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Abstract. This paper addresses an approach for a day-ahead operation of a wind-hydro power system in an electricity market. A wind-hydro system is able to mitigate the intermittence and the variations on wind power, mitigating the economic penalty due to unbalance in the satisfaction of the compromises. The approach consists in a model given by a mixed-integer linear programming. This model maximizes the profit in the day-ahead market, taking into consideration the operating constraints of both the wind the farm and the pumping-hydro system. Finally, numerical case studies illustrate the interest and effectiveness of the proposed approach.

Keywords: Collective awareness, day-ahead market; wind-hydro power system; optimal operation.

1 Introduction

New operational challenges have come into view in power system due to large-scale integration of renewable energy. In particular, high levels of wind integration have strongly conditioned the power system operating security and stability due to the inherent intermittence and variability on wind power [1], implying that wind power dispatchability is a challenging task, namely when the control and management of the active power output is required [2]. Management of the system requires the use of wind power forecasting methods in order to mitigate the impact of wind power variability. But forecasting methods are not able to provide enough accuracy results for wind power. Hence, in order to accommodate the absence of the enough accuracy, uncertainty on the wind power forecast should be included on the approach for optimal operational planning. Otherwise, for a wind power producer that acts in the day-ahead market the disregarding of uncertainty can lead to monetary penalties due to a significative deviation from offers [3]. An effective way to minimize the deviation losses is to combine a wind farm with conventional generating units. Examples of such combinations can be found in [2], [3] and [4]. In [3], a comprehensive study about the economic benefits of a wind farm with pumped-hydro system is analyzed in an electricity market environment. In [5], the effect of wind power with varying degrees of integration is examined in order to determine the costs and carbon emissions associated with a hydro-dominated with gas unit's power system.

In this paper, the main contribution is to provide an effective approach based on mixed-integer linear programming (MILP) to find the optimal planning for the operation of a single entity having to manage a wind farm and a pumped-hydro system, so as to maximize the profit in the day-ahead market.

2 Relationship to Collective Awareness Systems

The technological evolution on electric power system encouraged by the expansion of distributed generation has been crucial to create collective awareness systems useful to define new energy consumption and production patterns. A collective awareness system can result from the development of powerful optimization approaches for the management of power systems, helping to make decisions. The collective awareness system not only promotes the sustainable use of energy resources in favor of an effective low-carbon economy [6], but also processes the optimal decision. In order to achieve this optimal decision, besides real-time information on data, such as, the electricity prices and wind power, collective tools are essential to allow maximizing the profit. Hence, research on technological innovation for collective tools based on approaches for solving the day-ahead operation planning of a power producer is crucial to achieve guidelines for the best bidding in an electricity market.

3 State of the Art

The increased wind power integration in power system has drawn attention to large-scale energy storage techniques. In the technical literature, multiple storage technologies and optimization approaches have been analyzed from several perspectives. In [5] and [7], the impact of the intermittence and variability of wind power generation from an operation and economic perspective has been addressed respectively by a discrete dynamic quadratic program with linear constraints and by using the EnergyPLAN computer model. In order to accommodate excessive wind power generation, batteries energy storage [8] and flywheels [9] have been proposed. However, the aforementioned propose is unattractive for large-scale power systems [10]. A viable alternative to overcome the unattractiveness is the wind-hydro power system, combining a wind farm system with a pumped-hydro system, storing the excess wind energy and otherwise providing electric energy in favorable economic conditions. This alternative as shown attractiveness not only to balance the intermittence and variability of wind power in combined optimization settings [2] and [3], but also to enable the provision of firm capacity [11]. In [12], the operation of a wind-hydro power system is analyzed for the Greek islands, showing that the electricity cost is significantly reduced when conventional thermal units are changed by the wind-hydro power system. In [13], the sizing of a wind-hydro power system and the operational performance is examined for the Canary Islands, to optimize exploitation of available hydraulic and wind potential. In [14] and [15], a methodology is proposed for defining the best size of the several devices of a wind-hydro power system. In [2], daily planning for a wind-hydro power system is modeled by a linear programming. In [16], a dynamic programming for the operation planning of energy storage for wind farms in the electricity market is presented. In [17], a wind-hydro system is studied in order to find an energy balance analysis and economic viability. In [3], two approaches for minimizing the imbalance costs of the wind farm power output are addressed. The first approach considers only bidding for the wind farm in the day-ahead market, trying to minimize the risk of the bidding; the second one considers a wind-hydro power system to minimize the imbalance costs incurred by the wind farm system.

Unless other technology for storing energy can into play, for instance, the promising liquid storage battery [18], the state of the art has as a point in case the wind-hydro power system. This system has been shown in the literature as convenient for a wind farm in a day-ahead market, avowing imbalances due to wind power intermittence and variability.

4 Problem Formulation

The proposed MILP approach for the day-ahead operation planning of a wind-hydro power producer in an electricity market is developed in order to access an economic viability of this type of system. In the proposed approach, the operation planning is considered with hourly discretization. For each hour, the wind-hydro power producer offers in the day-ahead market based on assumption that the electricity prices are derived from a forecast. Also, the wind power is considered with an hourly discretization. The operation planning comprises at each hour the amount of: power output that should be offer; wind power; hydro power; and pumping power.

The wind-hydro power system considered for the optimal operation planning of a single entity managing a wind farm and a pumped-hydro system is shown in Fig. 1.

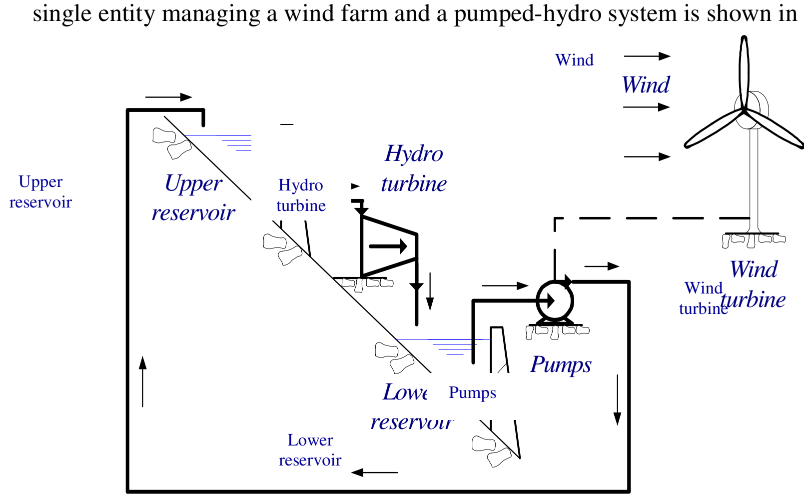

Fig. 1. Wind-hydro power system.

4.1 Objective Function

The problem formulation for the wind-hydro power system aims to maximize the power producer profit in a day-ahead market. The objective function to be maximized is stated as:

$$\sum_{t\in T}(\lambda_t^{da}\, p_t^{da} - c_t^{pump}\, p_t^{pump})\ . \tag{1}$$

In (1), t stands for the hour index and T stands for the time horizon, λ_t^{da} is the forecast electricity price in the day-ahead market, p_t^{da} is the power output injected into the grid, c_t^{pump} is the cost of the pumping operation; and p_t^{pump} is the power consumed by the pump operation. In (1), the objective function is the difference between the revenue of selling the energy and the cost of pumping.

4.2 Constraints

The objective function is subject to a set of technical and operational constraints. The constraints are stated as:

$$p_t^{da} = p_t^{W} + p_t^{hydro} - p_t^{pump} \tag{2}$$

$$\underline{p}^{W} + \underline{p}^{hydro} \le p_t^{da} \le \overline{p}^{W} + \overline{p}^{hydro} \tag{3}$$

$$\underline{p}^{W} \le p_t^{W} \le \overline{p}^{W} \tag{4}$$

$$0 \le p_t^{hydro} \le \overline{p}^{hydro}(1 - x_t) \quad \forall x \in \{0,1\} \tag{5}$$

$$0 \le p_t^{pump} \le \overline{p}^{pump}\, x_t \quad \forall x \in \{0,1\} \tag{6}$$

$$p_t^{hydro} \le \min\left\{\left(\frac{E_t - \underline{E}}{\Delta t} + \eta_{pump}\, p_t^{pump}\right)\eta_{hydro}\ ,\ \overline{p}^{hydro}\right\} \tag{7}$$

$$p_t^{pump} \le \min\left\{\left(\frac{\overline{E} - E_t}{\Delta t} - \frac{p_t^{hydro}}{\eta_{hydro}}\right)\frac{1}{\eta_{hydro}}\ ,\ \overline{p}^{pump}\right\} \tag{8}$$

$$E_{t+1} = E_t + \Delta t\, \eta_{pump}\, p_t^{pump} - \frac{\Delta t}{\eta_{hydro}}\, p_t^{hydro} \tag{9}$$

$$E_1 = E^{initial} \tag{10}$$

$$E_{24} = E^{final} \quad \textbf{(11)}$$

$$\underline{E} \leq E_t \leq \overline{E} \quad \textbf{(12)}$$

$$\underline{E} \leq E_t - \frac{\Delta t}{\eta_{hydro}} p_t^{hydro} \quad \textbf{(13)}$$

$$E_t + \Delta t\, \eta_{pump}\, p_t^{pump} \leq \overline{E}\,. \quad \textbf{(14)}$$

In (2), the power output injected into the grid in each hour t is composed by three terms: (*i*) the amount of the available wind power producer, p_t^W; (*ii*) the amount of the hydro power generated that is delivered to the grid, p_t^{hydro}; and (*iii*) the amount of the power consumed by the pump operation of the plant. In (3), the power output injected into the grid is limited by the lower and upper capacities of hydro and wind power systems. In (4), the wind power of the wind farm must be within operating limits. In (5) and (6), the limits on the hydro and pump power are set, which include a 0/1 variable, x_t, to avoid enabling both hydro and pumping operation modes. In (7), the maximum value of p_t^{hydro} depends on two main physical limits: (*i*) the amount of available energy in the reservoir, E_t, due to wind energy stored by pumping; and (*ii*) the maximum generation capacity of the hydro turbines, $\overline{p}^{hydro}$. In (8), the pumping power is limited by the maximum power of pumping and the power associated with the energy available in the reservoir. In (7) and (8), η_{pump} and η_{hydro} are the efficiencies of pumping and hydro generation, respectively. In (9), the energy balance in the reservoir is computed. At the beginning of the $(t+1)$ hour, the reservoir energy level depends on the energy level in the previous hour as well as the pumped energy and the energy supplied to the grid by the hydro generation. The reservoir energy level is reduced by hydro generation and is reloaded by pumping operation. In (10) and (11), the initial, $E^{initial}$, and final, E^{final}, energy levels of the reservoir must be satisfied. These energy levels are assumed to be known, in order to obtain a consistent planning scheme for the reservoir. In (12), the limits of the reservoir energy levels are set. In (13), the energy level has to satisfy the constraint depending on two terms: (*i*) the reservoir energy level; and (*ii*) the energy generated by the hydro plant. In (14), the energy level upper limit has to satisfy the constraint depending on two terms: (*i*) the reservoir energy level; and (*ii*) the stored energy through by the pump operation of the plant.

5 Case Study

The proposed MILP approach has been tested on case studies based on a wind-hydro power system composed of eight wind turbines and two cascading river dams with pumping-storage capability. The time horizon considered is one day, divided into 24 hourly intervals. The input to the proposed approach includes the day-ahead hourly electricity price from the Iberian electricity market [19] and the forecasted available wind power. The electricity price and available wind power are shown in Fig. 2.

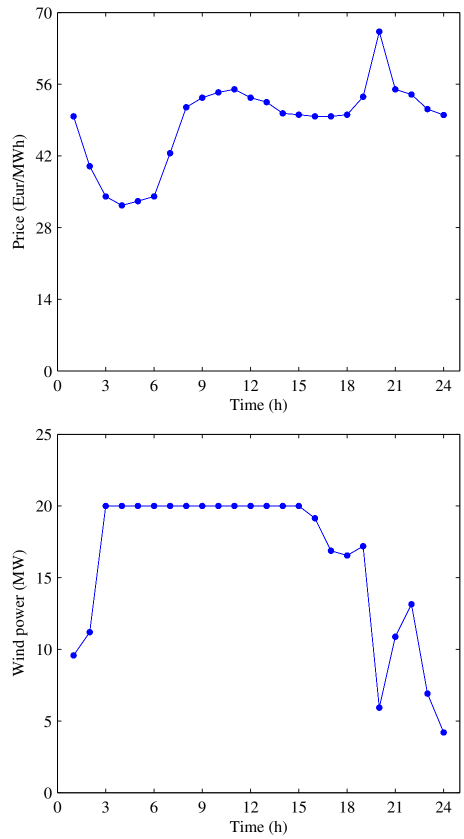

Fig. 2. Electricity prices (*left*) and available wind power (*right*).

The cost of the pumping operation assumes the same value as the electricity price at each hour. The computing time is less than 60 seconds on a 1.9-GHz-based processor with 2 GB of RAM using as a computing language the VBA for Microsoft Excel platform which is reasonable within a day-ahead decision making framework.

The operating data of the wind-hydro power system are shown in Table 1.

Table 1. Wind–hydro power system data

$\underline{p}^{W}$ (MW)	$\overline{p}^{W}$ (MW)	$\underline{p}^{hydro}$ (MW)	$\overline{p}^{hydro}$ (MW)	$\underline{p}^{pump}$ (MW)	$\overline{p}^{pump}$ (MW)	$\underline{E}$ (MWh)	$\overline{E}$ (MWh)	E^{final} (MWh)	η_{hydro}	η_{pump}
0	20	0	10	0	10	10	300	10	0.88	0.85

Two cases are presented in this section, considering different initial energy levels for the upper reservoir. The considered cases are as follows:

Case 1) The $E^{initial}$ is constrained to be equal to 20% of maximum energy level.

Case 2) The $E^{initial}$ is constrained to be equal to 75% of maximum energy level.

The two cases are analyzed with respect to the power producer's energy stored in the upper reservoir, optimal hourly power output injected into the grid and profit as follows.

The profiles of the energy stored in the upper reservoir over the 24 hour for both case studies are shown in Fig. 3.

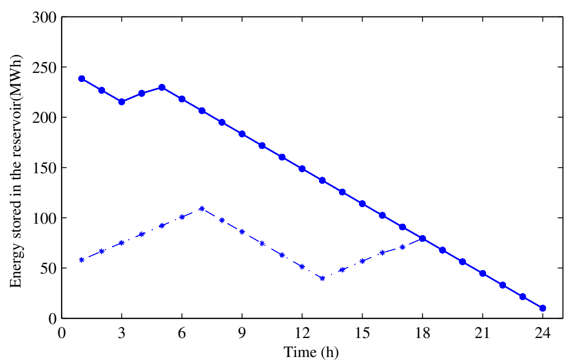

Fig. 3. Energy stored in the upper reservoir: Case 1 (*dashed-dot line*) and Case 2 (*solid line*).

In Fig. 3, the results for Case 1 show that the pumping operation occurs when the prices are low enough, i.e., for the hourly intervals between [1 , 7] h and [14 , 18] h. For the intervals [9 , 13] h and [19 , 24] h, the generating operation occurs in order to maximize the profit. In Case 2, the upper reservoir has an initial energy level greater than Case 1 then, the profit maximization is achieved with hydro production during 22 hours. Because the price is low in hours 4 and 5 the pumping operation occurs.

The hourly power output for both case studies is shown in Fig. 4.

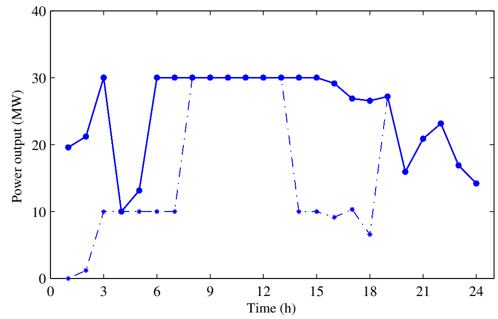

Fig. 4. Power output: Case 1 (*dashed-dot line*) and Case 2 (*solid line*).

In Fig. 4, a comparison between Case 1 and Case 2, as expected, shows that the wind-hydro power system tends to operate at a high production level when a high initial energy level in the reservoir is available. For a high initial energy level, the hydro system operates as a generator and sends the stored energy to the market until reaching the final value of energy required in the reservoir.

The power contribution of the wind farm and pumped-hydro system for both case studies in the day-ahead market is show in Fig. 5.

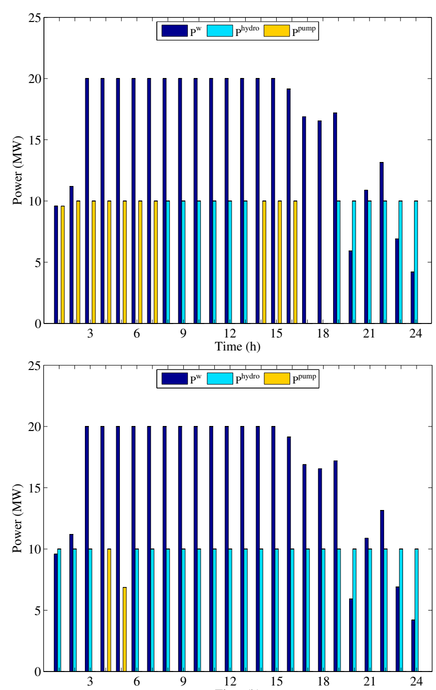

Fig. 5. Power contribution: Case 1 (*left*) and Case 2 (*right*).

In Fig. 5, for the wind power data is shown that when the upper reservoir starts with a higher level of energy stored the pumping is less required for the same electricity prices data. So, should be recommend that the initial energy stored in the starting of the time horizon should be kept at a highest value, i.e., the final energy stored should be aimed at this value.

The profits for each case study are shown in Table 2.

Table 2. Case study profits.

	Profit (Eur)
Case 1	25,164
Case 2	29,666

In Table 2, a comparison of the profits shows, as expected by the last figures, that the profit is higher when the initial energy level is higher.

6 Conclusions

A MILP approach is proposed for the optimal operation planning of a wind-hydro power system, combining a wind farm with a pumped-hydro system to improve wind farm profits. The approach developed is illustrated considering two case studies. A comparison between these two case studies allows concluding that a coordination between the forecasted wind power and the level of the energy stored at the reservoir in the initial and final hours of the time horizon have to be decided by an upper level hierarchical management system. The approach is able to mitigate wind energy curtailments and avoids penalty risks related to energy deviations.

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