Hydro-wind Optimal Operation for Joint Bidding in Day-ahead Market: Storage Efficiency and Impact of Wind Forecasting Uncertainty

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***Abstract*—Wind power production is uncertain. The imbalance between committed and delivered energy in pool markets leads to the increase of system costs, which must be incurred by defaulting producers, thereby decreasing their revenues. To avoid this situation, wind producers can submit their bids together with hydro resources. Then the mismatches between the predicted and supplied wind power can be used by hydro producers, turbining or pumping such differences when convenient. This study formulates the problem of hydro-wind production optimization in operation contexts of pool market. The problem is solved for a simple three-reservoir cascade case to discuss optimization results. The results show a depreciation in optimal revenues from hydro power when wind forecasting is uncertain. The depreciation is caused by an asymmetry in optimal revenues from positive and negative wind power mismatches. The problem of neutralizing the effect of forecasting uncertainty is subsequently formulated and solved for the three-reservoir case. The results are discussed to conclude the impacts of uncertainty on joint bidding in pool market contexts.**

***Index Terms*—Optimization, hydro power, wind power, uncertainty, joint bidding, pool market.**

I. Introduction

CURRENTLY, in the electricity sector, there are two distinct ways of purchasing energy: the regulated market where energy prices are regulated by the corresponding authority in the electricity sector, and the unregulated (also called competitive) market, where the regulator does not intervene, and producers compete among each other to increase their benefits. In the unregulated market, two different types of purchase and sale of electricity are practiced: ① bilateral contracts, where the order is set freely among producers and trading entities; ② pool market, also known as day-ahead market, where producers present their biddings. In pool markets, several power producers participate simultaneously, including wind energy producers, whose share of the generation portfolio has grown remarkably in recent years.

However, this important energy resource is difficult to forecast. Stochastic methods allows to obtain more reliable forecasting results of wind power generation, using physical models at the scale of the park and the information collected in wind farms. In Portugal, the information on wind power generation is available online and for the wind farms that have telemetry with transmission system operator [1]. In the literature, several statistical and physical forecasting models are presented for obtaining reliable power generation estimates [2]-[7]. In [8], a new method that improves the wind forecasting accuracy is proposed, which uses the boosting algorithm and a multi-step forecasting approach to improve the forecasting capacity. This method also estimates the error bounds. In [9], a pair-copula theory is introduced to construct a multi-variate model, which can fully consider the margin distribution and stochastic dependence characteristics of wind power forecasting errors. The characteristics of temporal and spatial dependence are modeled to improve the wind power forecasting.

Despite the improvements, significant errors are frequent in day-ahead forecasting [1], which introduce deviations with respect to the previously agreed commitments. This imbalance should be corrected so that the generation meets the demand by employing other units in reserve, thus increasing the production costs for those generators. There is also the intraday market, where wind power forecasting becomes more assertive, and some day-ahead power imbalances can be corrected. At present in Portugal and Ireland, wind producers are not penalized for non-compliance with the agreed commitments. However, in countries such as Sweden, Finland, or the UK, the cost of non-compliance is significant; and in countries such as Romania or Bulgaria, the energy default rates of up to 24 €/MWh may be applied, which make the wind power technology very unattractive from the perspective of market [10].

In the context of power default penalties, power imbalances inevitably cause a reduction in profits of the wind generation companies (W-GENCO). For W-GENCO, one way to

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solve this problem is to submit their bids jointly with hydro power generation companies (H-GENCO). In this context, wind producers safeguard possible power deviations resulting from wind forecasting errors. In case of overproduction from wind power, such power may be used in pumping water to the upstream reservoirs of the H-GENCO, thus increasing their profits. Therefore, this combination is expected to bring benefits to both W-GENCO and H-GENCO.

Several studies have been conducted on the topic of hydro-wind joint bidding in deregulated markets. In [11], [12], an optimization strategy for joint bidding is presented considering the availability of hourly wind power forecasting. Because of the hourly wind output gaps, several scenarios of hydro power production are considered to jointly optimize the production in each hour. In [13], [14], thermal, hydro, and wind generations are taken into account in the bidding, without considering the pumping possibilities. In [15], mixed integer linear programming is used to find the best hydro-wind joint bidding in the Spanish market, without considering the pumping possibilities, neither. In [16]-[19], risk strategies are developed to manage the daily wind production in association with hydro units. In [20]-[22], studies on intraday hydro-wind coordination are developed. In these studies, a Monte Carlo method is used for scenario generation. Mixed integer programming is then used to optimize the joint bidding.

In this work, the authors propose to solve an optimization problem of hydro power production for a cascade of three reservoirs, considering the forecasting of wind power and an estimate of market energy prices. The problem is solved with linear programming and the results are discussed with respect to the prospective benefits for both hydro and wind producers. The asymmetry in benefits that results from wind forecasting uncertainty is analyzed and discussed. A new optimization problem is formulated to determine the corrections in wind forecasting, which is necessary for the neutralization of asymmetry in benefits.

II. Problem Formulation

The formulation of problem presented here concerns the optimization of hydro power production associated with wind production forecasting, considering the forecasting of energy prices that will be practiced in the day-ahead pool market. In the first stage, the problem is solved by computing the optimum hydro power to be produced by each of the three reservoirs during the day, given the estimate of energy prices and a null deviation between the forecasted and supplied wind power. The second stage corresponds to the situation where there are deviations between the forecasted and produced wind power. If these deviations occur for lower values, i.e., the supplied wind power is lower than the forecasting result, the hydro power production provides this difference by increasing the generation output. This difference will also be produced optimally. If deviations occur for higher values, i.e., the supplied wind power is higher than the forecasting result, the surplus produced from wind power is used for pumping water to an upstream reservoir. The whole production and the corresponding adjustments are made hourly over a 24-hour horizon.

The objective function is given in (1), and it is composed of three sums. The double sum of the first term expresses the hydro power p_{hkj} produced in each hydro reservoir j at every hour k during K hours. The second sum represents the total power produced by the wind farm p_{wks} at each hour. The third sum is the energy p_{pkj} used in pumping to the reservoirs. All sums are affected by an energy price estimate λ_k at each hour. The maximization of (1) allows optimizing the production profits, providing one hydro power solution over 24 hours, based on the profiles of wind power estimates and energy prices. The optimization is subjected to equality and inequality constraints and the bounds of variables.

$$\max F = \lambda_k \left(\sum_{k=1}^{K} \sum_{j=1}^{J} p_{hkj} + \sum_{k=1}^{K} p_{wks} + \sum_{k=1}^{K} p_{pkj} \right) \tag{1}$$

s.t.

$$\sum_{k=1}^{K} \sum_{j=1}^{J} p_{hkj} + \sum_{k=1}^{K} p_{wks} \geq E_D \tag{2}$$

$$E_{Hf} = E_{Hi} + \sum_{k=1}^{K} (p_{wks} - p_{wkp}) \tag{3}$$

$$v_{kj} = v_{k-1,j} + a_{kj} + \sum_{k=1}^{K} \sum_{j=1}^{J} \left(q_{kMj} + s_{kMj} \right) - q_{kj} - s_{kj} + \sum_{k=1}^{K} \sum_{j=1}^{J} \left(v_{pkJj} - v_{pkMj} \right) \tag{4}$$

$$\sum_{k=1}^{K} \sum_{j=1}^{J} p_{hkj} + \sum_{k=1}^{K} p_{wks} \geq \sum_{k=1}^{K} p_{wkp} \tag{5}$$

$$\sum_{k=1}^{K} p_{wks} - \sum_{k=1}^{K} p_{wkp} = \sum_{k=1}^{K} \sum_{j=1}^{J} p_{pkj} \tag{6}$$

$$\sum_{k=1}^{K} p_{pk} \geq 0 \tag{7}$$

$$\sum_{k=1}^{K} \sum_{j=1}^{J} p_{pkj} = \sum_{k=1}^{K} \sum_{j=1}^{J} p_{hkj}^{-1} \tag{8}$$

$$0 \leq p_{pk} \leq p_{wk,\max} \tag{9}$$

$$p_{hkj} = q_{kj} \eta_{kj} \tag{10}$$

$$p_{hkj}^{-1} = q_{kj}^{-1} \eta_{kj}^{-1} \tag{11}$$

$$v_{j,\min} \leq v_{kj} \leq v_{j,\max} \tag{12}$$

$$q_{j,\min} \leq q_{kj} \leq q_{j,\max} \tag{13}$$

$$s_{j,\min} \leq s_{kj} \leq s_{j,\max} \tag{14}$$

where $k = 1, 2, \ldots, K$; $j = 1, 2, \ldots, J$; J is the set of reservoirs; E_D is the total wind-hydro daily energy demanded for a joint bidding on pool market; E_{Hf} is the total daily hydro energy to submit on pool market considering wind forecasting deviations; E_{Hi} is the total daily hydro energy to submit on pool market without wind forecasting deviations; p_{wkp} is the forecasted energy production by wind farm in hour k; p_{hkj}^{-1} is the hydro power consumption on pumping operation of plant j in hour k; p_{pk} is the hydro power energy used on pumping operation in hour k; $p_{wk,\max}$ is the maximum power supply capability by wind farm; v_{kj} is the water storage of reservoir j in hour k; $v_{j,\max}$ and $v_{j,\min}$ are the maximum and minimum water storages in reservoir j, respectively; $q_{j,\max}$ and $q_{j,\min}$ are the maximum and minimum water discharges of reservoir j in hour k, respectively; s_{kj} is the spillage discharge of reservoir j in hour k; and $s_{j,\max}$ and $s_{j,\min}$ are the maximum and minimum spillage discharges by reservoir j in hour k, respectively. The following text will further explain other variables in (1)-(14).

The equality constraint (2) presents an energy balance equation. In (3), it is guaranteed that the water supply will not be affected by the wind offset imbalance. In (4), the water balance equation is presented. The transition time of water discharges between the upstream and downstream reservoirs is considered null. The inequality in (5) ensures that the hourly power presented to the auction at hour k will always be fulfilled. In the case of wind forecasting failure by lower values, the hydro power production will bridge the gap between the forecasted wind energy E_{wpk} and supplied wind energy E_{wfk} at each hour. In (6), it is assumed that the difference between the hourly forecasted wind power p_{wkp} and the effectively supplied power p_{wks} will be used for pumping p_{pkj}, just in the case where such difference is positive (7). The total energy used in pumping is equal to the sum of the energy consumed by all hydro units (8). The total energy used in pumping will be limited by the maximum capacity of the wind farm (9). In (10), the water power generated in each reservoir p_{hkj} is expressed as a function of the water discharge q_{kj} and the efficiency of the plant η_{kj}. In (11), the energy consumed in pumping at the reservoir p_{hkj}^{-1} is obtained from q_{kj}^{-1} for a known efficiency η_{kj}^{-1}.

The hydro generation characteristics are mainly assumed as linear or piecewise linear in the hydro scheduling models, neglecting head variations. For long-term time horizons, the linearity assumption is reasonable, as the errors introduced by this assumption are expected to be small compared to the uncertainties with respect to hydro inflow [23]. For a particular configuration of the hydro system, the linearity assumption may be acceptable or not for short-term time horizons, depending on the importance of head variation over the time horizon. For the sake of simplicity, we assume the linearity between the generated power and the water discharge.

III. Case Study of Deterministic Optimization

This case study consists of the optimization of a cascade of three water reservoirs and a wind farm. As shown in Fig. 1, the first reservoir R1 is the sole with water inflow a_{k1} and pumping capability. Initially, all the reservoirs have a volume of 70 hm^3 and the water inflow only occurs at the 2nd and 3rd hours, with a value of 0.9 hm^3 in reservoir R1. The limits of variables are set as follows: $v_{j,\max} = 80\ hm^3$, $v_{j,\min} = 40\ hm^3$, $q_{j,\max} = 3\ hm^3/h$, $q_{j,\min} = 0\ hm^3/h$, $s_{j,\max} = 100000\ hm^3/h$, $s_{j,\min} = 0\ hm^3/h$. These values are considered equal for the three reservoirs.

In this case study, it has been considered that the W-GENCO provides an average production of 700 MWh distributed over 24 hours. The H-GENCO will produce 350 MWh at hours that are more economically advantageous, according to the forecasted market price.

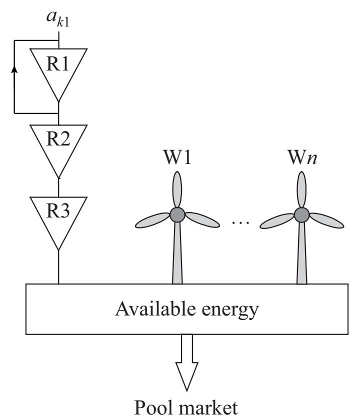

Fig. 1. Wind-hydro system with three reservoirs Ri (i = 1, 2, 3) and n wind turbines Wi (i = 1, 2, …, n).

Figure 2 shows a functional diagram of the wind-hydro optimization algorithm used in this study.

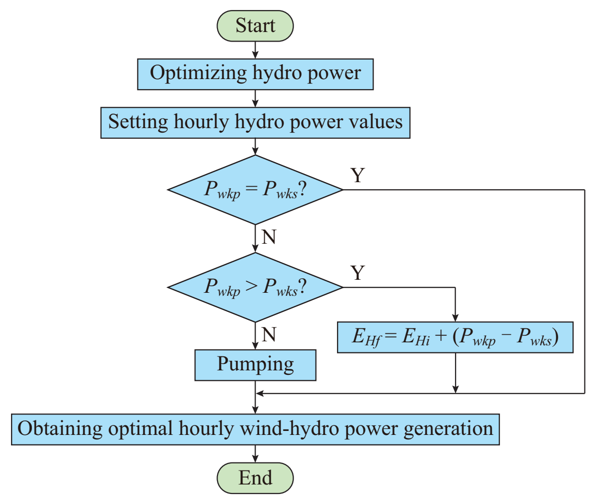

Fig. 2. Wind-hydro optimization algorithm.

Figure 3 shows the forecasted average energy prices of each hour within a day in the day-ahead market.

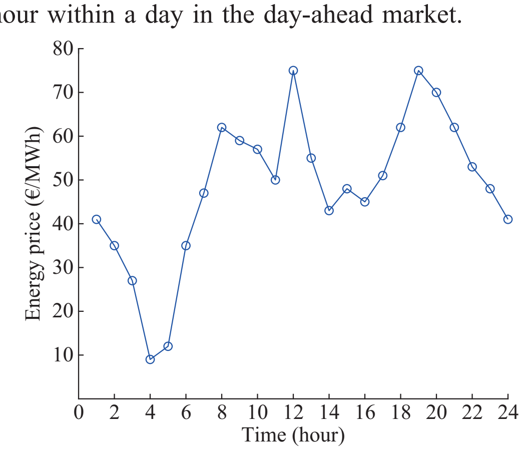

Fig. 3. Forecasted energy prices.

A. Wind-hydro Solution Without Wind Forecasting Deviations

In the first stage, the optimization problem is solved considering that the produced power and forecasted power are equal, i.e., $p_{wkp} = p_{wks}$. The corresponding optimization results are presented for turbine flows in Fig. 4 and reservoir volumes in Fig. 5, where the flows q_{R1}, q_{R2}, q_{R3}, and the volumes v_{R1}, v_{R2}, v_{R3} are depicted for reservoirs R1, R2, R3, respectively.

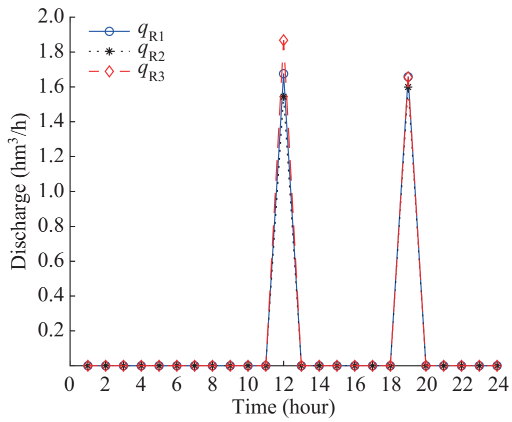

Fig. 4. Turbine flow evolutions for optimal solution without wind forecasting deviations.

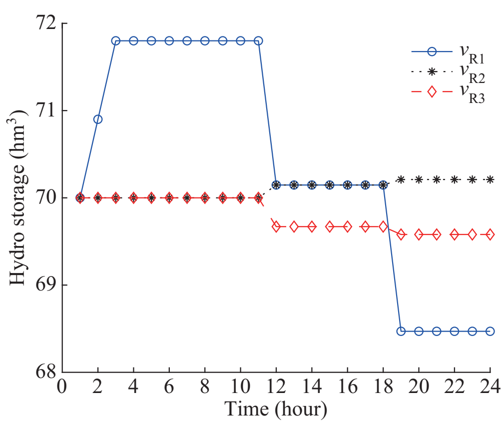

Fig. 5. Reservoir volume evolutions for optimal solution without wind forecasting deviations.

B. Wind-hydro Solution with Wind Forecasting Deviations

In the second stage, the optimization problem is solved considering that the power produced and forecasted are different, i.e., $p_{wkp} \neq p_{wks}$. Figure 6 shows the forecasted and supplied wind power along with their differential, which is used for pumping.

The corresponding optimization results are presented for turbine flows in Fig. 7 and reservoir volumes in Fig. 8.

In Fig. 8, the evolutions of the volumes in the three water reservoirs are presented throughout the day. Figure 6 shows that the main volumetric changes occur at reservoir R1, where pumping is carried out, and at reservoir R2, from which the pumped water comes. Reservoir R3 is maintained with the same evolution throughout the day in both cases.

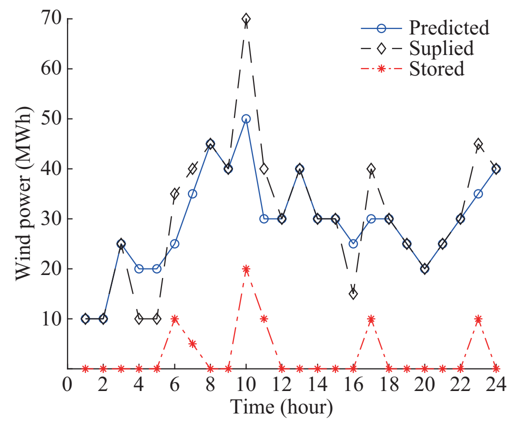

Fig. 6. Profiles of wind energy predicted, wind energy effectively supplied during the day, and the corresponding stored energy.

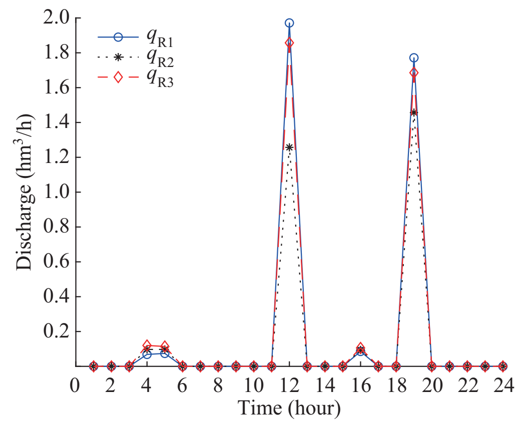

Fig. 7. Turbine flow evolutions for the optimal solution with wind forecasting deviations.

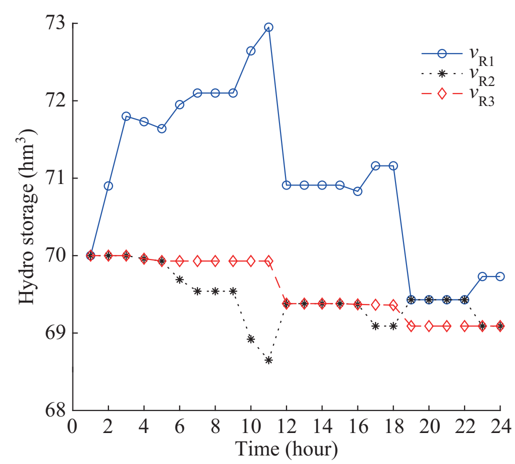

Fig. 8. Reservoir volume evolutions for the optimal solution wind forecasting deviations.

The optimal power values, for both cases, are presented numerically in Table I and Table II.

TABLE I
HYDRO OPTIMIZATION SOLUTION WITHOUT WIND DEVIATIONS

Hour	Energy prices (€/MWh)	Wind power forecasted (MWh)	Wind power supplied (MWh)	Hydro power of R1 (MWh)	Hydro power of R2 (MWh)	Hydro power of R3 (MWh)	Total hydro power (MWh)
1	41	10	10	0	0	0	0
2	35	10	10	0	0	0	0
3	27	25	25	0	0	0	0
4	9	20	20	0	0	0	0
5	12	20	20	0	0	0	0
6	35	25	25	0	0	0	0
7	47	35	35	0	0	0	0
8	62	45	45	0	0	0	0
9	59	40	40	0	0	0	0
10	57	50	50	0	0	0	0
11	50	30	30	0	0	0	0
12	75	30	30	58	54	66	178
13	55	40	40	0	0	0	0
14	43	30	30	0	0	0	0
15	48	30	30	0	0	0	0
16	45	25	25	0	0	0	0
17	51	30	30	0	0	0	0
18	62	30	30	0	0	0	0
19	75	25	25	58	56	58	172
20	70	20	20	0	0	0	0
21	62	25	25	0	0	0	0
22	53	30	30	0	0	0	0
23	48	35	35	0	0	0	0
24	41	40	40	0	0	0	0
Total		700	700	116	110	124	350

TABLE II
HYDRO OPTIMIZATION SOLUTION WITH WIND DEVIATIONS

Hour	Energy prices (€/MWh)	Wind power forecasted (MWh)	Wind power supplied (MWh)	Hydro power of R1 (MWh)	Hydro power of R2 (MWh)	Hydro power of R3 (MWh)	Total hydro power (MWh)
1	41	10	10	0	0	0	0
2	35	10	10	0	0	0	0
3	27	25	25	0	0	0	0
4	9	20	10	2.4	3.4	4.2	10
5	12	20	10	2.6	3.4	4.0	10
6	35	25	35	0	0	0	0
7	47	35	40	0	0	0	0
8	62	45	45	0	0	0	0
9	59	40	40	0	0	0	0
10	57	50	70	0	0	0	0
11	50	30	40	0	0	0	0
12	75	30	30	69.0	44.0	65.0	178
13	55	40	40	0	0	0	0
14	43	30	30	0	0	0	0
15	48	30	30	0	0	0	0
16	45	25	15	3.0	3.3	3.7	10
17	51	30	40	0	0	0	0
18	62	30	30	0	0	0	0
19	75	25	25	62.0	51.0	59.0	172
20	70	20	20	0	0	0	0
21	62	25	25	0	0	0	0
22	53	30	30	0	0	0	0
23	48	35	45	0	0	0	0
24	41	40	40	0	0	0	0
Total		700	735	139.0	105.1	135.9	380

According to the characteristics of the hydro production units, it is necessary for 1 hm^3 of water to produce 35 MWh. For the case of wind deviations, the additional flow is turbined at 4^{th}, 5^{th}, and 16^{th} hours to balance the wind power forecasting default. Regardless of the energy price, the hourly production is guaranteed, complying with the market bid contracted. The turbine flows at the 12^{th} and 19^{th} hours correspond to a production of 350 MWh, the same as before for the case without wind forecasting deviations. In both cases, the observable flows in the 12^{th} and 19^{th} hours correspond to a hydro production of 350 MWh.

In Table III, the detailed benefits throughout the day are presented together with the economic balance of the two energy producers. The benefits of the H-GENCO resulting from the pumped water with wind surplus are evaluated at the price of the corresponding times. The losses of the hydro producer (presented as benefits for the W-GENCO) resulting from water discharge used for compensating wind shortfalls are also evaluated at the corresponding price. The higher aggregate benefits shown for the hydro producer in this particular day result from the fact that the pumped water is turbined at times where the prices are low enough to compensate for the deviations between surplus and shortfall wind production and the roundtrip pumping inefficiencies.

IV. IMPLICATIONS OF WIND FORECASTING UNCERTAINTY

Errors in wind power prediction have an impact on the optimal solution for joint operation in an asymmetric way: the forecasting default errors tend to correspond to a more important depreciation in the performance of the solution than the valuation corresponding to the errors by excess. This is due to the roundtrip inefficiency of pumped storage.

Therefore, in order not to jeopardize the future efficiency of the hydro operation, the hydro-wind joint operation should seek to correct this asymmetry and be more conservative in the bidding of wind production.

Assuming that hydro and wind producers jointly bid into the market, the bidding strategy of the wind power producer should be based on underestimated forecasting in order not to negatively affect the performance of the hydro producer. Otherwise, the hydro producer will not have an incentive to join the wind producer in the bidding process. The higher the uncertainty of the wind forecasting is, the more conservative the wind production biddings should be.

In this section, we quantify the depreciation of the wind bids with respect to the forecasting necessary to neutralize the effect of the asymmetry by expressing such depreciation as a function of the forecasting uncertainty itself.

TABLE III
BENEFITS FROM ENERGY PRODUCTION DEVIATIONS

Hour	Energy price (€/MWh)	W-GENCO benefits (€/h)	H-GENCO benefits (€/h)
1	41	0	0
2	35	0	0
3	27	0	0
4	9	90	0
5	12	120	0
6	35	0	350
7	47	0	235
8	62	0	0
9	59	0	0
10	57	0	1140
11	50	0	500
12	75	0	0
13	55	0	0
14	43	0	0
15	48	0	0
16	45	450	0
17	51	0	510
18	62	0	0
19	75	0	0
20	70	0	0
21	62	0	0
22	53	0	0
23	48	0	480
24	41	0	0
Balancing		660	3215

It is a complex task to characterize the wind forecasting uncertainty realistically [24]. For a low wind power forecasting, the forecasting tends to under-predict the actual wind power produced, whereas when the forecasting is for high power, it tends to over-predict the actual wind power. Most works in this field neglect the influence of wind forecasting levels on forecasting uncertainty, and analyze wind forecasting errors as a whole [25]. Here, we consider that the uncertainty regarding the forecasting of wind production profile can be well enough represented by two symmetric scenarios relative to the forecasting profile level, one that deviates upwards p_{wkp}^{up} and another that deviates downwards p_{wkp}^{dn}, i.e.:

$$p_{wkp}^{up} = (1+\delta)p_{wkp}^{av} \tag{15}$$

$$p_{wkp}^{dn} = (1-\delta)p_{wkp}^{av} \tag{16}$$

where δ is the deviation wind energy relative at average wind production; and p_{wkp}^{av} is the average forecasted energy production by wind farm in hour k.

The scenario representation of uncertainty is simple, but it is crucial to focus our analysis onto the intrinsic asymmetry of optimal solutions, ignoring other asymmetries such as those of wind forecasting uncertainty and their dependence on wind forecasting itself.

To analyze the intrinsic asymmetry of optimal solutions, we designate the value of the optimal solution for the joint bids found for the expected value of the forecasting by Ψ, and the values of the optimal solutions for each of the symmetric scenarios by Ψ^{up} and Ψ^{dn}, respectively. The effect of asymmetry can be evaluated by comparing the optimal solution for the expected value of the forecasted Ψ with the average value of the optimal solutions of each scenario, as explained in (17). We designate the first solution Ψ as the deterministic equivalent value, and the second solution Ψ^{u} as the under-uncertainty value defined by:

$$\Psi^{u} = \frac{\Psi^{up} + \Psi^{dn}}{2} \tag{17}$$

The results of the comparison between the deterministic equivalent and the under-uncertainty values are presented in Table IV for the case study.

TABLE IV
EFFECT OF UNCERTAINTY ON OPTIMAL SOLUTION VALUE

Deviation	Ψ^{up}	Ψ^{dn}	Ψ^{u}
$\delta = 0$ ($\Psi^{u} = \Psi$)	1398.9	1398.9	1398.9
$\delta = 0.1$	1485.1	1282.8	1383.9
$\delta = 0.2$	1570.0	1166.8	1368.4
$\delta = 0.3$	1653.4	1050.7	1352.1

The results of the comparison show that the deterministic equivalent is always optimistic in the sense that it "predicts" results that are always higher than the under-uncertainty values. Moreover, the comparisons show that the higher the forecasting error is, the more optimistic the result is. Note that the last column of Table V presents decreasing values of Ψ^{u} with respect to deviation δ.

In face of the inherent uncertainty of wind power forecasting, the decision to make joint bidding based on deterministic equivalents of such power production does not consider wind uncertainty. This represents an unjustifiably optimistic attitude that ultimately compromises the efficiency of the hydro operation, whose role is central in correcting wind forecasting deviations.

To correct the depreciation trend in hydro operation efficiency, bidding should be based on more conservative forecastings and reduce the expected value of forecasting p_{wkp}^{av} by an appropriate factor. This factor can be determined as a function of the forecasting errors, represented by the two scenarios deviated by δ.

The problem of determining the adequate factor to correct the depreciation trend can be formulated as the following problem:

$$p_{wkp}^{*}: \Psi^{*} = \frac{\Psi^{up} + \Psi^{dn}}{2} \tag{18}$$

$$\Psi^{*} = \max\left(\sum_{k=1}^{K} \sum_{j=1}^{J} p_{hkj} + \sum_{k=1}^{K} p_{wkp}^{*} + \sum_{k=1}^{K} p_{pkj} \right) \tag{19}$$

where p_{wkp}^{*} is the wind energy needed to correct the asymmetry effect at hour k. The corrections to the original predicted values are presented in Table V for the case under study. The values presented for the forecasting corrections are obtained as percentage variations ε of the original prediction, calculated with (20).

$$\varepsilon=\frac{p_{wkp}^{*}-p_{wkp}^{av}}{p_{wkp}^{av}} \tag{20}$$

TABLE V
NECESSARY CORRECTIONS TO WIND PREDICTED VALUES

Deviation	ε (%)
$\delta=0.1$	−1.23
$\delta=0.2$	−2.53
$\delta=0.3$	−3.87

The corrections are negative and of small magnitude, even for significant uncertainties in the wind production forecasting. Note that if the uncertainty needs to be represented by two scenarios of ±30%, the correction to the expected value of the wind production required to avoid depreciating hydro efficiency is found to be less than 4%.

The necessary small corrections to keep the hydro efficiency unchanged indicate that joint bidding with hydro producers is a promising strategy to engage important energy resources such as wind in pool market participation.

V. CONCLUSION

The restructuring of electricity sector has promoted important changes in the planning and operation of electric power systems, which creates a competitive environment where all producers aim to optimize the entire production process to increase their profits.

Wind production plays a particularly important role in the global energy landscape, but it presents predictability problems that may jeopardize the profits of owners in such market environments. In this context, the possibility of a wind producer to make joint bidding with hydro producers seems promising. This study formulates the optimal joint bidding problem under deterministic scenarios of wind production, and illustrates its solution with a simple three-reservoir cascade. The effects of uncertainty in wind forecasting are then analyzed to conclude that wind power deviations from the predicted wind have asymmetric effects on the optimal revenues of hydro producers. The problem is subsequently formulated to optimally correct the expected wind production to neutralize such effect, and in this way, to allow hydro producers to make joint bidding with wind producers without compromising their revenues. Finally, the solution of the problem for correcting the wind forecasting is illustrated and discussed.

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