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Pumped-Storage Plant as a Good Complement for Wind and Solar Plants

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Abstract*—One of the main obstacles in wind and solar power penetration is intermittence. So to cope with this problem Pumped-Storage Plant (PSP) has been proposed as a good complement that can handle positive and negative imbalances. This paper, with the goal of imbalance cost minimization and profit maximization, proposes a stochastic model for optimal energy management. In this paper, the uncertainties related to the forecasted values for available output power of wind and solar units, imbalance market price and market price are modeled by a scenario-based stochastic programming. Scenarios, in the presented method, are generated by a roulette wheel mechanism based on probability distribution functions of the input random variables. Then in order to increase the optimization process speed, number of scenarios is decreased in a scenario reduction process. Finally the proposed offering model is compared with disjoint operations of wind, solar and pumped-storage and it has proved improvement and satisfactory results of joint operation profit.

Keywords: Joint operation, Pumped-storage plant (PSP), Solar plant, Uncertainty, Wind plant

I. INTRODUCTION

Today, world is facing major and serious environmental challenges like irregular weather patterns, global warming, rising fossil fuel prices, oil insecurity and concerns about climate change due to overuse of coal, oil and nuclear energy. These issues encourage the researchers for environmental friendly alternative solutions [5]. On the other hand, deregulating in power systems has motivated the electricity companies to utilize the distributed generators near the energy consumers [2]. GENCo's, which participate in the market, are expected to present offers and deliver the accepted amount of energy in a given period. So, participation of wind and solar power producers in the market without considering supportive strategies may reduce their profits, due to the uncertain behavior of wind and solar power generation [16]. Large-scale integration of Variable Renewable Electricity Sources (VRES), bring remarkable uncertainty into operation and planning of electrical power systems. Electric Energy Storage (EES) is considered as a tool for mitigating the impacts of VRES uncertainty [9-12].

Above claims have encouraged many researches to perform some studies in order to optimize DGs' profit and minimize their cost. In [15], an offering strategy for wind power producers under New Electricity Trading Arrangements (NETA) rules is proposed, allowing participants to offer only a few hours before the operation time. Recently, joint of wind farms and other units are studied in many articles. In this regard, the modelling of Joint Operation (JO) of wind farms and hydro-power units is studied in [8]. This model is used to simulate different market scenarios and to determine the optimal bidding strategy of units to reduce the imbalance cost of wind farms. JO modelling of pumped-storage units and wind farms is investigated in [17]. In [3], JO modeling and the simulation of wind farms and solar radiation system are performed without considering their uncertainties. Pumped-storage plants have high ability to manage the positive and negative energy imbalances of other units by scheduling the transmission of the water between their upper and lower reservoirs [6], [4]. In [6], bidding strategy for wind power generation by considering uncertainties of market price is presented and pumped-storage unit is used as a complementary unit to cover wind uncertainties.

In this paper pumped-storage unit is used to complement positive and negative imbalances of wind and solar power. The rest of the paper is organized as follows: In section 2 nomenclatures are listed. In section 3 the problem is presented in detail. Section 4 presents the proposed method for modeling the uncertainty of wind and solar power production and market prices. Section 5 is devoted to the mathematical formulation of the separate and integrated operation of wind, solar and pumped-storage units. The comparative analyses are presented in section 6. Finally section 7 concludes this paper's findings.

II. NOMENCLATURE

S, s	Index of scenarios.
H, h	Index of hourly periods.
η	Pump-turbine cycle efficiency [p.u.].
N	Number of pumped-storage units.
g_{sh}^{PV}	The forecast of solar power generation in scenario s and period h [MW].
g_{sh}^{W}	The forecast of wind generation in scenario s and period h [MW].
π_{sh}	Expected market price in scenario s and period h [$/MWH].
ρ_s	Probability of scenario s [p. u.].

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g^{Wmax}	Wind unit installed capacity [MW].
g^{PVmax}	Solar unit Installed capacity [MW].
c^{su}, c^{sd}	Start-up and shut-down costs of pumped-storage units [$].
v^{du}, v^{dl}	Lower reservoir capacity limits [MWH].
v^{uu}, v^{ul}	Upper reservoir capacity limits [MWH].
vf^{u}, vf^{l}	Final levels in upper and lower reservoir [MWH].
d^{lp}, d^{up}	Pumping power limits for each pumped-storage unit [MW].
v^{u}_{sh}, v^{l}_{sh}	Energy stored in upper and lower reservoir in scenario s at the end of period h [MW].
x^{PV}_{h}	Energy bid by solar unit to the day-ahead market in period h [MW].
x^{W}_{h}	Energy bid by the wind unit to the day-ahead market in period h [MW].
x^{P}_{h}	Energy bid by pumped-storage units to the day-ahead market in period h [MW].
x^{PVWP}_{h}	Energy bid by coordinated wind, solar and pumped-storage units to the day-ahead market in period h [MW].
α^{+}_{sh}	Positive imbalance price ratio in scenario s and period h.
α^{-}_{sh}	Negative imbalance price ratio in scenario s and period h.
$\Delta^{+W}_{sh}, \Delta^{-W}_{sh}$	Excess and lack of wind power with respect to the schedule in scenario s and period h [MW].
$\Delta^{+PV}_{sh}, \Delta^{-PV}_{sh}$	Excess and lack of solar power with respect to the schedule in scenario s and period h [MW].
$\Delta^{+P}_{sh}, \Delta^{-PV}_{sh}$	Excess and lack of pumped-storage unit's power with respect to the schedule in scenario s and period h [MW].
Δ^{+PVWP}_{sh}	Excess of wind, solar and pumped-storage power with respect to the schedule in scenario s and period h [MW].
Δ^{-PVWP}_{sh}	Lack of wind, solar and pumped-storage power with respect to the schedule in scenario s and period h [MW].
d^{P}_{sh}	Pumping power input of the pumped-storage plant in scenario s and period h [MW].
g^{P}_{sh}	Discharge power output of the pumped-storage plant in scenario s and period h [MW].
Δ^{W}_{sh}	Total power deviation of the wind with respect to the schedule in scenario s and period h [MW].
y_{sh}, z_{sh}	Number of start-up and shut-down units in the pumped-storage in scenario s and period h.
t_{sh}	Binary variable which indicate the pumped-storage plant can work as a turbine or not, in scenario s and period h.
u_{sh}	Integer variable that indicates the plant can work as a turbine or not.

III. PROBLEM DESCRIPTION

The trading energy market for both suppliers and consumers is the day-ahead market, where they submit their hourly bids to the market operator in this paper.

A. Wind Power Stochastic Approach

Estimating the amount of wind power which will be generated in next 24 hours is the first step for participating wind power in day-ahead market [7]. To do this task, generated power for each hour of next day is forecasted by using Neural Networks (NN); but there is always an error between predicted value and real one. So to improve the efficiency of prediction method, diurnal, seasonal and annual characteristics of the wind speed should be included to minimize the prediction error. Consequently generated powers of wind turbines are predicted [10].

B. Solar Energy

Solar technology is one of the most environment friendly technologies. It requires only sunlight and no other energy fuel. As mentioned above, solar radiation for each hour of next day should be predicted using neural networks. The solar power generation for any solar radiation can be predicted by using the following equation:

$$p_{pv} = A_{pv}x^2 + B_{pv}x + C_{pv} \quad (1)$$

The power-radiation curve of solar energy is shown in figure 1.Due to the randomness nature of solar radiation, like wind power, there would be an amount of error between real and forecasted value.

C. Pumped-storage Plant

Assume that the generation company decides to build a PSP in order to give support to its wind and solar generation. If energy production is complemented with a pumped-storage plant, the flexibility provided by this facility can substantially help the producer to comply with commitments acquired in the market. For instance, suppose that in the real time operation, the owner of the wind and solar farm observes that the production is higher than the scheduled amount in the market. In such a situation, the excess of energy could be used to pump water from the lower reservoir to the upper one in order to storage the surplus energy. In the opposite case, i.e. when the production is smaller than the scheduled program, the lack of energy could be obtained by the hydro turbine. This way, the net power delivered to the network could follow very accurately the schedule cleared in the market, although such accuracy would also rely on the technical characteristics of the pumped-storage facility such as capacity of the upper and lower reservoirs, number of units, discrete operating points, etc. The basic operation concept of pumped storage plant is very much similar to the conventional hydro power plant [11-12].

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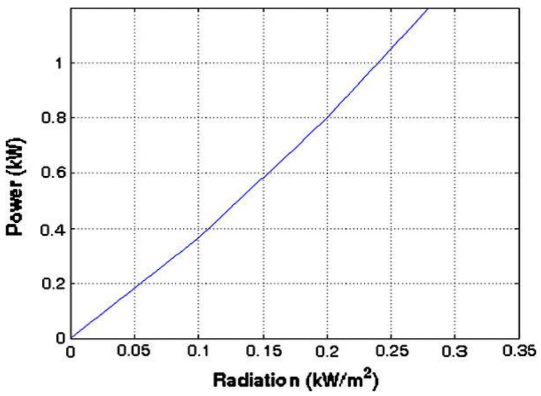

Fig.1. Power-radiation curve of solar energy.

IV. MODELING UNCERTAINTIES

The scheduling problem can be converted to stochastic optimization problem in order to determine the optimal bidding strategy of the units by considering uncertainties. The stochastic optimization problem could be converted to a deterministic one by using the concept of the expected value. In this problem, the uncertain variables are the marginal price, imbalance price, solar radiation and power output of wind turbine units in the study horizon. In order to model these uncertainties, scenario-generation process and scenario reduction methods should be performed.

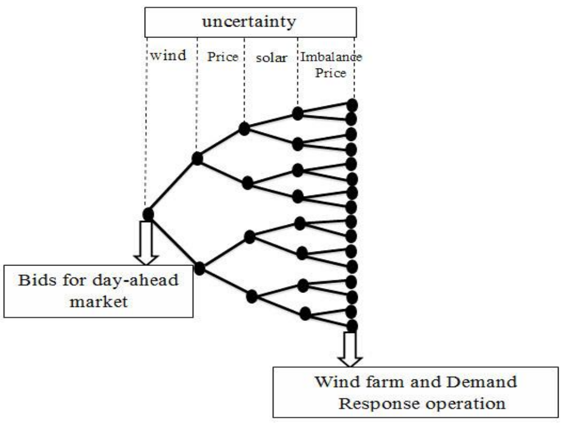

Fig.2. Four source uncertainty tree.

A. Scenario-Generation Process

The following steps should be performed to generate scenarios.

- Wind speed is predicted for 1 month period by historical values of wind speed.
- The prediction error hourly values for the respective month are obtained as follows:

$$error_t = \frac{S_t - \overline{S_t}}{S_t} \times 100 \quad (2)$$

Where S_t and $\overline{S_t}$ are the real and forecasted values of wind speed at hour t, respectively.

- Hourly error values are categorized in 1% distances and each category is corresponding to a probabilistic scenario. After summation the number of error values and computing the density of error in each category, by dividing the number of hourly error values in each category to the whole number of hours in the respective month, probability distribution function of the prediction error is calculated.
- According to different categorizes and probabilities which obtained by their distribution function, Roulette Wheel mechanism is applied to generate favorite number of scenarios for each hour.
- By predicting wind speed of the next 24 hour, wind speed of each scenario is obtained as:

$$S_{i,t} = \hat{S}_{i,t} + e_i \times \overline{S_{i,t}} \qquad i = 1, \ldots, I \quad (3)$$

Where $S_{i,t}$ is the likely wind speed of hour t in the ith scenario; e_i represents the corresponding error of the ith scenario and I (here 10) is the number of all scenarios. Distribution function of prediction error is obtained from hourly prediction error from Sotavento wind farm in this period (9/Jan/2021-9/Feb/2021).

- Consequently, wind speed at each scenario of each hour is converted to wind power and then the probability of each scenario should be calculated.

In this paper in addition to wind power, day-ahead market price, imbalance market price and solar radiation are also assumed to be uncertain and previous steps are repeated to generate 10 scenarios for each one. Totally 10000 scenarios are made to model uncertainties. The stochastic tree used in this paper is shown in figure 2.

B. Scenario-Reduction Process

In order to increase the optimization process speed, number of scenarios is reduced in a way that the similar scenarios or the ones that have very small probability of occurrence, have been omitted. Although a higher number of scenarios can result in a better modeling of the uncertainty while it requires a higher computational burden, but a proper scenario reduction strategy can also keep a good approximation of system's uncertain behavior [6]. For using scenario reduction process following steps should be applied:

- Consider S as an initial set of scenarios and DS is the scenarios which should be deleted. The initial DS is null. Compute the distance of all scenario pairs by using (4):

$$DT_{s,s'} = \sqrt{\sum_{i=1}^{d} \left(v_i^s - v_i^{s'}\right)^2} \qquad s, s' = 1, \ldots, N \quad (4)$$

- For each scenario k, $DT_{k,r} = min DT_{k,s'}, s', k \in S$, r is the scenario index which has the minimum distance with scenario k.
- For each scenario, calculate $\pi_s \times DT_{k,r}$ and select the d as the scenario which has minimum amount. The selected scenario is the one which has the least happening probability and the most similarity to other scenarios.
- Compute S=S-$\{d\}$, DS=DS+$\{d\}$, $\pi_r = \pi_r + \pi_d$.
- Repeat steps 2-4 till the mitigated number confronts our favorite request which is assumed to be 256 in this paper.

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V. Mathematical Formulation

In this paper two different configurations are studied: Uncoordinated Operation (UO) and Joint Operation (JO) are studied for selling and buying power in the market. Figure 3 shows JO schematic representation of all utilities in the day-ahead market.

A. Uncoordinated Operation (UO)

The wind, solar and pumped-storage units try independently to maximize their incomes from selling energy to the day-ahead market and reduce penalization for imbalance, when operating in a separate way. The two maximization problems can be solved separately and each utility makes its bids to the market while satisfying its own technical constraints.

B. Wind unit modeling

The objective function aims to maximize income obtained from selling the offered wind generation, minus a penalization for the deviations from the bid X_h^W. The proposed model has decomposed the imbalances of wind power into the sum of positive and negative imbalances, Δ_{sh}^{+w} and Δ_{sh}^{-w}. In the optimal vector, one of these imbalances is always zero and ratio of penalty factor are greater than 1 when there is lack of generation and it is less than 1 when there is excess of generation.

$$\max \sum_{s\in S}\rho_s \sum_{h\in H}\left(\pi_{sh}.X_h^W + \alpha_{sh}^{+}.\pi_{sh}.\Delta_{sh}^{+W} - \alpha_{sh}^{-}.\pi_{sh}.\Delta_{sh}^{-W}\right) \quad (5)$$

Constraints:

$$0 \le X_h^W \le g^{Wmax} \quad (6)$$

$$\Delta_{sh}^{-W} = X_h^W - g_{sh}^W \quad (7)$$

$$\Delta_{sh}^{+W} = g_{sh}^W - X_h^W \quad (8)$$

$$\Delta_{sh}^{W} = \Delta_{sh}^{+W} - \Delta_{sh}^{-W} \quad (9)$$

$$\Delta_{sh}^{W} = g_{sh}^W - X_h^W \quad (10)$$

$$0 < \Delta_{sh}^{-W} < g^{Wmax} \quad (11)$$

$$0 < \Delta_{sh}^{+W} < g_{sh}^{W} \quad (12)$$

Equation (5) has made up of three parts: the first part represents wind power producer's income from selling offered power in day-ahead market, the second part indicates the income of producing more than the offered value, in this case exceeded energy is sold cheaper than day-ahead market's price so 0< α_{sh}^{+} <1. The last sentence shows production penalty when produced value is less than offered one, so lack of energy is bought more expensive than day-ahead market's price and $\alpha_{sh}^{-} \succ 1$ [1].

C. Solar unit modeling

Solar unit modeling is as the same as wind power and its generation is free. Here it is enough to substitute solar energy in the above formula to find optimal bidding.

$$\max \sum_{s\in S}\rho_s \sum_{h\in H}\left(\pi_{sh}.X_h^{PV} + \alpha_{sh}^{+}.\pi_{sh}.\Delta_{sh}^{+PV} - \alpha_{sh}^{-}.\pi_{sh}.\Delta_{sh}^{-PV}\right) \quad (13)$$

Constraints:

$$0 \le X_h^{PV} \le g^{PVmax} \quad (14)$$

$$\Delta_{sh}^{-PV} = X_h^{PV} - g_h^{PV} \quad (15)$$

$$\Delta_{sh}^{+PV} = g_h^{PV} - X_h^{PV} \quad (16)$$

$$\Delta_{sh}^{PV} = \Delta_{sh}^{+PV} - \Delta_{sh}^{-PV} \quad (17)$$

$$\Delta_{sh}^{PV} = g_{sh}^{PV} - X_h^{PV} \quad (18)$$

$$0 < \Delta_{sh}^{-PV} < g^{PVmax} \quad (19)$$

$$0 < \Delta_{sh}^{+PV} < g_{sh}^{PV} \quad (20)$$

D. Pumped-storage unit modeling

The expected market profit of the pump-storage unit result from selling energy X_h^P to the market, taking into account the pumping start-up and shut-down costs c^{sd} and c^{su}, and a penalization for the deviations from the bid. For each reservoir, the water balance equation must be satisfied, (22) and (23), where the energy pumped from the lower reservoir to the upper is affected by the efficiency. Both reservoirs must satisfy their capacity limits (24) and (25). The energy stored at the end of the time scope considered is given by (26) and (27). In addition, the pumped-storage plant is made up of N identical units, start-up and shut-down costs which considered in the objective function by means of the integer variables y_{sh} and z_{sh}. The variable u_{sh} represents the number of pump-turbine units that are functioning in the hour considered. The logical relations between these variables are considered in (28). The pumping and turbine capacity is limited by the pumped-storage plant characteristics (29) and (30). These capacities also represent a limit to the size of market bids (32). Also, equation (30) guarantees that the pumped-storage plant does not work simultaneously as a pump and a turbine by means of the binary variable t_{sh}. This variable is set to a null value by (31) when any of the units is working as a pump [11-12].

$$\max \sum_{s\in S}\rho_s \sum_{h\in H}[\pi_{sh}.X_h^P - c^{su}.y_{sh} - c^{sd}.z_{sh} + \alpha_{sh}^{+}.\pi_{sh}.\Delta_{sh}^{+P} - \alpha_{sh}^{-}.\pi_{sh}.\Delta_{sh}^{-P}] \quad (21)$$

Constraints:

$$v_{sh}^u = v_{sh-1}^u + \eta.d_{sh}^P - g_{sh}^P \qquad \forall s \in S, \forall h \in H \quad (22)$$

$$v_{sh}^l = v_{sh-1}^l - \eta.d_{sh}^P + g_{sh}^P \qquad \forall s \in S, \forall h \in H \quad (23)$$

$$v^{du} \le v_{sh}^u \le v^{uu} \qquad \forall s \in S, \forall h \in H \quad (24)$$

$$v^{dl} \le v_{sh}^l \le v^{ul} \qquad \forall s \in S, \forall h \in H \quad (25)$$

$$v_{sh}^u = vf^u \qquad \forall s \in S, h = 24 \quad (26)$$

$$v_{sh}^l = vf^l \qquad \forall s \in S, h = 24 \quad (27)$$

$$u_{sh+1} = u_{sh} + y_{sh} - z_{sh} \qquad \forall s \in S, \forall h \in H \quad (28)$$

$$d^{lp}.u_{sh} \le d_{sh}^P \le d^{up}.u_{sh} \qquad \forall s \in S, \forall h \in H \quad (29)$$

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$$0 \le g_{sh}^{P} \le t_{sh}.g^{up}.N \qquad \forall s \in S, \forall h \in H \tag{30}$$

$$t_{sh} \le 1 - \frac{1}{N}.u_{sh} \qquad \forall s \in S, \forall h \in H \tag{31}$$

$$-d^{up}.N \le X_{h}^{P} \le g^{up}.N \qquad \forall h \in H \tag{32}$$

$$u_{sh}, y_{sh}, z_{sh} \in \{0,1,..,N\} \tag{33}$$

$$t_{sh} \in \{0,1\} \tag{34}$$

$$\Delta_{sh}^{+P} = X_{h}^{P} - g_{sh}^{P} + d_{sh}^{P} \tag{35}$$

$$\Delta_{sh}^{-P} = g_{sh}^{P} - X_{h}^{P} - d_{sh}^{P} \tag{36}$$

E. Joint Operation (JO)

In the JO, wind, solar and PSP offer a single bid to the market as:

$$\max \sum_{s\in S}\rho_s \sum_{h\in H}[\pi_{sh}.X_{h}^{PVWP} - c^{su}.y_{sh} - c^{sd}.z_{sh} + \alpha^{+}.\pi_{sh}.\Delta_{sh}^{PVWP} - \alpha^{-}.\pi_{sh}.\Delta_{sh}^{-PVWP}] \tag{37}$$

Constraints:

$$-d^{up}.N \le X_{h}^{PVWP} \le g^{upv} + g^{uw} + g^{up}.N \qquad \forall h \in H \tag{38}$$

$$\Delta_{sh}^{-PVWP} = X_{h}^{PVWP} - g_{sh}^{W} - g_{sh}^{PV} - g_{sh}^{P} + d_{sh}^{P} \tag{39}$$

$$\Delta_{sh}^{+PVWP} = g_{sh}^{W} + g_{sh}^{PV} + g_{sh}^{P} - X_{h}^{PVWP} - d_{sh}^{P} \tag{40}$$

The second group of constrains related to the PSP are exactly like (22)-(31).

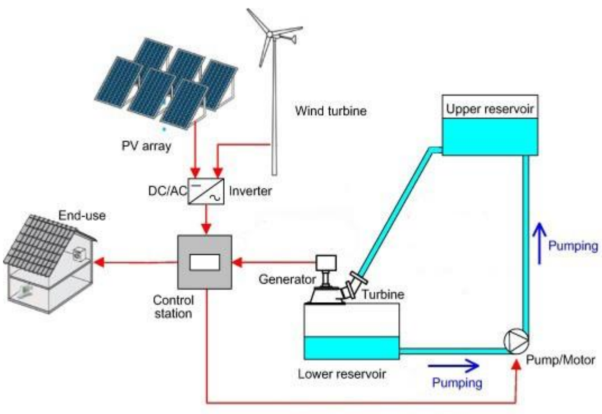

Fig.3. JO Schematic representation.

VI. Numerical Results

In this section, the UO and JO of wind, solar and PSP are simulated and analyzed to show the benefits of JO.

A. Information

A 50 MW wind farm and a 30 MW solar farm, which are consist of twenty 2.5 MW wind turbines and twenty 1.5 MW photovoltaic arrays. The case study is simulated for February 10th- 2021. The Market Clearing Price (MCP) of the Spanish electricity market [14] is used in this section. Also wind speed data of Sotavento wind farm in Spain [13] is used as wind speed prediction data. To convert the wind speed into wind power, the power curve of Nordex N80/2500MW is used. Also a 10 MW pumped-storage plant is taken into account which consists of 2 identical pump operators in a discrete mode of 5 MW. The start-up cost for each unit is considered to be c^{su} = 100$ and the shut-down cost has been fixed to 10% of the start-up cost. The number of scenarios considered in the optimization after scenario reduction process is 1000. The characteristics of pumped-storage plant are shown in table 2.

TABLE I. PSP CHARACTERISTICS.

	v^u	v^l	vf	d^{lp}	$N \times d^{up}$	$N \times g^{up}$
lower	80	0	25	5	10	12
upper	80	0	15	5	10	12

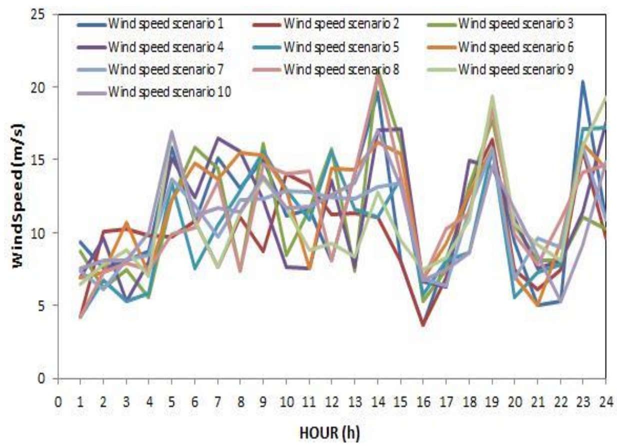

Fig.4. Wind speed scenarios considered in the studied case.

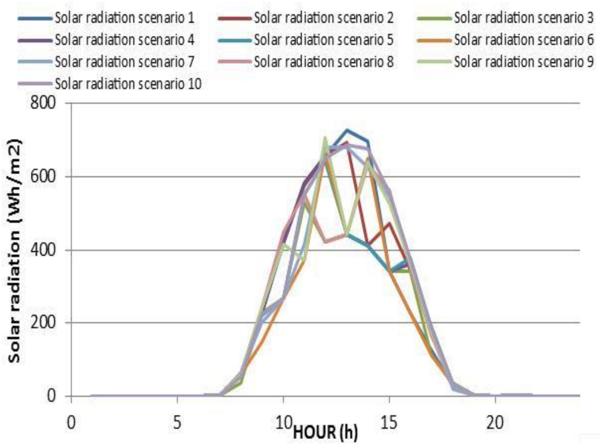

Fig.5. Solar radiation scenarios considered in the studied case.

B. Results

Figures 4-8 show the utilized scenarios for each uncertainty source in the studied case.

The presented model has been implemented in GAMS, using the commercial solver CPLEX to solve the Mixed Integer Linear Programming (MILP) problems. The solution of the optimization models contains the set of optimal bids for the daily market for the configurations considered. Figure 9 shows the hourly bid quantities obtained for each configuration. According to these amounts, offering in the JO increases in expensive hours in comparison with wind and solar independent offers because of the flexible pumped-storage plant's operation. In fact, pump's consumption and reserve increases during cheap hours i.e. store more energy, when the wind and solar output is high. This energy could be sold and complement generation uncertainties of wind and solar in the expensive hours.

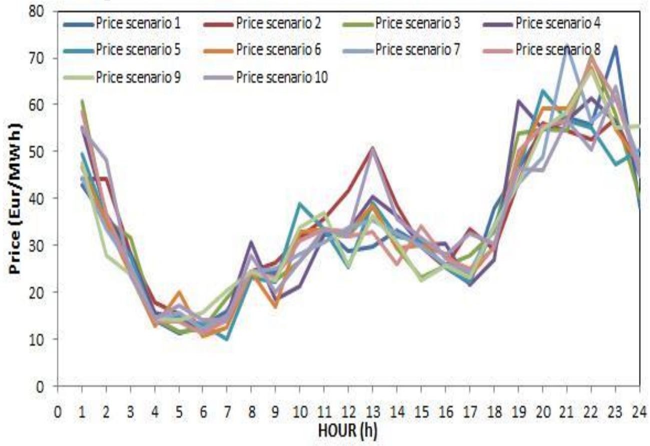

Fig.6. Day-ahead market price scenarios considered in the studied case.

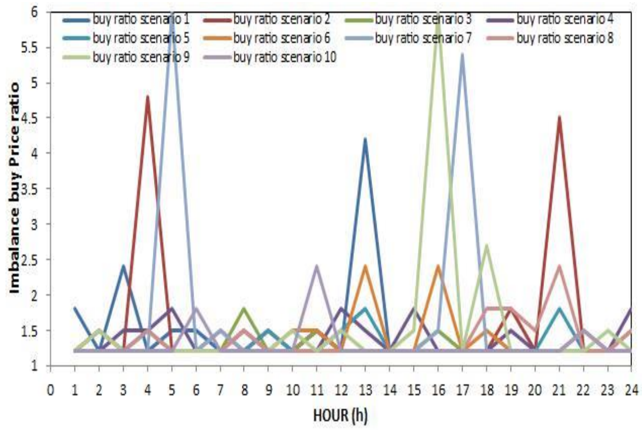

Fig.7. Negative imbalance price ratio scenarios considered in the studied case.

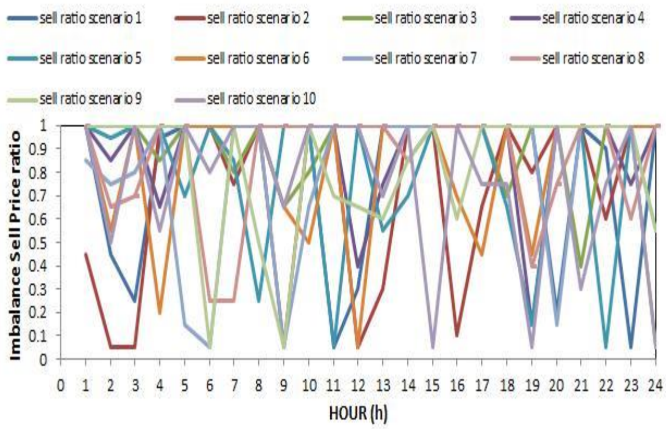

Fig.8. Positive imbalance price ratio scenarios considered in the studied case.

With regard to the expected profits, table 3 shows the results for each configuration. As seen, in the JO, pumped-storage plant provides hedging against solar and wind production uncertainty by pumping water to upper reservoir and saving energy during cheap hours and releasing water and generating energy during expensive hours. It can be resulted that the coordination of all utilities (wind, solar and PSP) represents a 0.6% profit increment in the case study.

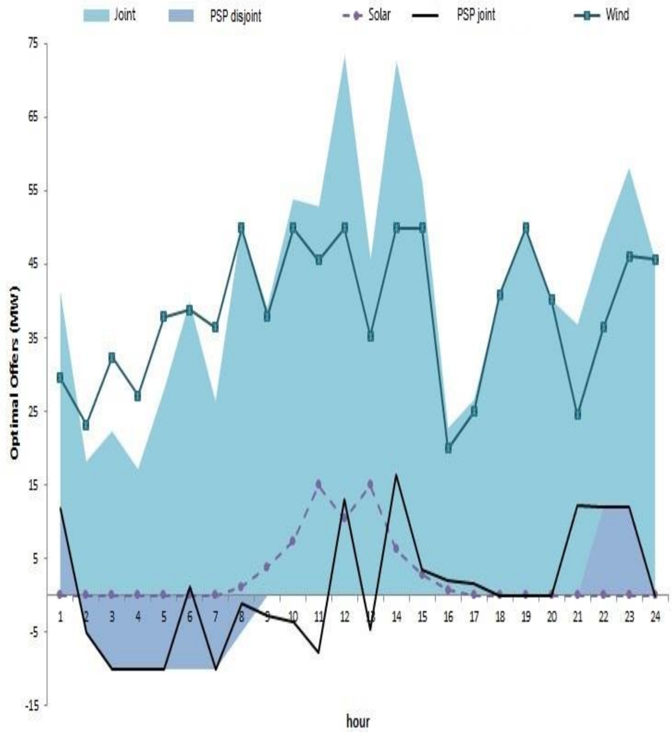

Fig.9. Hourly offering quantities for five different cases on 10/Feb/2021.

Figure 10 shows the resultant operation in the upper reservoir for each scenario. The reservoir level during peak hours reaches the maximum volume due to the pumping process. The operation of the pumped-storage plant for one of the considered scenarios is shown in figure 11 (scenario 102).

TABLE II. EXPECTED PROFITS FOR EACH CONFIGURATION.

Configuration		Profit[$]
	Wind farm	29266
	Solar	2167
	PSP	1005
	Sum (wind, solar and PSP)	32438
JO		32629

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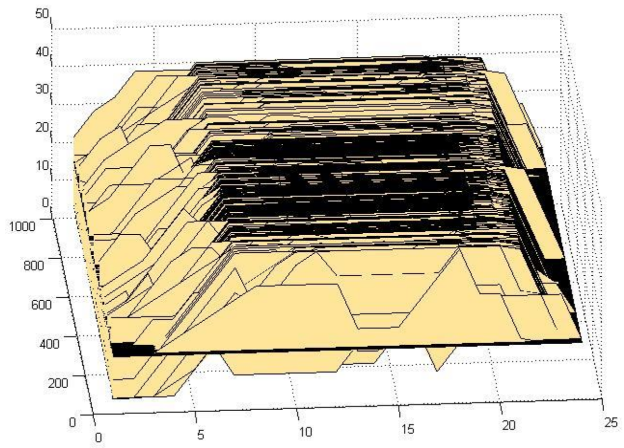

Fig.10. Obtained operation through the day in the upper reservoir for each scenario of JO.

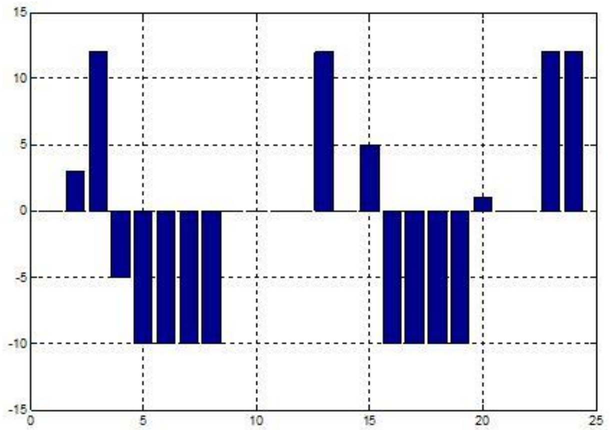

Fig.11. Pumped-storage plant operation in scenario 102.

VII. Conclusion

In this paper, a scenario based method has been used to solve stochastic JO problem of clean sources such as wind, solar and pumped-storage plant with the goal of profit maximization. To consider the uncertainties of wind power, solar radiation, day-ahead market price and imbalance market price, scenario generation process based on roulette wheel mechanism has been used. Then scenario reduction process has been utilized to increase the speed of optimization process.

The four-stage stochastic programming approach has proven to be an effective way to model the real decision-making process that wind and solar power operators face in day-ahead market framework under uncertainty.

The case study results has showed the profit improvement of the JO in comparison with the independent operations of wind, solar and pumped-storage plants and this proves that pumped-storage units have complemented wind and solar power uncertainty effectively. Therefore, pumped-storage plant is a very useful method to store wind and solar power and the amount of profit could be increased by increasing storage capacity.

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