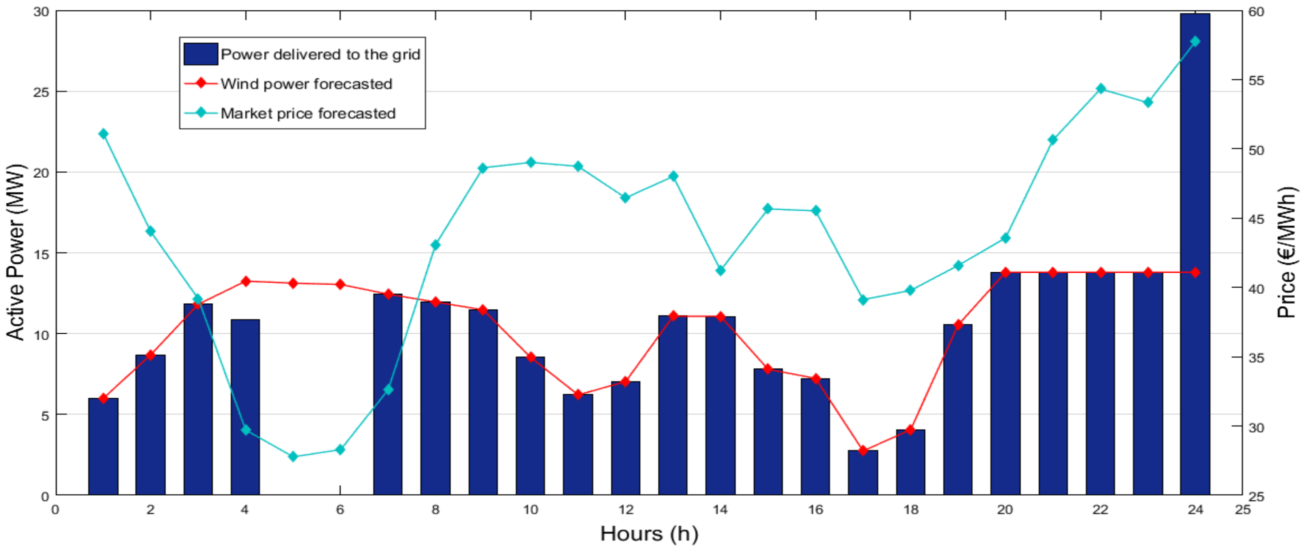

Figure 1 - Power bids to be placed in the day-ahead market accompanied by the wind power produced by the 4 wind turbines and forecasted market prices on the 10th of April 2018

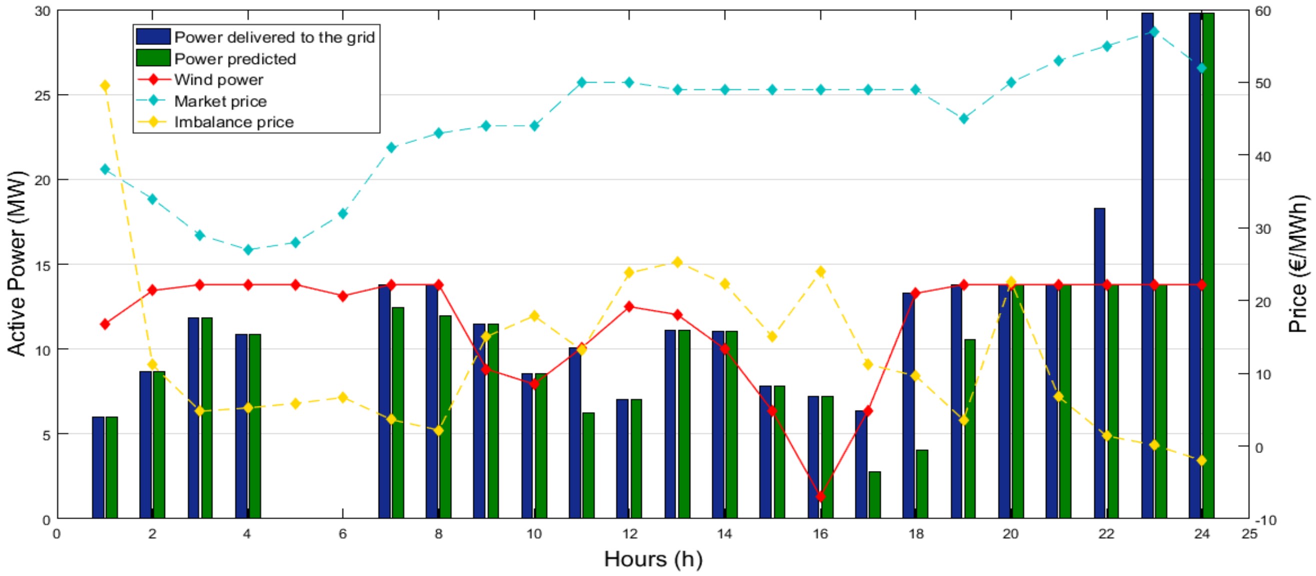

Figure 2 - Wind power produced, power delivered to the grid during the ODS, power bids placed in the DA market, along with the spot market and imbalance prices on the 10th of April 2018

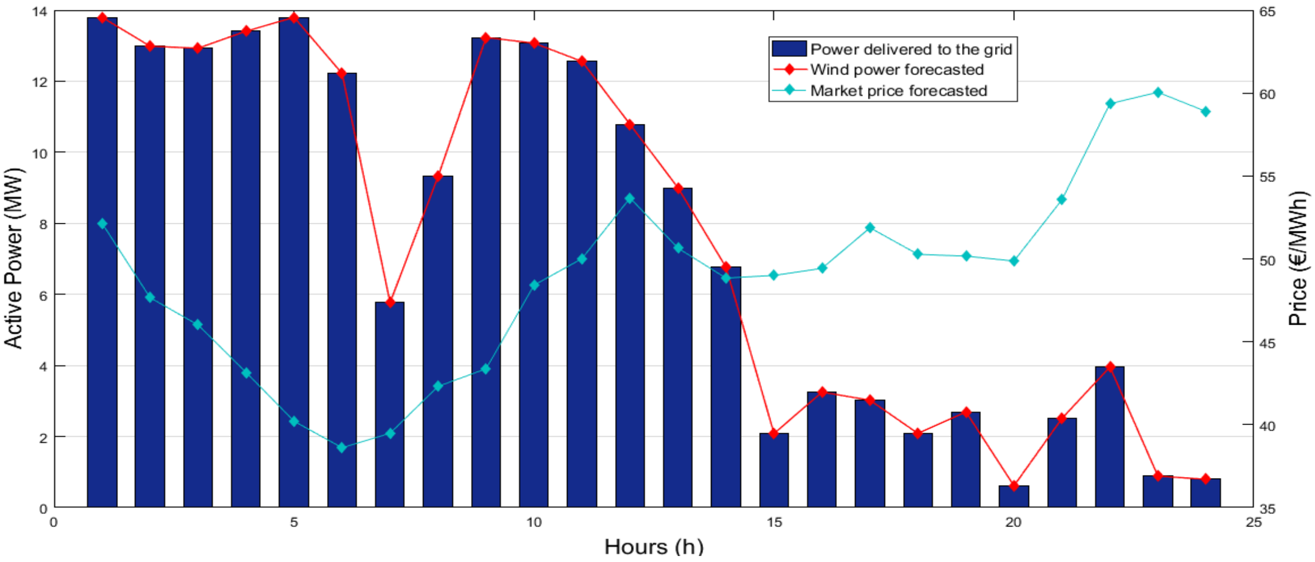

Figure 3 - Power bids to be placed in the day-ahead market accompanied by the wind power produced by the 4 wind turbines and forecasted market prices on the 10th of May 2018

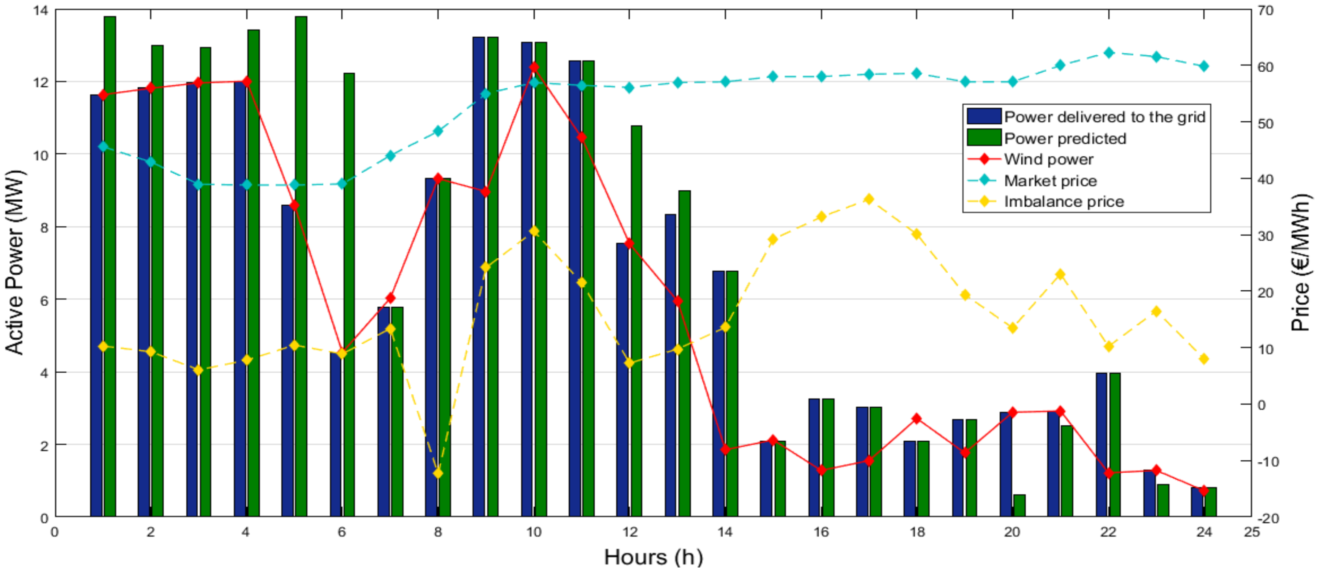

Figure 4 - Wind power produced, power delivered to the grid during the ODS, power bids placed in the DA market, along with the spot market and imbalance prices on the 10th of May 2018

lance 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.

B. 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. the overall results for all the simulations elaborated is presented in Figure 5. 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.

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.

V. Conclusions

The study 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,

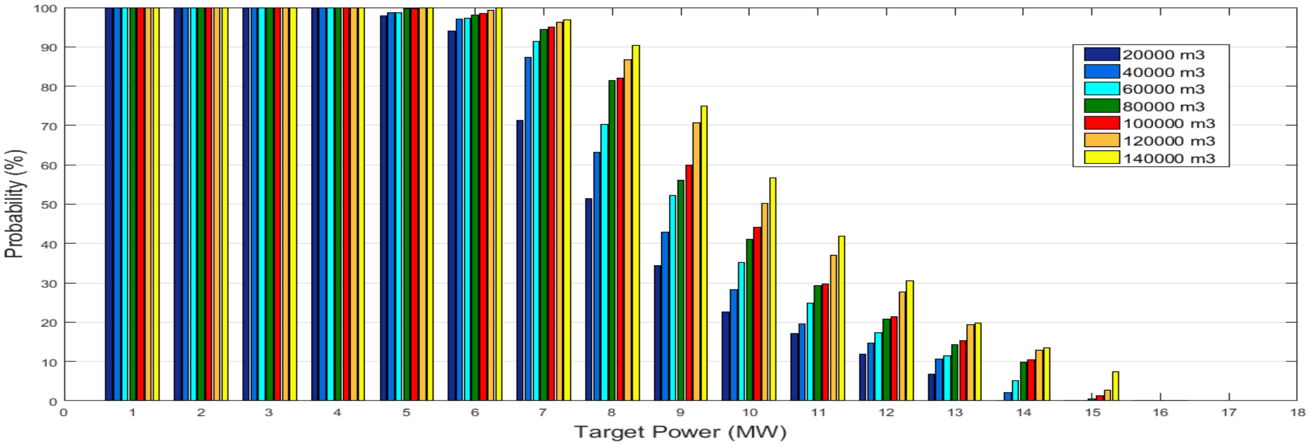

Figure 5 - Probability of maintaining a certain target power for different initial water volumes in upper reservoir

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 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.

REFERENCES

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

[2] 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.

[3] 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, 2004

[4] 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.

[5] 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

[6] 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.

[7] 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.

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

[9] 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.

[10] 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].

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

[12] 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].

[13] 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].