Stochastic joint optimization of wind generation and pumped-storage units in an electricity market

Javier García-González, *Member, IEEE*, Rocío Moraga, Luz Matres, and Alicia Mateo

***Abstract*— One of the main characteristics of wind power is the inherent variability and unpredictability of the generation source, even in the short-term. To cope with this drawback, hydro pumped-storage units have been proposed in the literature as a good complement to wind generation for their ability of managing the positive and negative energy imbalances along the time. This paper investigates the combined optimization of a wind farm and a pumped-storage facility in a market environment, where some decisions must be taken before the uncertainty is unveiled. The optimization model is formulated as a two-stage stochastic programming problem considering two random parameters: market prices and wind generation. The optimal bids for the day-ahead spot market are the "here and now" decisions while the optimal operation of the facilities are the recourse variables. Two different joint configurations are modeled and compared with the reference case of the uncoordinated operation. A realistic example case is presented where the different developed models are tested with satisfactory results.**

***Index Terms*—Wind power, energy storage, optimization, day-ahead electricity markets, profit maximization.**

I. NOMENCLATURE

The notation used throughout the paper is stated as follows:

A. Sets and indexes:

S, s	Set and index of scenarios
H, h	Set and index of hourly periods

B. Parameters and constants:

π_{sh}	Market price in scenario *s* in period *h* [€/MWh]
W_{sh}	Wind generation forecast in scenario *s* in period *h* [MW]
ω	Penalty factor over the market price for energy imbalances [p.u]
ρ_s	Probability of scenario *s* [p.u]
η	Efficiency of the pump-turbine cycle [p.u]
$\underline{g}^p, \overline{g}^p$	Generation power limits for the pumped-storage plant [MW]
$\underline{d}^p, \overline{d}^p$	Pumping power limits for the pumped-storage plant [MW]
$\overline{g}^w$	Maximum installed power of the wind farm [MW]
$\underline{v}^u, \overline{v}^u$	Capacity limits of the upper reservoir [MWh]
$\underline{v}^l, \overline{v}^l$	Capacity limits of the lower reservoir [MWh]
vo^u, vf^u	Initial and final levels in the upper reservoir [MWh]
vo^l, vf^l	Initial and final levels in the lower [MWh]

C. Variables:

v^u_{sh}	Energy stored in the upper reservoir in scenario *s* at the end of period *h* [MWh]
v^l_{sh}	Energy stored in the lower reservoir in scenario *s* at the end of period *h* [MWh]
g^p_{sh}	Discharge power output of the pumped-storage plant in scenario *s* in period *h* [MW]
d^p_{sh}	Pumping power input of the pumped-storage plant in scenario *s* in period *h* [MW]
g^w_{sh}	Power output of the wind farm in scenario *s* in period *h* [MW]
x^p_h	Energy bid to the Market by the pumped-storage plant in period *h* [MWh]
x^w_h	Energy bid to the Market by the wind farm in period *h* [MWh]
x^{wp}_h	Joint energy bid to the market by the wind farm and the pumped-storage plant in period *h* [MWh]

II. INTRODUCTION

Currently, there is an increasing concern over the environmental impact and sustainability of conventional fossil-fueled power plants. As a consequence, renewable energy sources are becoming an important portion of the generation mix in many countries, and in particular, wind energy is one of the fastest growing renewable energy technologies in the world. For instance, the countries with the highest total installed capacity are Germany (18,428 MW), Spain (10,027 MW), the USA (9,149 MW), India (4,430 MW) and Denmark (3,122). One of the main drawbacks of this technology is the intermittent nature of the wind, which makes it difficult to forecast the output power of a wind farm

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even in the next hours.

Besides this, energy regulatory policies all around the world have been characterized by the introduction of competition in the power system industry, both at the wholesale and at the retail levels. This is the case of Spain where the electricity market has been functioning since Jan 1, 1998. This market is organized basically as a day-ahead spot market (DM) where power suppliers and consumers submit their hourly bids and the Market Operator performs the clearing algorithm in order to select the accepted and rejected bids. The system marginal price is found for each hour as the intersection between the aggregated supply function and the demand function, and it is used to remunerate all the generation. Subsequent secondary reserve (SM) and balancing markets (ID1,…, ID6) allow ensuring the generation-demand balance with an appropriate reliability level as real time operation is getting closer.

The key point is that the Spanish system, unlike the German system, allows wind farm operators to choose, each year, whether they prefer to receive feed-in compensation at a fixed rate or to participate in the spot market as the rest of generation technologies in addition to a defined bonus. In the last case, the wind generators have to submit every day (D) the set of bids for the 24 hours of the following day (D+1). Normally, as it happens with run-of-river hydro power, the price of these bids is 0 €/MWh in order to ensure that the expected schedule will be cleared in the market. However, as the day-ahead auction closes at 10:00 a.m., wind producers have to forecast their production from 00:00 to 24:00 of the following day, 14 hours in advance. Therefore, they face a significant level of uncertainty regarding the final output power with a typical error in the range of 30-45%. Balancing markets allow correcting possible mismatches between the last energy schedule cleared in the market and the best available output forecast. Producers can obtain better forecasts in the intraday balancing markets as the prediction horizon is reduced (5 to 8 hours in advance), covering the remaining hours of the trading day. In this case, the forecasting error can be reduced to values in the range of 15-25%. The final error between the last energy schedule and real production of the wind producer is penalized according to the same criterion used for all generators.

To deal with the variability and uncertainty of wind power, some authors, such as [11], [8], [2], and [6], have proposed to take the electrical energy from the wind farm and convert it into a different form of energy that can be stored to be used when desired (pumped-storage facilities, underground compressed air facilities, etc.). Another interesting approach is presented in [4], where financial hedging strategies -purchasing options- are compared with physical hedging. Among them, in this paper we follow the approach of using isolated pumped-storage plants in order to provide flexibility to the wind farm producer and to reduce the penalties for energy deviations in a market environment.

In this framework, the objective of this paper is to study the problem of coordinating the joint operation of a wind farm and a supporting pumped-storage unit. The main contributions of this research with respect to previous works are the following ones:

- The optimization of both facilities is performed in a realistic market environment under uncertainty.
- Besides the optimal schedules, the model provides the optimal bids that should be submitted to the day-ahead market in order to optimize the expected profit.
- Uncertainty about market prices and wind generation is introduced under a two-stage stochastic programming approach. Therefore, the non-anticipativity criterion is taken into account.
- Two different joint configurations are considered. In the first one, the resulting joint-unit formed by the pumped-storage and the wind farm is allowed to sell and to buy power in the market. In the second one, the joint-unit acts only as a generator, and therefore only supply bids are permitted. These two configurations are used to assess the extra revenue obtained when comparing them with the un-coordinated operation.
- A numerical study about the influence of the pumped-storage size is also presented. This could help the investors when selecting the optimal size of the pumped-storage installation.

This paper is laid out as follows. First of all, section 3 presents the model overview. Then, the mathematical formulation of each optimization model is presented in section 4. After that, a realistic example case is presented in section 5. Finally, concluding remarks are given in section 6.

III. MODEL OVERVIEW

A. Optimal bidding under uncertainty: a two-stage stochastic programming approach

When a wind farm operates without any additional support of other generators, and in case that price uncertainty in the successive energy auctions does not allow making arbitrage between the spot and the balancing markets, the most common bidding strategy of the wind generator is to offer each hour the expected value of its forecasted generation.

However, in case of having a pumped-storage station, the decision maker has the possibility of moving energy from some hours to others, trying to optimize the operational profit defined as the difference between market incomes and variable costs. For a thermal unit, variable costs are related mainly to the fuel consumption and the operating and maintenance costs (O&M). For pumped-storage units and wind farms, there are no fuel costs and in this paper O&M costs are neglected. Therefore, the criterion of the decision maker used in this paper is the maximization of the net market revenues, where the demand bids related to the pumping, if necessary, are also considered as costs in the objective function.

In case of having perfect information about future market prices and wind generation, it is possible to formulate a deterministic optimization problem to find the optimal schedule of the pumped-storage unit and the wind farm. This is the approach followed in [2], where independent deterministic optimizations are performed for different scenarios sampled by Monte-Carlo simulation. However, in order to build the optimal bids for the day-ahead spot market, the decision maker has to make “here and now” decisions, which are the bids to be submitted simultaneously for the 24 hours of the following day. Therefore, it is necessary to introduce the non-anticipativity principle in the optimization model.

In this paper, two sources of uncertainty are considered within the optimization model: the hourly market prices and the wind speed. The first one plays an important role when assessing the volatility of market revenues, as the system marginal price is used to remunerate all the generation. The second one is also very important for wind farm owners, as the energy content of the wind varies with the cube of the average wind speed.

To deal with these sources of uncertainty, in this paper we propose to use a discrete representation of both continuous random variables, in order to build a stochastic tree as the one shown in the left picture of Fig. 1. Notice that both random parameters can be merged in single scenarios as no decision variables have been considered between the market-clearing (i.e. when price uncertainty is unveiled) and the moment of having a better wind production forecasting.

The wind farm company is supposed to have a small size and therefore it can be modeled as a price-taker. However, the global wind generation of a system might influence the resulting marginal prices (the higher the global wind generation, the lower the prices as high-merit order units are taken out from the dispatch). As the individual generation of the wind farm of interest would be correlated with the global wind generation of the system, some statistical dependency could exist, and should be reflected in the stochastic tree, between considered marginal prices and wind generation scenarios.

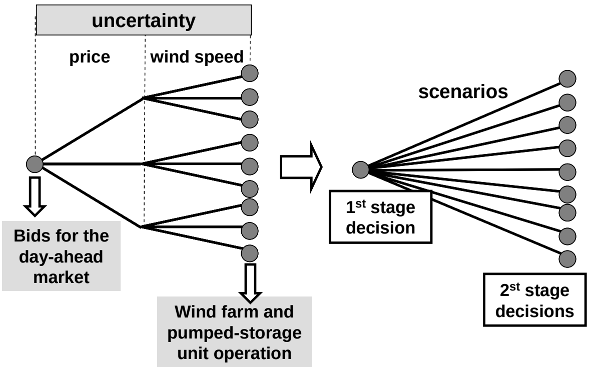


Fig. 1 Uncertainty representation and the two-stage model

In the right picture of Fig. 1 the resulting two-stage scenario tree is represented. In the first stage, the generators make the optimal decision about the bids that are submitted to the day-ahead market, considering both the pumped-storage unit and the wind farm. In the second stage, once the market has been cleared and the uncertainty about wind generation is smaller, the optimal pumped-storage unit operation is obtained. Therefore, the bids are the “here and now” decisions, while the hourly operation of the units are the recourse variables.

B. Price scenarios and wind power forecasting

There are many different approaches to analyze and forecast electricity prices, [1]. In this paper, the Input/Output Hidden Markov Model (IOHMM) approach presented in [7] is applied in order to generate electricity price scenarios. The main feature of this approach is that the switching nature of the electricity market can be represented by a set of dynamic models sequenced together by a Markov chain. In the IOHMM, different market states are firstly identified and characterized by their more relevant explanatory variables. These market states are related to the discrete changes in competitors´ strategies along the time, where a conditional probability transition matrix governs the probabilities of switching among them. The most relevant feature of this approach is that the IOHMM model provides the probability density functions of the hourly market prices, conditioned to a set of input variables, which can be used to generate a predetermined number of price scenarios.

Regarding wind power forecasting, many different approaches can found in the literature. Numerical weather prediction (NWP) models can be complemented by advanced statistical methods, such as auto-regressive filters and neural networks, which can use historic production data as explanatory variables. While statistics and time series analysis models tend to perform well for very short-term forecasting, numerical NWP-based models are normally superior for longer prediction horizons, [5]. For that reason, in the literature many successful forecasting models combine both approaches, [10], [9].

C. Wind farm representation

The wind generation is a function of the wind speed to cube. Despite the fact that normally, the predictions are made over the wind speed, we will consider directly in our model estimations of wind energy available for each scenario. The real wind production in each scenario will be thus limited to these predictions.

D. Pumped-storage modeling

The pumped-storage plant considered is composed of an upper reservoir and a lower reservoir. Typically, a reversible pump-turbine allows storing energy in off-peak hours to be sold to the market during peak hours, provided that the operation is economically profitable. In this paper, the pumped-storage plant can be used as well to provide hedging to a wind farm taking part in the spot market. Thus, the pump-turbine will work as a turbine when water is released from the upper reservoir to the lower, injecting its production to the network. Likewise, when operating as a pump, the energy is consumed to store water in the upper reservoir which will be available later on for hydroelectric generation. Natural inflows in the reservoirs are not considered as the pumped-storage unit is supposed to be isolated from the hydro chain. Moreover, the net head dependency of the production is treated in a simplified way as it is assumed that the sum of the energy stored in both the upper and the lower energy reservoirs is constant. Additionally, the model allows the consideration of different pumping and discharging limits.

The variables associated to the pumped-storage plant in the model are considered in terms of energy. Thus, in each period, the state of the upper and lower reservoirs will be determined by the energy stored in them at the end of the period. Likewise, the volume capacity of both reservoirs will be expressed as a maximum and minimum energy level that can be stored in the reservoirs.

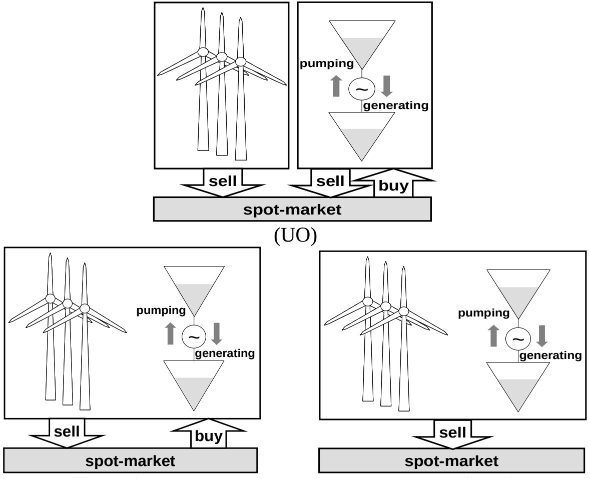
E. Pricing rule and imbalance penalties payment

In this paper, a marginalist pricing rule is considered. Therefore, the settlement consists of paying each hour the real generation multiplied by the resulting price. Moreover, energy imbalances, i.e., the differences between the real generation and the cleared quantities, are penalized. In this paper we penalize the absolute value of the imbalance at a given percentage of the market price. This is the rule used in the Spanish market, where this percentage in unknown in advance as it depends on the final prices. Thus, an expected value is considered as input-data.

The absolute value function can be expressed in the context of linear programming (LP) by adding some auxiliary variables for positive and negative deviations. Therefore, in the following mathematical formulation we will use directly the absolute value function. Finally, note that in case a different penalization were applied for upward or downward imbalance, it could be formulated in the proposed models.

F. Configurations of the wind farm and the pumped-storage unit.

In this paper we study three different configurations: uncoordinated operation (UO), joint operation for selling and buying power in the market (JO-SB), and joint operation just for selling (JO-S). Fig. 2 presents a schematic representation of the three configurations analyzed:



(UO)

(JO-SB)

(JO-S)

Fig. 2. Schematic representation of the three configurations analyzed.

In the first configuration, the wind farm and the pumped-storage unit are operated independently. This configuration will be used as a reference case for subsequent benchmarking. In the other two configurations, the wind farm takes advantage of the energy management capacity of the pumped-storage unit in order to minimize its deviations along the day: in the hours in which the wind power production is greater (lower) than the offered production, the energy surplus (deficit) will be used to store (produce) energy by pumping (discharging) water between both the upper and the lower reservoirs. In both joint configurations, the pumped-storage station and the wind farm are merged in the same entity, so the wind power and hydro generation are sold jointly. In the JO-SB, the energy purchase in the market is allowed with the only constraint of not exceeding the maximum pumping capability. In the JO-SB model, the joint entity must act as a supplier, and therefore purchasing bids are not allowed. Therefore, in this case, energy required for pumping water from the lower reservoir to the upper one must be served completely by the wind farm.

IV. MATHEMATICAL FORMULATION

The next subsections present the detailed mathematical formulation of the optimization models related to each one of the configurations explained in section III. F. Notice that the duration of each temporal interval is omitted in all the equations as they are hourly periods.

A. Uncoordinated Operation, (UO)

When operating in a separate way, both the wind farm and the pumping utility try to maximize independently their incomes from selling their energy production to the spot market, minus a penalization for imbalance. The two maximization problems can be solved separately: each utility makes its bid to the market while satisfying their own technical constraints.

- *Wind farm*:

$$\max \sum_{s\in S} \rho_s \cdot \sum_{h\in H} \left[\pi_{sh} \cdot g^{w}_{sh} - \omega \cdot \pi_{sh} \cdot \left|g^{w}_{sh} - x^{w}_{h}\right|\right] \quad (1)$$

s.t.

$$0 \le g^{w}_{sh} \le W_{sh} \qquad \forall s \in S, \forall h \in H \quad (2)$$

$$0 \le x^{w}_{h} \le \overline{g}^{w} \qquad \forall h \in H \quad (3)$$

The hourly wind generation in each scenario is given by the estimation provided for the scenario considered, (2). Additionally, the bid is limited to the installed capacity of the wind farm, (3). Notice that as the optimal bids are the “here and now” decisions, they do not depend on the scenario.

- *Pumped-storage plant*:

$$\max \sum_{s\in S} \rho_s \cdot \sum_{h\in H} \left[\pi_{sh} \cdot \left(g^{p}_{sh} - d^{p}_{sh}\right) - \omega \cdot \pi_{sh} \cdot \left|g^{p}_{sh} - d^{p}_{sh} - x^{p}_{h}\right|\right] \quad (4)$$

s.t.

$$v^{u}_{sh} = v^{u}_{sh-1} + \eta \cdot d^{p}_{sh} - g^{p}_{sh} \qquad \forall s \in S, \forall h \in H \quad (5)$$

$$v^{l}_{sh} = v^{l}_{sh-1} + g^{p}_{sh} - \eta \cdot d^{p}_{sh} \qquad \forall s \in S, \forall h \in H \quad (6)$$

$$\underline{v}^u \leq v_{sh}^u \leq \overline{v}^u \qquad \forall s \in S, \forall h \in H \tag{7}$$

$$\underline{v}^l \leq v_{sh}^l \leq \overline{v}^l \qquad \forall s \in S, \forall h \in H \tag{8}$$

$$v_{sh}^u = vf^u \qquad \forall s \in S, h = 24 \tag{9}$$

$$v_{sh}^l = vf^l \qquad \forall s \in S, h = 24 \tag{10}$$

$$\underline{g}^p \leq g_{sh}^p \leq \overline{g}^p \qquad \forall s \in S, \forall h \in H \tag{11}$$

$$\underline{d}^p \leq d_{sh}^p \leq \overline{d}^p \qquad \forall s \in S, \forall h \in H \tag{12}$$

$$-\overline{d}^p \leq x_h^p \leq \overline{g}^p \qquad \forall h \in H \tag{13}$$

For each reservoir, the water balance equation (expressed in energy) must be satisfied, (5) and (6), where the energy pumped from the lower reservoir to the upper is affected by the efficiency η. Besides, it is assumed that for $h = 1$, $v_{sh-1}^u = vo^u$ and $v_{sh-1}^l = vo^l$ (initial levels). Also, both reservoirs must satisfy their capacity limits, (7) and (8). The energy stored at the end of the time scope considered is given by (9) and (10). In addition, the pumping and turbine capacity is limited by the pump-turbine characteristics, (11) and (12). These capacities also represent a limit to the bids to the market, (13).

B. *Joint Operation, Selling and Buying: (JO-SB)*

In this configuration, the wind farm and the pumped-storage plant offer a single bid to the market, whether that is an offer of sale or purchase.

$$\begin{aligned} \max \quad & \sum_{s\in S} \rho_s \cdot \sum_{h\in H} \left[\pi_{sh} \cdot \left(g_{sh}^w + g_{sh}^p - d_{sh}^p \right) \right. \\ & \left. - \omega \cdot \pi_{sh} \cdot \left| g_{sh}^w + g_{sh}^p - d_{sh}^p - x_h^{wp} \right| \right] \end{aligned} \tag{14}$$

s.t.

$$0 \leq g_{sh}^w \leq W_{sh} \qquad \forall s \in S, \forall h \in H \tag{15}$$

$$v_{sh}^u = v_{sh-1}^u + \eta \cdot d_{sh}^p - g_{sh}^p \qquad \forall s \in S, \forall h \in H \tag{16}$$

$$v_{sh}^l = v_{sh-1}^l + g_{sh}^p - \eta \cdot d_{sh}^p \qquad \forall s \in S, \forall h \in H \tag{17}$$

$$\underline{v}^u \leq v_{sh}^u \leq \overline{v}^u \qquad \forall s \in S, \forall h \in H \tag{18}$$

$$\underline{v}^l \leq v_{sh}^l \leq \overline{v}^l \qquad \forall s \in S, \forall h \in H \tag{19}$$

$$v_{sh}^u = vf^u \qquad \forall s \in S, h = 24 \tag{20}$$

$$v_{sh}^l = vf^l \qquad \forall s \in S, h = 24 \tag{21}$$

$$\underline{g}^p \leq g_{sh}^p \leq \overline{g}^p \qquad \forall s \in S, \forall h \in H \tag{22}$$

$$\underline{d}^p \leq d_{sh}^p \leq \overline{d}^p \qquad \forall s \in S, \forall h \in H \tag{23}$$

$$-\overline{d}^p \leq x_h^{wp} \leq \left(\overline{g}^w + \overline{g}^p \right) \qquad \forall h \in H \tag{24}$$

It is important to highlight that in this case, the imbalance is computed over the single joint offer, (14). The technical constraints for the wind farm and the pumped-storage plant are not affected by the joint operation and remain the same as in the independent operation. In this case a single bid is made. This bid, which can be for selling or purchasing electricity, is limited by the installed capacity of the wind and pumping facilities, (24).

C. *Joint Operation, only Selling: (JO-S)*

In this configuration, the wind farm and the pumped-storage plant offer a single bid to the market. However, only selling offers are accepted.

$$\max \sum_{s\in S} \rho_s \cdot \sum_{h\in H} \left[\pi_{sh} \cdot \left(g_{sh}^w + g_{sh}^p \right) - \omega \cdot \pi_{sh} \cdot \left| g_{sh}^w + g_{sh}^p - x_h^{wp} \right| \right] \tag{25}$$

s.t.

$$0 \leq g_{sh}^w - d_{sh}^p \leq W_{sh} \qquad \forall s \in S, \forall h \in H \tag{26}$$

$$v_{sh}^u = v_{sh-1}^u + \eta \cdot d_{sh}^p - g_{sh}^p \qquad \forall s \in S, \forall h \in H \tag{27}$$

$$v_{sh}^l = v_{sh-1}^l + g_{sh}^p - \eta \cdot d_{sh}^p \qquad \forall s \in S, \forall h \in H \tag{28}$$

$$\underline{v}^u \leq v_{sh}^u \leq \overline{v}^u \qquad \forall s \in S, \forall h \in H \tag{29}$$

$$\underline{v}^l \leq v_{sh}^l \leq \overline{v}^l \qquad \forall s \in S, \forall h \in H \tag{30}$$

$$v_{sh}^u = vf^u \qquad \forall s \in S, h = 24 \tag{31}$$

$$v_{sh}^l = vf^l \qquad \forall s \in S, h = 24 \tag{32}$$

$$\underline{g}^p \leq g_{sh}^p \leq \overline{g}^p \qquad \forall s \in S, \forall h \in H \tag{33}$$

$$\underline{d}^p \leq d_{sh}^p \leq \overline{d}^p \qquad \forall s \in S, \forall h \in H \tag{34}$$

$$0 \leq x_h^{wp} \leq \left(\overline{g}^w + \overline{g}^p \right) \qquad \forall h \in H \tag{35}$$

The objective function considers the maximization of the incomes from selling the wind and hydro generation to the spot market, (25). Since only bids for sale are accepted, the energy required to pump water from the lower reservoir to the upper one must be necessarily taken from the wind energy available in each scenario, (26). These selling bids are limited again by the installed capacity, (35).

V. EXAMPLE CASE

The presented model has been implemented in GAMS, using the commercial solver CPLEX 9.0 to solve the resulting LP problems. Table I shows the size of the problems and the solution time when solved in a Pentium 4 processor, 3MHz and 1GB RAM memory. In this section we present the numerical results obtained after applying the proposed models to a realistic case.

A. *Input Data*

The methodology developed is applied to a 30 MW wind farm and to a 10 MW pumped-storage unit. The number of scenarios considered in the optimization problems is 420. This scenario tree is composed of 20 different prices predictions (see Fig. 3) obtained by applying the methodology proposed in [10] to the Spanish daily-market hourly prices, and 21 wind production estimations, introduced as input data.

The pumped-storage unit characteristics are shown in Table I.

TABLE I
PUMPED-STORAGE CHARACTERISTICS

	$\overline{v}$ [MWh]	$\underline{v}$ [MWh]	$vo{=}vf$ [MWh]	$\underline{d}$ [MW]	$\overline{d}$ [MW]	$\underline{g}$ [MW]	$\underline{g}$ [MW]	η [p.u]
upper	80	0	15	0	10	12	0	0.7
lower	80	0	25					

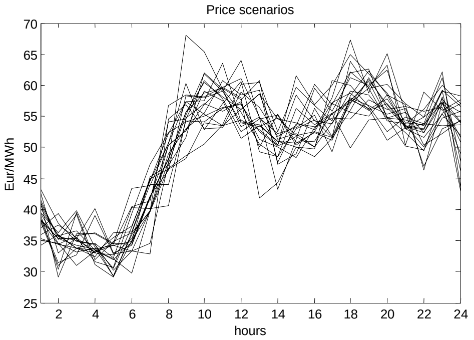


Fig. 3. Price scenarios considered in the example case.

B. *Operation and economic results*

Table II shows the CPU time required to solve each model. Note that, despite the analogous structure of JO-SB and JO-B the resolution time required for solving the last one increases notably.

TABLE II
EXAMPLE CASE CHARACTERISTICS

	UO	JO-SB	JO-S
CPU solution time (s)	19.697	68.497	91.870

The solution of the optimization models contains the set of optimal bids for the daily market for the three configurations considered. Fig. 4 shows the hourly bid quantities obtained for each configuration. Note that in the JO-S model, quantities are always positive, while in the JO-SB, the joint unit presents offers for purchasing in the off-peak hours.

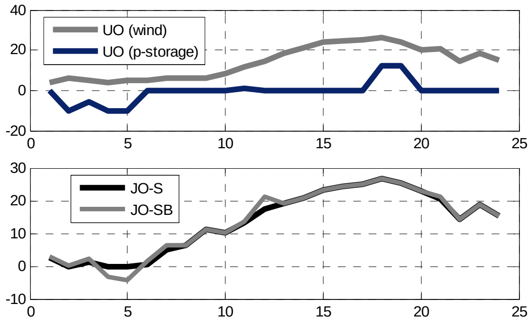


Fig. 4. Obtained optimal hourly bids for the three configurations.

Storage levels along the 24 hours, and the pumped-storage plant strategy for the day are also determined. For instance, Fig. 5 shows the obtained operation along the day in the lower reservoir for each scenario. This result is presented for both the JO-SB and the JO-S configuration. Note that in the second one, the reservoir level during off-peak hours remains higher as pumping available power is limited to the wind farm generation. Similar results could be obtained for the upper reservoir.

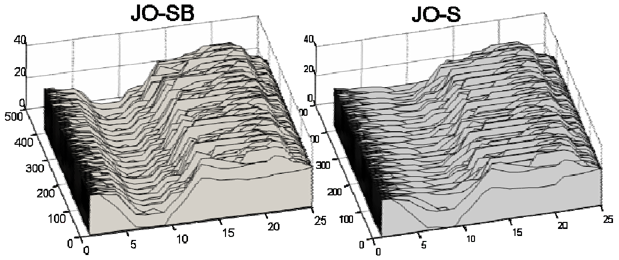


Fig. 5. Obtained operation along the day in the lower reservoir for each scenario, and for each joint configuration.

Regarding the expected profits, Table III shows the results for each configuration studied. As can be seen, both strategies of joint operation, i.e. JO-SB and JO-S, increase the wind farm profits since the pumped-storage unit provides hedging against its production uncertainty as well as a more efficient operation, storing energy during off-peak hours to increase the energy sold during peak hours. Furthermore, it can be stated that the coordination of both utilities represents a profit increase for both the wind farm and the pumped-storage unit, as the joint operation models achieve higher profits than when adding the individual profits obtained in the uncoordinated model.

TABLE III
EXPECTED PROFITS FOR EACH CONFIGURATION

Configuration		Profits [€]
UO	Wind farm	16301
	Pump-storage	254.5
	Sum	16555.5
JO-SB		17074
JO-S		17018

In the JO-SB model the energy purchase in the market is allowed, restricting the buying bid to the pumped-storage plant capacity. That is why this operation model's profits will be compared with the sum of profits that the wind farm and the pumping station obtain when operating in an uncoordinated way. Thus, from the incomes shown in Table III, the JO-SB model increases the profits of the wind farm and the pumped-storage unit in a 3.13%. Likewise, the profits of the JO-S model are compared to the uncoordinated wind farm profits. This comparison allows estimating the benefits obtained by a wind farm when a pumped-storage unit taking its consumption from the wind production provides hedging. The increase observed in this case study is a 4.39%.

Table IV shows the expected decrease in the penalties for imbalance that the pumped-storage hedging provides to the wind farm in the joint models. The imbalancing penalty in each coordinated model is reduced by nearly a 43%.

TABLE IV
PENALTIES FOR IMBALANCE

Configuration	Penalties [€]
UO	1652.9
JO-SB	945.47
JO-S	945.21

Despite the fact that the penalties are practically the same in both joint configurations, it is important to notice that the profits for the JO-SB are higher, since the pumped-storage unit has more flexibility to buy and sell energy, allowing a more efficient participation in the market.

C. The influence of the pumped-storage size

An additional study has been conducted for this example case. The aim is to asses the effect of size of the pumped-storage equipment on the hedging provided to a specific wind farm. For this, the expected profits and penalties are calculated for a set of different pumped-storage sizes. The study considers different pumping capacities from 5 to 30 MW. The turbine and reservoirs capacities are also modified so that the same proportion rate with the pumping power is kept. The resulting pumped-storage plant characteristics that are considered are shown in Table V.

TABLE V
PUMPED-STORAGE CHARACTERISTICS

Pump unit	$\overline{d}$ [MW]	$\overline{g}$ [MW]	$\overline{v}$ [MWh]
CB1	5	7	40
CB2	10	12	80
CB3	15	17	120
CB4	20	22	160
CB5	25	27	200
CB6	30	32	240

Fig. 6 shows the relative increase of the expected profits of the JO-SB and the JO-S configurations when compared to the uncoordinated wind farm profits and to the sum of the utilities uncoordinated benefits. The graphs show a growing tendency. However, the benefit increases faster initially when the pumped-storage plant dimensions are still small compared to the wind farm power and remains almost constant when the values of the pumping capacity approaches the wind farm's.

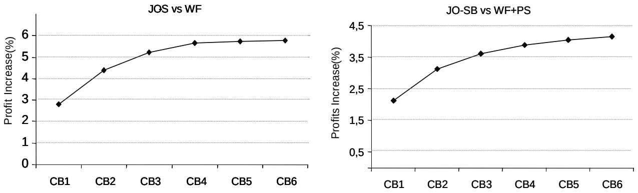


Fig. 6. Relative profit variations for each pumped-storage size.

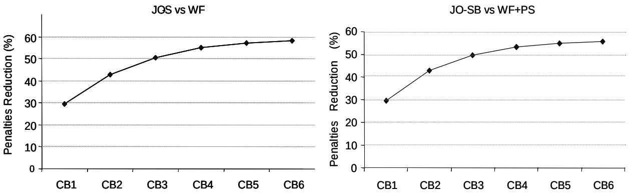


Fig. 7 Relative penalty variations for each pumped-storage size

As for the penalties, Fig. 7 shows that the expected penalty for imbalance can be diminished up to almost 60% and that the decrease slows down, illustrating that a satisfactory hedging can be obtained with reduced pumped-storage capacity.

VI. CONCLUSIONS

The increased level of wind penetration in power systems requires integrating this renewable energy with other existing technologies. In this paper we have demonstrated that a joint short-term operation of a wind farm and an isolated pumped-storage unit can be obtained by solving the presented optimization models. The two-stage stochastic programming approach has proven to be an effective way to model the real decision making process that wind park operators face in a spot-market framework under uncertainty. The wind farm operator has been modelled as a risk-neutral agent. Future research could be conducted to introduce in the optimization model some risk-aversion measures, such as the Conditional Value at Risk applied in [3] for hydro generation. Finally, the models presented in this paper could be useful for assisting in the investment decision about new pumped-storage. In that case, the illustrative study presented in section V. C. should be extended to a broader range of prices and wind generation scenarios to extract robust conclusions.

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