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Research Article

Coordination Scheduling of Wind-Hydropower Generation and Profit Allocation Based on Shapley Value Method

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The volatility of wind makes the forecasting of wind speed unreliable. The inaccurate forecast in wind speed always leads to generation imbalance and causes Wind Generating Companies' (WGenCOs) losses in the intrahour market. In contrast to wind power, Hydrogenerating Companies (HGenCOs) can utilize the reservoir volume to settle the fluctuation of water inflow easily. When treated as a specialized Spinning Reserve (SR) unit for wind power, hydropower can help to settle the generation imbalance and obtain more profit in the power market for both power plants. In this paper, the author establishes a coordination scheduling model of wind-hydro alliance which covers the day-ahead market and the intrahour market. First, to evaluate the deviation of the wind-hydro generation in the intrahour market, an imbalance charge rule considering each period of schedule horizon is constructed. Second, the author introduces two parameters to control the resources that hydropower can use to coordinate with wind power. Finally, the author introduces the Shapley value method to allocate the profit of the alliance which comprises several independent entities fairly. For the simulation of uncertainties, the scenario-based approach is used to simulate the water inflow of a reservoir considering the Monte Carlo (MC) method. The wind speed for the intrahour market is forecasted with the Autoregressive Integrated Moving Average (ARIMA) model. Simulations are implemented, and the results show that when treated as an SR unit for wind power, hydropower can diminish the imbalance charges significantly and will improve the revenue of the wind-hydro alliance. Furthermore, the coordination operation also helps reduce the spillage of the reservoir and the curtailment of the wind power to achieve better utilization of renewable energy.

1. Introduction

The great fluctuation and uncertainty of wind speed make it very difficult to forecast the wind speed [1, 2], which introduces challenges for Generating Companies (GENCOs). The inaccurate forecast in wind speed makes the future horizon schedule unreliable and always leads to generation imbalance charges and causes GENCOs losses [3]. The fluctuations of wind energy may reach a relatively larger ratio of its installed capacity within a short time. The expenditure arising from inaccuracies in wind speed forecasts may cost up to almost 10% of total generation profit [4, 5]. Therefore, the uncertainty of wind speed becomes a potential risk for GENCOs and it becomes important to improve the accuracy of the wind speed forecast. The latest forecasting techniques help improve the accuracy of the wind speed forecast for the next day within an error between 10% and 15% of the installed capacity [6]. However, the accuracy for a particular schedule period is not ideal. Research studies on the forecast of the wind speed have been carried out a great deal. In reference [7], the autoregressive moving average (ARMA) model is investigated for its use in wind speed forecast and the results are tested through the standard *F*-test and *Q*-statistic method. Furthermore, the ARMA models with consideration of diurnal and seasonal effects were proposed in references [8, 9].

Aside from the volatility of wind speed, the fluctuation of energy price also leads the WGenCOs into disadvantaged status in the power market competition [10]. Zhao developed an Autoregressive Integrated Moving Average model (ARIMA) model to get a better locational marginal price prediction [11]. Based on the wavelet transform theory, the day-ahead electricity prices are forecasted by using the ARIMA model [12].

The stochasticity of wind speed and energy prices together weakens the competitiveness of WGenCOs in the power market [13]. The difficulty of wind speed prediction causes generation deviation and the disability of dispatching the wind power, and it is also very difficult to store and reallocate the wind resources later. Therefore, for WGenCOs, there are few solutions except for imbalance charges and sometimes even the curtailment of the wind.

For HGenCOs, losses from the fluctuation of water inflow can be settled by self-scheduling for most of the cases because of the flexibility and adjustability [14, 15]. Hydropower superiors to the wind power in that it can distribute the water resource flexibly and the water resource can be stored and used for later scheduling.

Taking the characteristic of the flexible operation of the hydropower into consideration, WGenCOs adopt storage units or hydropower units to coordinate the renewable energies [16–18]. Korpaas presents a method in which energy storage is introduced to balance generation errors for wind power generation, and a dynamic programming algorithm is employed to find the optimal energy exchange with the market [19]. The research in [13] constructed an hourly model which consists of wind units and cascaded reservoirs, and the latter is treated as storage to help compensate the generation deviation caused by wind power. The security-constrained daily hydrothermal generation scheduling model which takes into account the intermittency and volatility of wind power generation is proposed [20, 21]. In [22–24], the interval optimization technique for the coordination of hydrounits with wind power generation in Pennsylvania-New Jersey-Maryland (PJM) power market is applied and discussed. Among the related research studies, Liu et al.'s contribution is worth mentioning. Liu et al. discussed the operation policies which include deviation charges in PJM, and instead of applying probability distributions, their work mainly focused on the application of the interval numbers on the simulation of intrahour energy price and the fluctuations of the wind power generation [23]. However, the water inflow in his work is considered being deterministic and the fluctuations of the hydropower are not considered. In this paper, water inflow is scenario-based to focus on the fluctuation of the hydropower in the wind-hydro alliance.

Another issue this paper looks into is how to distribute the revenue of the power plants properly. Normally, the revenue of the alliance is equally distributed [13] which ignores the marginal contribution from each power plant. When both plants operate together, they may help each other to diminish the imbalance charges at the cost of a decrease in revenue for one power plant [25]. Aside from the marginal contribution, in this paper, the Shapley Value method [26] is applied to help distribute the revenue fairly and a case study is also provided.

The main contributions of this paper are as follows. First, a scenario-based model for maximizing the sum of the day-ahead profit and the intrahour profit of the wind-hydro alliance is established. The model includes imbalanced charge rules which help to evaluate the oversupply or undersupply of electric energy in the intrahour market in each period of the schedule horizon. Second, to better allocate the resources that hydropower provides in both markets during coordination operation, two parameters are proposed. Proper combinations of the two parameters can help GENCO obtain more revenue by reducing imbalance charges while maximizing the utilization of the water volume. Third, the introduced Shapley Value method for allocating the profit of the wind-hydro alliance improves the competitiveness of the WGenCOs and stimulates the penetration of nonhydro renewable energy. Finally, the model proposed in this paper can help the GENCO to make better decisions in making the preferred generation plan for wind-hydro alliance through case study and solid data analyzing.

2. Model Formulation

In this paper, a two-stage optimal model for the coordination operation of wind power and hydropower is proposed, in which the volatilities of water inflow are simulated while energy price and wind power for next schedule horizon are forecasted.

2.1. Model Formulation for Wind-Hydro Coordination Problem

2.1. Model Formulation for Wind-Hydro Coordination Problem. For a GENCO, maximizing the payoff of the coordination alliance is known as the object which means the maximum of the difference between the revenue from the sales of energy and the operation cost of GENCO. The operation cost includes the production cost of power plants, the commitments costs, and imbalance charges as a result of the wind power generation volatilities. The author focuses on the coordination strategy of wind and hydropower plants and other costs are neglectable compared to imbalance charges; thus, the reason the costs mentioned above other than imbalance charges are assumed to be zero.

The stochastic problem this paper proposed consists of several two-stage cases. When the parameters are set, the first-stage problem (the day-ahead market problem) will be solved together with maximizing the revenue of hydropower in the day-ahead market as the objective function. The decision variables from first-stage problem will serve as the initial inputs and parameters for the second-stage problem (the intrahour market problem). Each variable in second stage is scenario-based and it will be solved with constraints which will be checked to decide whether the author properly set the parameters in both stages are properly. Furthermore, the parameters will be calibrated until both cases come to convergence. The author discusses next the stochastic formulation for the wind-hydro coordination.

2.1.1. Coordinated Scheduling of Wind-Hydro Alliance. When the coordinated scheduling of hydropower and wind power is considered, the decision variables of wind power and hydropower are correlated. Therefore, the optimal scheduling of the two power plants can be considered two aspects of the same problem. Equation (1) is the objective function of wind-hydro alliance. The stochastic problem refers to the maximizing of the GENCO's expected payoff in both markets. The first term in the objective function is the revenue of both power plants from the day-ahead markets. The second term represents the revenue from the intrahour market which includes the revenue for selling electricity and the imbalance charges for the generation deviation:

$$\text{MaxProfit} = \text{Profit}_{\text{DA}} + \text{Exp}\left[\text{Profit}_{\text{RT}}\right], \tag{1}$$

$$\begin{aligned}\text{Profit}_{\text{DA}} &= \text{Profit}_{\text{DA}}^{\text{wind}} + \text{Profit}_{\text{DA}}^{\text{hydro}} \\ &= \Delta t \sum_{t=1}^{96}\left(P_t^{\text{wind}} * \text{Pr}_t^{\text{wind}} + P_t^{\text{hydro}} * \text{Pr}_t^{\text{hydro}}\right).\end{aligned} \tag{2}$$

The two terms in equation (1) can be expanded into equation (2) and equation (3) that stand for the revenue in the day-ahead market and intrahour market, respectively. Each of them comprises two terms which include the revenue from the two power plants. For equation (2), the wind power output and energy price are deterministic. When it comes to hydropower, a self-optimal scheduling problem is solved and the objective function is to maximize the revenue in the day-ahead market. In the objective function, the decision variable is q_t. Each period in the schedule horizon is 15 minutes; therefore, $T = 96$ in the model:

$$\text{Exp}\left[\text{Profit}_{\text{RT}}\right] = \text{Profit}_{\text{RT}}^{\text{wind}} + \text{Exp}\left[\text{Profit}_{\text{RT}}^{\text{hydro}}\right], \tag{3}$$

$$\begin{aligned}\text{Profit}_{\text{RT}} = &\sum_{k=1}^{96}\left(\Delta P_k^{\text{wind}} * \text{Pr}_k^{\text{wind}} - \left|\Delta P_k^{\text{wind}}\right| * \text{Penalty}_k^{\text{wind}}\right) \\ &+ \Delta t \frac{\Delta t}{\text{scene}} \sum_{s=1}^{\text{scene}} \sum_{k=1}^{T}\left(\Delta P_{k,s}^{\text{hydro}} * \text{Pr}_k^{\text{hydro}}\right. \\ &\left. - \left|\Delta p_{k,s}^{\text{hydro}}\right| * \text{Penalty}_k^{\text{hydro}}\right).\end{aligned} \tag{4}$$

Equation (3) shows that hydropower revenue from the intrahour market is scenario-based; therefore, it is the expected value. However, the decision variable for wind power is the actual power outputs which are not scenario-based.

Equation (4) is the expanded formula for (3). The intrahour revenue contains two terms: one being the revenue from sales that are generated from the electricity of both power plants, and the other being the imbalance charges owing to the generation deviation.

There are ISOs such as PJM, MISO, CAISO, NYISO, ISO-NE, ERCOT, and some European TSOs such as Svenska Kraftnat. Owing to the sophistication of the PJM that has been operating in the U.S. for many years, this paper chooses PJM as a research object. The deviation charges consist of two terms for each power plant: one being the deviation of generation, and the other being the absolute value of the deviation of generation. The author forms the first part according to the operational policy in PJM, which holds a policy that a GENCO will be paid extra when the deviation is greater than the day-ahead contract. Otherwise, the GENCO will have to pay the ISO for the generation shortage. As can be seen in the first term of equation (4) for hydropower it is $\Delta P_k^{\text{hydra}} * \text{Pr}_k^{\text{hydra}}$ and $\Delta P_k^{\text{wind}} * \text{Pr}_k^{\text{wind}}$ for wind power.

For the second term, the policies for both power plants are the same. As the author calculates deviation charges in every time period when taking wind power, for example, no matter the GENCO delivers more generation in the intrahour market or not, the GENCO will have to pay the deviation charges ($|\Delta P_k^{\text{wind}}| * \text{Penalty}_k^{\text{wind}}$). The term $|\Delta P_k^{\text{wind}}|$ is the absolute value of the deviation of wind power generation in period k:

$$\begin{aligned}&\sum_{t=1}^{T} q_t \Delta_t = W_{\text{DA}}, \\ &\sum_{k=1}^{T} q_{k,s} \Delta_k = W_{\text{RT}}^{s},\end{aligned} \tag{5}$$

$$\begin{aligned}v_t &= v_{t-1} + \left(\text{inflow}_t - q_t - q\text{loss}_t\right)\Delta_t, \\ v_{k,s} &= v_{k-1,s} + \left(\text{inflow}_{k,s} - q_{k,s} - q\text{loss}_{k,s}\right)\Delta_k,\end{aligned} \tag{6}$$

$$\begin{aligned}P_t^{\text{hydro}} &= \eta K q_t h_t, \\ P_k^{\text{hydro}} &= \eta K q_{k,s} h_{k,s},\end{aligned} \tag{7}$$

$$\begin{aligned}h_t &= \text{ZV}\left(v_t\right) - \text{ZQ}\left(q_t\right), \\ h_{k,s} &= \text{ZV}\left(v_{k,s}\right) - \text{ZQ}\left(q_{k,s}\right),\end{aligned} \tag{8}$$

$$\begin{aligned}&\underline{P_t^{\text{hydro}}} \le P_t^{\text{hydra}} \le \overline{P_t^{\text{hydro}}}, \\ &\underline{P_k^{\text{hydro}}} \le P_{k,s}^{\text{hydra}} \le \overline{P_k^{\text{hydro}}},\end{aligned} \tag{9}$$

$$\begin{aligned}&\underline{q_t} \le q_t \le \overline{q_t}, \\ &\underline{q_k} \le q_{k,s} \le \overline{q_k},\end{aligned} \tag{10}$$

$$\begin{aligned}&\underline{v_t} \le v_t \le \overline{v_t}, \\ &\underline{v_k} \le v_{k,s} \le \overline{v_k}, \quad \text{when } k \ne T,\end{aligned} \tag{11}$$

$$\begin{aligned}&\underline{q\text{loss}_t} \le q\text{loss}_t \le \overline{q\text{loss}_t}, \\ &\underline{q\text{loss}_k} \le q\text{loss}_{k,s} \le \overline{q\text{loss}_k},\end{aligned} \tag{12}$$

$$P_{k,s}^{\text{hydro}} + P_k^{\text{wind}} = P_t^{\text{hydro}} + P_t^{\text{wind}}, \tag{13}$$

$$\min\left(P_{k,f}^{\text{wind}}, P_{k,\max}^{\text{wind}}\right) \le P_k^{\text{wind}} \le P_{k,\max}^{\text{wind}}. \tag{14}$$

Equation (5) shows the water availability in the day-ahead and the intrahour market. Equation (6) shows the water balance constraints that the reservoir follows. Equation (7) represents the water-to-power conversion relationships of the hydropower plant. Equation (8) shows the calculation of the head of the reservoir. Equations (9)–(12) give the upper and lower limit of other variables. Constraint

(13) shows that both power plants should follow the contracts in the day-ahead market when they are coordinated in the intrahour market. The intrahour operational mechanism of wind power without coordination can be seen in constraint (14). The upper limit of the intrahour wind generation $P_{k,\max}^{\text{wind}}$ is the maximum output available in the intrahour market. The lower limit adopts the lower value between forecasted value ($P_{k,f}^{\text{wind}}$) and the maximum output available for wind power in the intrahour market. This will help to maximize the wind power utilization by reducing the curtailment of wind power.

To analyze the ability of hydropower to coordinate the deviation of wind power generation in the intrahour market, the author introduces a parameter σ to reserve a certain amount of the ability for hydropower generation in the day-ahead market for later use. Therefore, equation (7) becomes equation (15) for the coordination model:

$$P_t^{\text{hydro}} = \sigma\eta K q_t h_t, \quad \sigma \in (0, 1]. \tag{15}$$

Introducing σ offers decision maker (DM) a tool to control the generation potentiality of hydropower, and it serves in a way similar to SR units for the coordination operation in the day-ahead market.

To analyze the maximum utilization of the reservoir volume for hydropower in the intrahour market, the author introduces another parameter ρ which controls the reservoir volume at the end of the scheduling horizon in equation (16). A higher value of ρ means more utilizable of the reservoir volume, and a lower one means lesser consumable volume. This parameter turns the reservoir into an SR unit for wind power in the intrahour market. Therefore, the reservoir volume can be dispatched for coordination when needed. In this circumstance, hydropower undertakes the risks of lesser revenue for being an SR unit for wind power:

$$\rho v_{\text{ini}} \le v_{T,s}^{\text{end}} \le (2-\rho) v_{\text{ini}}, \quad \rho \in (0, 1]. \tag{16}$$

The difference between the two parameters is that though they both treat the reservoir as an SR unit, they have dissimilar ways of achieving it. The former achieves it by calibrating the power outputs in the day-ahead market without changing the reservoir volume consumed and the latter consumes more reservoir volume in the intrahour market.

When both power plants operate alone, the author builds a model for the uncoordinated scheduling. Equations (1)–(12) can be reused, while equations (13) and (14) turn into (17) and (18):

$$\begin{aligned} P_k^{\text{hydra}} + \Delta P_{k,s}^{\text{hydra}} &= P_t^{\text{hydra}}, \\ P_k^{\text{wind}} + \Delta P_k^{\text{wind}} &= P_t^{\text{wind}}, \end{aligned} \tag{17}$$

$$P_k^{\text{wind}} = \min\left(P_{k,f}^{\text{wind}}, P_{k,\max}^{\text{wind}}\right). \tag{18}$$

Constraint (17) shows that the intrahour market for both power plants should follow the contract in the day-ahead market separately when they run alone. The intrahour operational mechanism of wind power without coordination can be seen in constraint (18). The wind power can fulfill the contract only when $P_{k,\max}^{\text{wind}} \ge P_{k,f}^{\text{wind}}$, otherwise wind power will face balance chargers for generation shortage in intrahour market. When $P_{k,\max}^{\text{wind}} > P_{k,f}^{\text{wind}}$, curtailment of wind power occurs.

2.1.2. The Solving of the Coordinated Wind-Hydro Alliance. The stochastic problem can be decoupled into several two-stage cases. When the parameters are set, the author can solve the first-stage problem (the day-ahead market problem) together with maximizing the revenue of hydropower in the day-ahead market as the objective function. The decision variables from first-stage problem will serve as the initial inputs and parameters for the second-stage problem (the intrahour market problem). Each variable in second stage is scenario-based and the author will solve it with constraints which will be checked to decide whether the parameters in both stages are properly set. Furthermore, the parameters will be calibrated until both cases come to convergence.

As for the wind power in the day-ahead market, the wind speed, wind power outputs, and energy price are constant. In the intrahour market, the author forecasts the wind speed, the maximum wind power available, and energy prices with the ARIMA model (will be discussed in Section 3.1) based on the data from the previous day. The intrahour wind power outputs' decision is variable according to the coordination operation. The energy balance price is ISO decided.

As for the hydropower in the day-ahead market, the water inflow and energy price are constant for coordinated and uncoordinated cases. Then, the hydropower plant generates its own generation plan and schedule plan according to the data provided. For the feasibility of coordination operation, constraint (15) must be added for coordination cases in the intrahour market.

As for the hydropower in the intrahour market, constraint (5) should be added for the uncoordinated case. As the major premise of the Shapley Value method (will be discussed in Section 2.1.3), the resources are a member in the alliance injects to both cooperative operation and uncooperative operation must be the same. Therefore, the water consumed for the hydropower generation must be the same for both coordinated and uncoordinated operation. To get the correct water consumption for the uncoordinated case, the research must first obtain the optimal decision the intrahour market when both power plants coordinate. The total water consumption is then determined and used as the constraint for the hydropower when it operates alone.

Figure 1 shows the procedure of solving the coordinated cases proposed in this paper. In the first-stage case, the optimal problem is initialized with the wind speed, water inflow, and energy prices set as inputs for both power plants, and the parameter σ is set according to the preference of the decision maker. Then, the author solves the problem and obtains the decision variables including the power outputs and revenue of both power plants. In the second stage, the decision variables obtained in the first stage is set as the initial conditions and parameter $\rho = 1$ is set as the initial value. The second-stage problem is then solved and the feasibility of the problem is checked. If the optimal problem is infeasible, the parameter ρ will be set lower by a step of 0.05 and the second-stage problem is solved again. This procedure is repeated until the optimal solution is found. If ρ is at the lower bound 0.8, but the optimal problem is still infeasible, then the parameter σ in the first stage should be calibrated. For the reservoir cannot fulfill the contract signed in the day-ahead market with the current parameter combination, the next step is to resolve the intrahour problem again under the new parameter combination. Finally, the whole procedure mentioned above is repeated until the optimal solution is found.

As can be seen in Section 2.1.1, the proposed stochastic scheduling problem for the wind-hydro alliance is an NLP problem with discrete variables; therefore, it is modelled and solved by a Discontinuous Nonlinear Program (DNLP) solver (CONOPT 3.15L) included in GAMS 24.1.3.

2.1.3. The Allocation of Profit Based on the Shapley Value Method. Because of the coordination operation, hydropower undertakes significant risk to help balance the deviation of wind power generation, and this operation will lower its revenue compared to the case it operates alone, and even sometimes unexpected spillage may occur and cause hydropower potential loss. The same thing may happen to the wind power plant when it coordinates to help hydropower, in which unscheduled generation deviation and wind curtailment may also lead to a potential loss. The coordination operation between each power plant mentioned above can be modelled as a cooperative game.

According to game theory, the alliance exists based on two principle rules [27].

For the alliance, the overall revenue is greater than the sum of the revenue when each of its members operates alone.

As far as the alliance is concerned, there should be a Pareto improvement distribution rule for profits, that is, each member can obtain more benefits than when it operates alone.

A cooperative game is defined as follows. There is a set N (of n players) and a function v that map subsets of players to the real numbers: v: $2^N \longrightarrow \mathbb{R}$, with $v(\varnothing) = 0$, where $\varnothing$ denotes the empty set. The function v is called a characteristic function.

If s is a coalition of players, then $v(s)$ values the worth of alliance s. It is the total expected payoffs obtained in the cooperation of all the players of s.

Both power plants cooperate to obtain more profit, and because they both are independent entities, the profit of both members must be fairly allocated according to its contribution to the alliance. For such alliance, the Shapley Value method distributes the profits according to the marginal contribution of each participating members, which perfectly represents the mechanism of the coordination operation and fairly distributes the profits for each member [28].

Before the Shapley value method is applied to distribute the total payoffs to the players, it is assumed that all players are cooperative; then, the amount that player i gets, given in a cooperative game (v, N), is

$$\varphi_i(v) = \sum_{S \subseteq N/\{i\}} \frac{|S|!\,(N - |S| - 1)!}{N!}\,(v(S \cup \{i\} - v(S))), \qquad (19)$$

where N is the total number of players and the sum extends over all subsets S of N without player i. The formula means that, imagining the coalition being formed with one player at a time, each player demands their contribution $v(S \cup \{i\} - v(S))$ as a fair compensation and takes the average of this contribution over the possible different permutations in which the coalition can be formed.

In this paper, the model for the cooperative game of wind-hydro alliance is established and the Shapley Value method is introduced to allocate the profit of the alliance.

According to the analysis above, the Shapley Value for hydropower can be calculated and shown in Table 1:where $\text{Profit}_{\text{DA}}^{\text{hydo}\cdot\text{uc}}$ and $\text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}$ are the day-ahead and the intrahour revenue of hydropower when it runs alone, while $\text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}}$ and $\text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}}$ are the revenue of wind power when it runs alone. $\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}}$ is the total revenue of both power plants when they operate jointly. All the equations listed above can be referred from the equations proposed in Sections 2.1.1 and 2.1.2.

$$\sum \varphi(a)_{\text{hydro}} = \frac{\left(\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}} + \text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}} - \text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}}\right)}{2}, \qquad (20)$$

The first column of Table 2 shows the calculation process of the marginal contribution of the hydropower when it operates alone. In this case, it itself is the alliance. As for the second column, it is the marginal contribution of the hydropower when both power plants coordinate. Then, the sum of the last row in each column in Table 2 presents the marginal contribution in the alliance for hydropower.

Similar to the hydropower case, it is easy to find the marginal contribution to the alliance when the wind power operates alone or coordinates with the hydropower. The Shapley Value for wind power can be calculated, as shown in Table 2.

As can be seen from Table 2, the Shapley Value of the wind power is $\sum \varphi(a)_{\text{wind}}$:

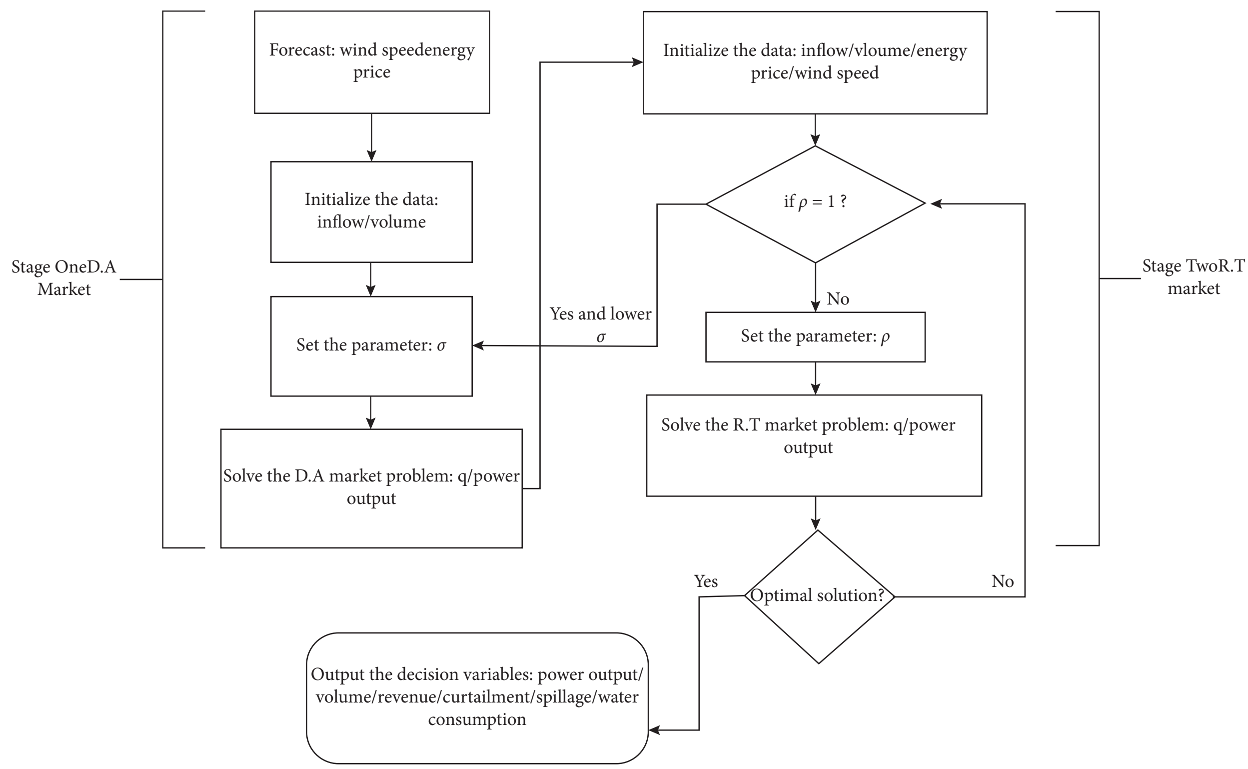

Figure 1: The flowchart of the procedure of solving the coordinated case.

Table 1: The table for calculating the Shapley value of hydropower in both markets.

Alliance s	Hydropower operates alone	Coordinated operation of both power plants
$\nu(s)$	$\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}$	$\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}}$
$\nu(s\backslash a)$	0	$\text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}}$
$\nu(s) - \nu(s\backslash a)$	$\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}$	$\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}} - \text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}}$
$W\|s\|$	1/2	1/2
$\varphi(a)_{\text{hydra}}$	$(\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}})/2$	$(\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}} - \text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}})/2$

Table 2: The table for calculating the Shapley value of hydropower in both markets.

Alliance s	Wind power operate alone	Coordinated operation of both power plants
$\nu(s)$	$\text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}}$	$\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}}$
$\nu(s\backslash a)$	0	$\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}$
$\nu(\text{s}) - \nu(\text{s}\backslash\text{a})$	$\text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}}$	$\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}} - \text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}$
$W\|s\|$	1/2	1/2
$\varphi(a)_{\text{wind}}$	$(\text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}})/2$	$(\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}} - \text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}})/2$

$$\sum \varphi(a)_{\text{wind}} = \frac{\left(\text{profit}_{\text{DA}}^{\text{co}} + \text{profit}_{\text{RT}}^{\text{co}} + \text{Profit}_{\text{DA}}^{\text{wind}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind}\cdot\text{uc}} - \text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}\right)}{2}. \tag{21}$$

Table 3: The table for calculating the Shapley value of the hydropower plant in both markets.

s_i	p_i	$p_i \cup p_j$	$p_i \cup p_k$	$p_i \cup p_j \cup p_k$
$\nu(s)$	$\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}$	$\text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co1}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co1}} + \text{profit}_{\text{DA}}^{\text{wind}\cdot\text{co1}} + \text{profit}_{\text{RT}}^{\text{wind}\cdot\text{co1}}$	$\text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co2}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co2}} + \text{profit}_{\text{DA}}^{\text{wind2}\cdot\text{co}} + \text{profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}}$	$\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{co}'} + \text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{co}'} + \text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}'}$
$\nu(s\backslash a)$	0	$\text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{uc}}$	$\text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{uc}}$	$\text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{uc}} + \text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{uc}}$
$\nu(s) - \nu(s\backslash a)$	$\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}}$	$\text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co1}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co1}} - \text{profit}_{\text{DA}}^{\text{wind}\cdot\text{co1}} - \text{profit}_{\text{RT}}^{\text{wind}\cdot\text{co1}} + \text{profit}_{\text{DA}}^{\text{wind}\cdot\text{uc1}} + \text{profit}_{\text{RT}}^{\text{wind}\cdot\text{uc1}}$	$\text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co2}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co2}} + \text{profit}_{\text{DA}}^{\text{wind2}\cdot\text{co}} + \text{profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}} - \text{profit}_{\text{DA}}^{\text{wind2}\cdot\text{uc}} - \text{profit}_{\text{RT}}^{\text{wind2}\cdot\text{uc}}$	$\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{co}'} + \text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{co}'} + \text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}'} - \text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{uc}} - \text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{uc}}$
$W\|s\|$	1/3	1/6	1/6	1/3
$\varphi(a)_{\text{hydra}}$	$(\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}})/3$	$(\text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co1}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co1}} + \text{profit}_{\text{DA}}^{\text{wind}\cdot\text{co1}} + \text{profit}_{\text{RT}}^{\text{wind}\cdot\text{co1}} + \text{profit}_{\text{DA}}^{\text{wind}\cdot\text{uc1}} + \text{profit}_{\text{RT}}^{\text{wind}\cdot\text{uc1}})/6$	$(\text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co2}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co2}} + \text{profit}_{\text{DA}}^{\text{wind2}\cdot\text{co}} + \text{profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}} + \text{profit}_{\text{DA}}^{\text{wind2}\cdot\text{uc}} + \text{profit}_{\text{RT}}^{\text{wind2}\cdot\text{uc}})/6$	$(\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{co}'} + \text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{co}'} + \text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{co}'} + \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}'} - \text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{uc}} - \text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{uc}} - \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{uc}})/3$

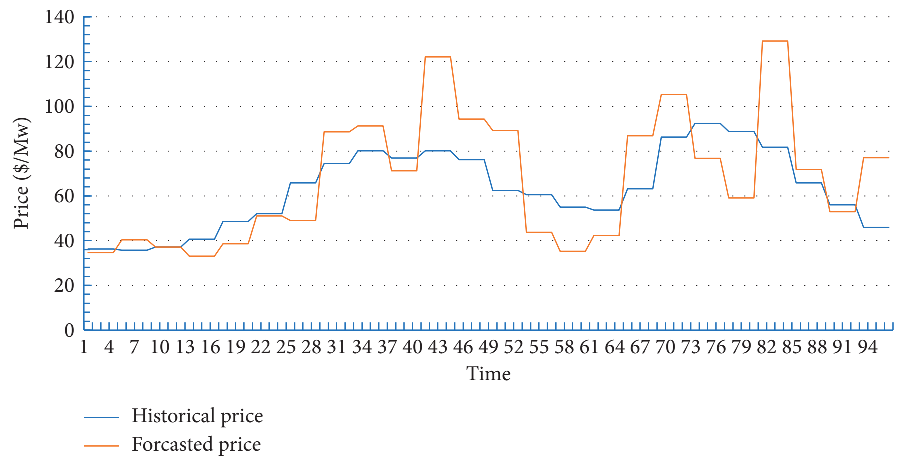

Figure 2: Result of intrahour energy price forecast.

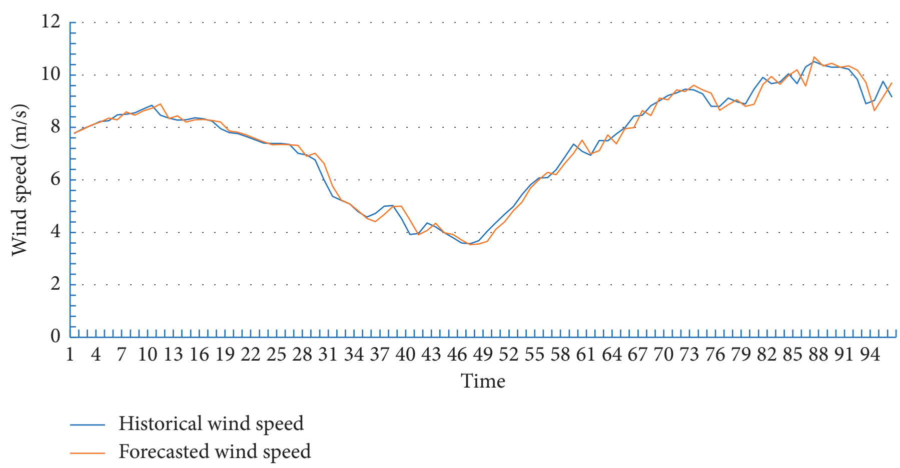

Figure 3: Result of wind speed forecast.

When the case includes three players, similar equations can be listed in Table 3:

$$\varphi(a)_{\text{hydra}} = \frac{\begin{array}{l} 2\text{Profit}_{\text{DA}}^{\text{hydro}\cdot\text{uc}} + 2\text{Profit}_{\text{RT}}^{\text{hydro}\cdot\text{uc}} + \text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co1}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co1}} + \text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{co}} \\ + \text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co2}} + \text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co2}} + \text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}} + 2\text{profit}_{\text{DA}}^{\text{hydro}\cdot\text{co}'} + 2\text{profit}_{\text{RT}}^{\text{hydro}\cdot\text{co}'} \\ + 2\text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{co}'} + 2\text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{co}'} - \text{Profit}_{\text{DA}}^{\text{wind1}\cdot\text{uc}} - 2\text{Profit}_{\text{RT}}^{\text{wind1}\cdot\text{uc}} - \text{Profit}_{\text{DA}}^{\text{wind2}\cdot\text{uc}} - 2\text{Profit}_{\text{RT}}^{\text{wind2}\cdot\text{uc}} \end{array}}{6}. \quad (22)$$

The head of the table shows all the suballiances the plants can make. The indexes i, j, and k used in the above equation represent the hydropower plant and wind farm 1 and wind farm 2, respectively. When the hydropower plant allies with different allies, the profit varies.

The 1st column is the marginal contribution of the hydropower plant. The 2nd column is the marginal contribution of suballiance constituted by the hydropower plant and wind farm 1. Take this column, for example, the 1st cell is the revenue for the suballiance. The 2nd cell indicates the revenue when the wind farm 1 works independently. The rest cells in column 2 are self-understanding. Column 4 is like column 3, as the hydropower plant allies with wind farm 2. When the three plants ally, their marginal contribution can be found in the 4th column. Finally, equation (22) gives the marginal contribution of hydropower.

3. Results and Discussion

3.1. Data Preparation and Scenario Simulation. As described above, a coordination operation of a wind power and a hydropower plant is proposed. In this section, the required

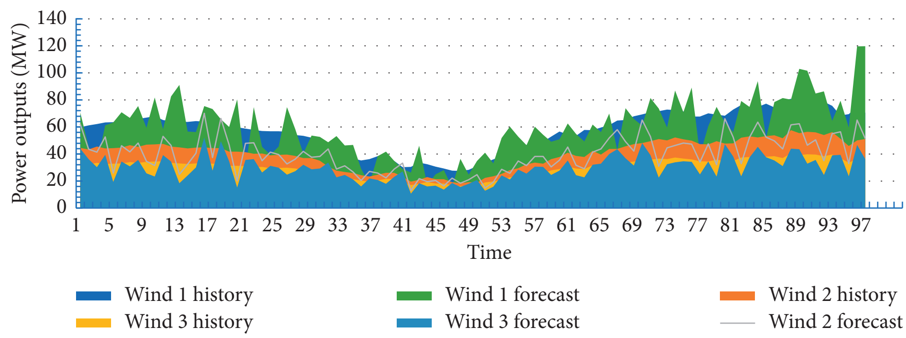

Figure 4: Forecast value considering 20% deviation of wind power outputs.

Table 4: Revenue in both markets for Cases 1–3 under different parameter combinations.

Cases	σ	ρ	WP(DA) ($)	WP(RT) ($)	HP(DA) ($)	HP(RT) ($)	Net WP ($)	Net HP ($)	Revenue of alliance ($)
1	1	1	141758.5	−20036.2	111552.9	0	121722.4	111552.9	233275.3
2.1	1	1	141758.5	−11916.3	111552.9	8296.1	129842.3	126786.8	256629.1
2.2	1	0.95	141758.5	−48.3	111552.9	110201.6	141710.2	221754.5	363464.7
3.1	0.9	1	141758.5	−2307.2	111179.0	2131.1	1139451.3	113310.1	252761.4
3.2	0.85	1	141758.5	−2307.6	110954.4	235.6	139450.9	111190.0	250640.9

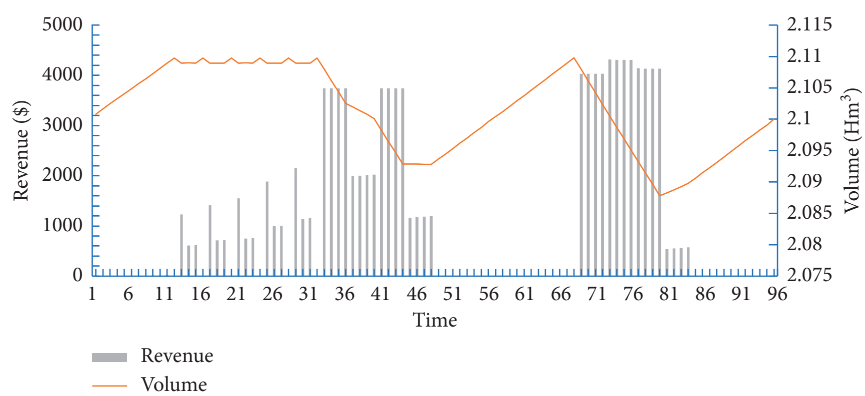

Figure 5: The revenue of hydropower and volume of reservoir in the day-ahead market.

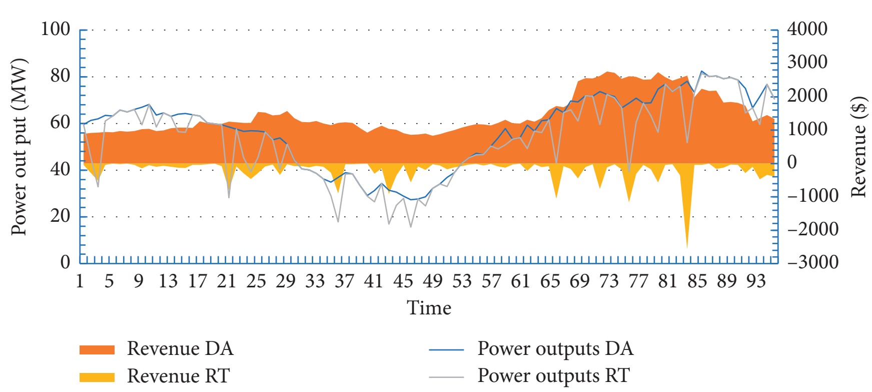

Figure 6: The power outputs and revenue of wind power in both markets.

Table 5: Reservoir volume in Case 2.

ρ	$\underline{v_{96}}$ (Hm^3)	$\overline{v_{96}}$ (Hm^3)
1.00	2.100	2.100
0.95	1.995	2.205

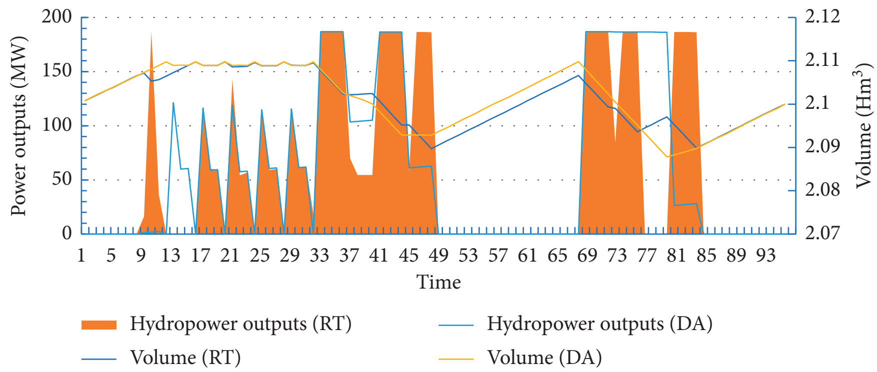

Figure 7: Power outputs of hydropower and volume of reservoir in both markets ($\rho = 1$).

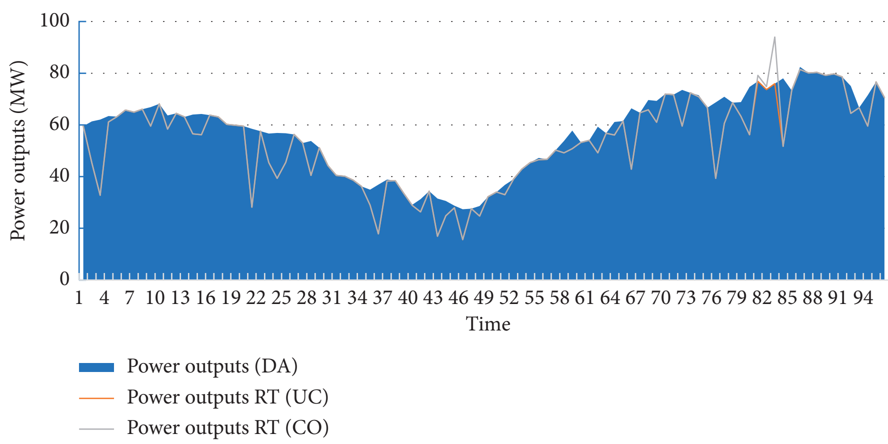

Figure 8: Power outputs of wind power when it operates coordinately or not in intrahour market.

data will be presented and processed, and the scenarios for reservoir inflow will be constructed.

The wind speed data is collected from 60 MW and 30 MW wind farms. The data of the reservoir is collected from a 180 MW hydropower station. For the intrahour energy prices, the model is ARMA (2, 2). The price of the wind power is 1.65 folds the hydropower price. The historical intrahour energy prices for wind and hydropower are set as those of 1 July 2017. Based on these historical prices on 1 July 2017, the prices in the intrahour market on 2 July 2017 are forecasted using the ARMA model in EViews8. The forecasting of day-ahead energy prices is carried out in the same way except the date is set a day ahead. Figure 2 shows the result of intrahour energy price (in red) based on historical energy price (in blue).

For the intrahour wind speed, three parameters are fitted according to the historical data, $P = 2$ of AR(p) model, $q = 3$ for MA(q) model, and $d = 2$ for $I(d)$ model. Therefore, the ARMA model becomes ARIMA (2, 2, 3) model.

Figure 3 shows the result of intrahour wind speed (in red) based on historical wind speed (in blue).

Then, the wind power forecasting is implemented using equations (23) and (24) which depicts two wind farms.

For the simulation cases 1–4, the wind energy formula of wind farm 1

$$f_p(v) = 6.656(v-3)^{1.117}, \quad v \in (3.0, 12.0), \tag{23}$$

For the simulation in Case 5, two different wind farms are discussed. Wind farm 2 is 2/3 scale of the wind farm 1. Wind farm 3's power output is 30 MW, and the wind energy formula equation is

$$f_p(v) = 11.95(v-3)^{0.8938}, \quad v \in (3.0, 12.0). \tag{24}$$

The deviation of the wind power is simulated by normal distribution in Figure 4, in which the standard deviation is 20% of the forecasted wind power which covers most of the cases for simulating the volatility of the wind power.

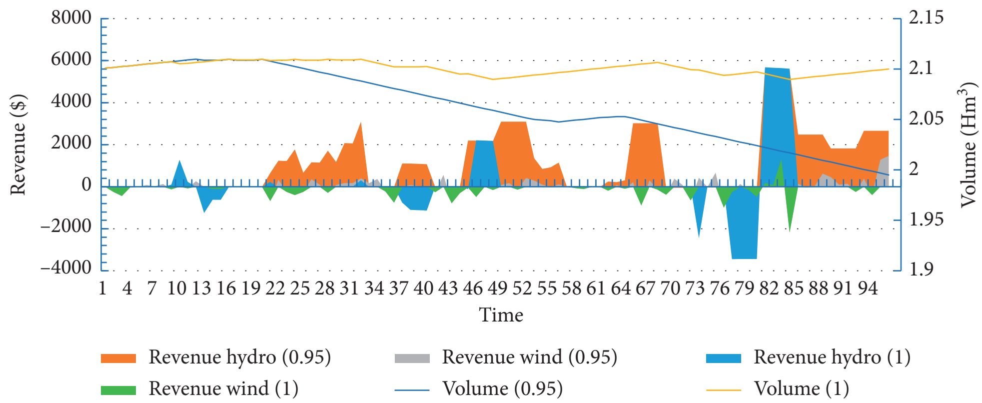

FIGURE 9: Power outputs of both power plants in the intrahour market when ρ varies from 1 to 0.95.

In this paper, the fluctuation of the water inflow is considered using gamma distribution $Gamma_t(SHAPE_t, SCALE_t)$, in which the water inflow in each time period of the schedule horizon is fitted using the historical data of the last 20 years. 96 pairs of the gamma distribution function are fitted and the intrahour inflow is simulated with the Monte Carlo (MC) method, in which 10,000 scenarios are generated. The operating characteristics of the hydropower are adopted from [14] which is a previous work of the author.

The energy price forecast and wind speed forecast are implemented in EViews 8, and the fitted gamma distribution function of inflow for the reservoir is programmed in MATLAB 2013a, other initial data for simulations are processed in excel, and the model proposed is programmed and solved in GAMS 24.1.

3.2. Case Study. To study the alliance of wind power and hydropower, several cases (and subcases) are discussed in this paper.

In Case 1, the author discusses the revenue of both power plants when they run alone; therefore, no distribution of the revenue is needed in this case.

In Case 2, both power plants ally with each other to pursue greater revenue in markets, and the author treats the hydropower as an SR unit in the intrahour market. To evaluate the performance of the virtual SR unit for coordination operation in the intrahour market, the reservoir volume will be relaxed in the intrahour market with different values of parameter . The parameter will be set as 1 and 0.95 in Case 2.1 and Case 2.2, respectively.

In Case 3, another parameter σ is applied to calibrate the power outputs of the hydropower in the day-ahead market, and the author treats the hydropower as an SR unit in the day-ahead market. The parameter σ will be set as 0.9 and 0.85 in Case 3.1 and Case 3.2, respectively.

In both Case 2 and Case 3, the revenue for both power plants is distributed according to their outputs in the intrahour market.

Case 4 focuses on two issues. One is the spillage and curtailment with or without coordination operation. The other is the distribution of the profit based on the Shapley Value method.

Case 5 distributes the revenue for three power plants using the Shapley Value method and introduces a third wind farm to form a new alliance with the wind-hydro alliance. The author validates the efficacy of allocating revenues using the Shapley value method for three power plants. The author applies a wind-scale parameter to the model to investigate the influence of the different scales of wind power on the coordination operation of each power plant.

Table 4 enumerates all the revenue for both power plants in both markets under different parameter combinations. WP(DA) and HP(DA) denote the revenue of the wind power and hydropower in the day-ahead market, respectively. Net WP and Net HP denote the net revenue of the wind power and hydropower, respectively. The content of this table will be explained in the following text.

The initial volume of the reservoir is 2.1 Hm^3 for all the cases.

3.2.1. Case 1: Uncoordinated Scheduling of Wind Power and Hydropower. As shown in Figure 5, the hydropower can run flexibly if the power outputs vary dramatically to pursue greater payoff. This is the operational characteristic of hydropower and the foundation for the existence of the wind-hydro alliance.

In several periods such as 1–8, 49–68, and 85–96, the reservoir's power outputs approximately equal zero under the optimal operation of the self-schedule mechanism. While in the intrahour market, the hydropower fulfills the contract without deviation charges. Therefore, in Table 3, the revenue in the intrahour market for hydropower is zero, the total revenue in both markets is 111,552.9$. As a result, the total water consumption is 0.081153734 Hm^3.

In Figure 6, the volatilities of the wind power lead to sharply deviation of generation. Thus, the generation and operation plan submitted in the day-ahead market meets great challenges when it comes to the intrahour market because of the inaccurate forecast of wind power generation. In some extreme cases such as periods 3, 21, 36, and 84, the wind power plant has to pay for the deviation charges of 678.65$, 1,038.11$, 1,162.32$, and 3,346.66$ separately. On the contrary, in the periods 34, 42, 52, 75, 95, and 96, it gains extra revenue of 382.7$, 580.66$, 466.04$, 698.53$,

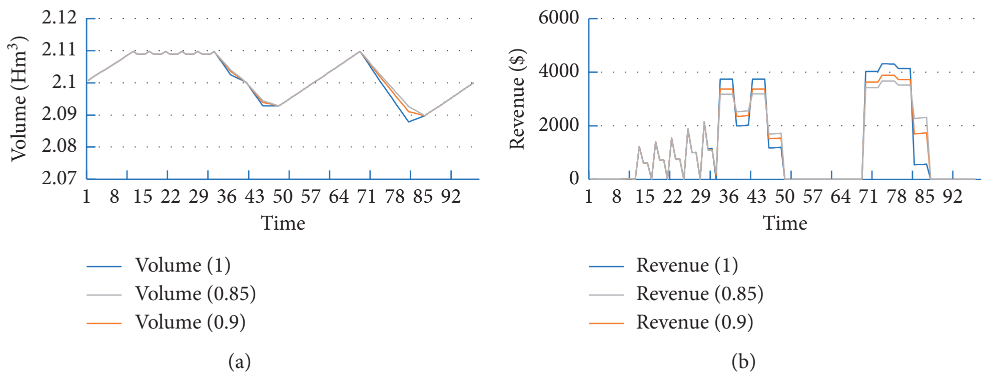

FIGURE 10: (a) Volume of reservoir when σ varies in the DA market; (b) revenue of hydropower when σ varies in the DA market.

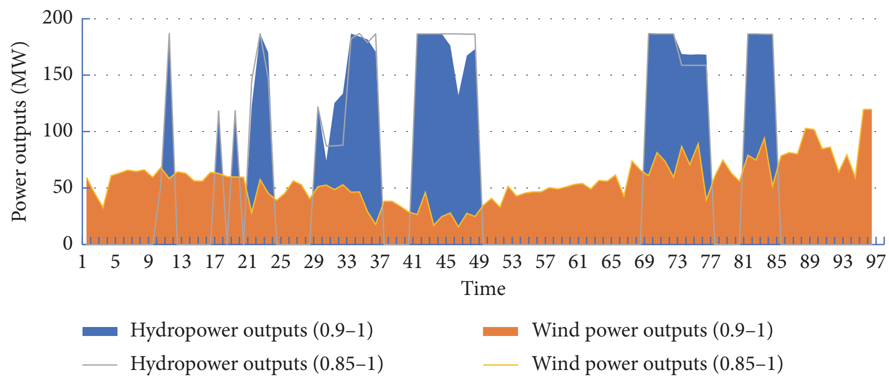

FIGURE 11: Power outputs of wind power and hydropower under different parameter combinations in the intrahour market. The legend hydropower outputs (0.9–1) denote the parameter $\sigma = 0.9$ and $\rho = 1$.

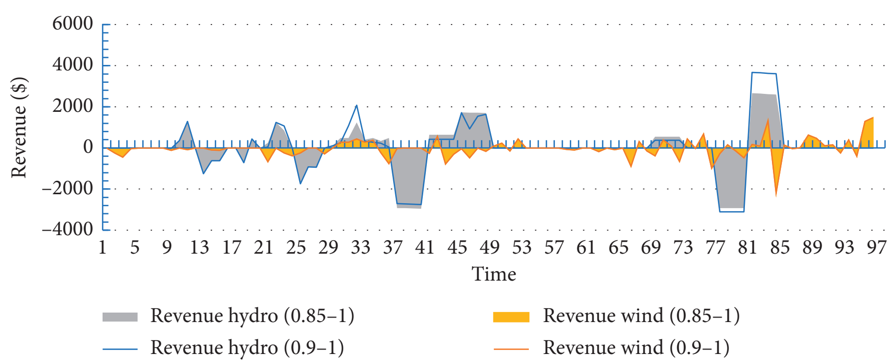

FIGURE 12: The revenue of both power plants under different parameter combinations in the intrahour market.

1,335.78$, and 1530.54$ from the intrahour market for selling more electricity to the market than the day-ahead market contract. In all, it gets 141,758.54$ in the day-ahead market, but loses −20,036.16$ in the intrahour market consequently imbalance charges. Therefore, the total revenue is 121,722.35$. Compared to the hydropower, the wind power faces much greater loss in the intrahour market.

To sum up, it can be concluded that the uncertainties of the wind power make the generation plan submitted in the day-ahead market unreliable, and the wind power faces a significant loss in the intrahour market. On the contrary, with the same water consumption as in the day-ahead market, the self-scheduling of the hydropower can help fulfill the contract in the intrahour market, and it can withstand the volatilities of the water inflow in the intrahour market.

3.2.2. Case 2: Calibrate the Hydropower in the Intrahour Market to Coordinate with the Wind Power. In this case, the coordinated operation of wind-hydro alliance is studied, but the water of the hydropower that is available to help balance the deviation of wind power generation is limited.

This case consists of two cases, Case 2.1 and Case 2.2. In both cases, the parameter σ equals to 1 as it does in Case 1. However, other than Case 1, the parameter is set as 1 and

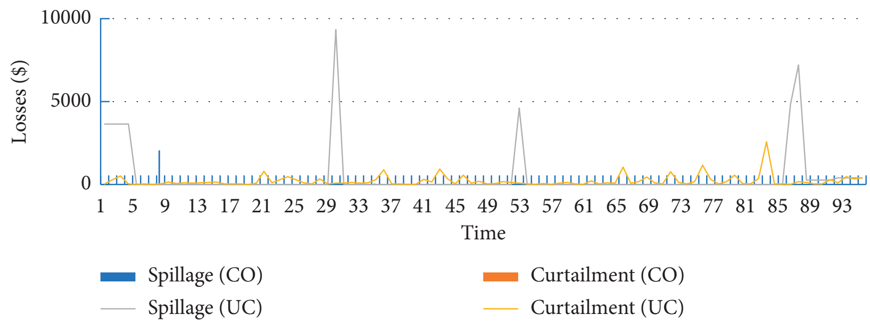

FIGURE 13: The losses of wind power and hydropower under different parameter in Case 4.

0.95, respectively, to observe the optimal decision in the coordinated operation in the intrahour market. Though the parameter combination is the same as in Case 1, Case 2.1 is totally different. Both power plants coordinate to help each other to settle the generation deviation in Case 2.1. The difference between Case 2.1 and Case 2.2 is whether the volume can be used freely without considering the volume availability for the next schedule horizon. With the parameter combinations mentioned above, the upper and lower bounds of volume of the reservoir are listed in Table 5.

Figure 7 shows the result when both power plants operate coordinately. For Case 2.1, the total water resource available is the same as in Case 1. However, in most of the scheduling horizon, the outputs of the hydropower change significantly. In time period 10, the power outputs of the hydropower increase from 1.89 MW to 186.9 MW, and in the periods 46–48, the outputs increase from nearly 60 MW to 186 MW as compared to the day-ahead contract. In periods 13–15, the reservoir generator shuts down in the intrahour market as a comparison to the day-ahead contract. As shown in Table 4, the revenue for the hydropower is 8,296.063297$ in the intrahour which is elevated greatly compared to Case 1. The reason the hydropower achieves more revenue is that the coordinational operation helps balance the generation deviation of wind power. This result shows the flexibility of the hydropower in generation operation.

Figure 8 indicates that due to the maximum power outputs limitation in the intrahour market, the wind power outputs curve is below the day-ahead contract curve. However, the wind power outputs show some difference in some periods such as 81–83. Take time period 83, for example, the wind power outputs are much greater than the day-ahead contract. This is because the energy price is greater than it is in the day-ahead market, and the wind power will obtain more revenue even with imbalance charges. In periods 46–48, the hydropower reaches its maximum outputs to coordinate the deviation from the wind power. In periods 76 and 84, great power deviation can be observed, the deviation cannot be settled even with the coordination of the hydropower. Summing up all the revenue in the whole schedule horizon, the imbalance charges of the wind power are diminished significantly into 11,916.3$ in the intrahour. Therefore, both power plants coordinate to help balance the generation deviation of each other, and both members individually and as an alliance can benefit from such coordination.

Figure 9 shows the comparison of the revenue of both power plants and volume of reservoir when ρ varies from 1 to 0.95. In this figure, the legend revenue hydro (1) denotes the revenue of the hydropower in the intrahour market when $\rho = 1$.

In Case 2.1, the imbalance charges for the wind power is −11,916.3$ which is nearly half the value in Case 1 without the coordination operating. Furthermore, more revenue is observed for the hydropower in the intrahour market when it allies with the wind power. In all, the wind-hydro alliance acquires 256,629.08$.

In Case 2.2, the reservoir volume at the end of the scheduling horizon is relaxed, therefore more water resources can be utilized to compensate the deviation of the wind power generation. The curve shows that, after time period 21, the hydropower reaches its maximum power outputs and the volume of the reservoir drops rapidly to the lower bound of 1.995 Hm^3. In periods such as 6–8, 29–34, 38, and 39, the wind power attains more revenue than it does with the parameter ρ set as 1. For the hydropower, in periods 20–33, 38–41, 46–57, 61–67, and, 80–95, it gets much more revenue than it does in Case 2.1. Especially in periods 13–16, 37–40, and 73–80, deviation charges are settled by coordination of wind power. During the whole procedure, the hydropower gets much more revenue from selling electricity, and it also helps the wind power in diminishing the deviation. The total revenue for the hydropower and wind power in the intrahour are 110,201.62$ and −48.30$ separately. In Case 2.2, the hydropower almost doubles his revenue and the wind power almost fulfills its day-ahead contract with the help of coordination operation.

Therefore, with more water resources utilized, more revenue is expected for the alliance of the wind power and hydropower.

Furthermore, the lower parameter ρ is also studied. For example, when $\rho = 0.9$, remarkable change is not observed in the result. This can be explained by the fact that though more potentiality of generation is reserved, the hydropower cannot generate more electricity or do more to help the wind power because of the upper limit of $q_{k,s}$.

3.2.3. Case 3: Calibrate the Parameters in Both Markets for the Wind-Hydro Alliance. Based on Case 2's conclusion, the relaxation of the reservoir volume helps reduce the generation deviation and improves the revenue of both power

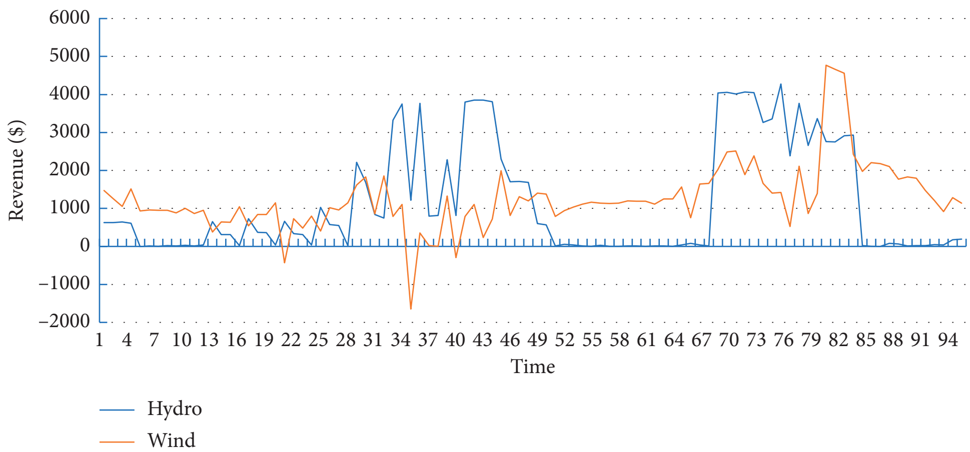

Figure 14: The Shapley value of both power plants in every time period in Case 4.

Table 6: Losses and revenue in Case 4.

Cases	Parameter		Losses ($)		Revenue ($)	
	σ	ρ	Spillage	Curtailment	Wind	Hydro
4.1(UC)	1.00	1.00	20036.20	43206.20	121722.40	111552.90
4.2(CO)	0.85	1.00	16.68	2112.21	128273.13	103596.25

Table 7: Shapley value for the revenue of both power plants in Case 4.

	Wind	Hydro	Overall
4.2 (CO)	128273.13	103596.25	231869.38
Shapley value	121019.43	110849.95	231869.38

plants. However, the overusing of the water volume may make the hydro plant less operational in the next scheduling horizon because the volume may be unavailable when needed. Therefore, it is essential to find a way to utilize the volume more thoroughly, and it maintains the sustainable operation of the hydropower at the same time.

This paper proposes that the hydropower can operate like an SR unit in the day-ahead market in the wind-hydro alliance. Therefore, the overusing of the volume in the intrahour market can be subsided. The parameter σ is then introduced into equation (14). To analyze the influence of parameter σ on the coordination of both power plants, two cases are studied in the following.

In Case 3.1 and Case 3.2, the reservoir operates as an SR unit for the wind power by setting $\sigma = 0.9$ and $\sigma = 0.85$ in the day-ahead market.

In the day-ahead market, when σ varies from 1 to 0.85, the revenue of the hydropower decreases from 111,552.9$ to 110,954.4$, as lower power outputs make the day-ahead revenue lower.

Figure 10 shows the reservoir volume and the hydropower revenue when both parameters vary. The hydropower shows great flexibility during operation when the total water utilization is determined and it can self-regulate to balance the deviation.

Figure 11 shows the intrahour power outputs of both power plants under different parameter combinations. When σ decreases, more generation potential will be reserved for the intrahour usage. The power outputs of wind power in the intrahour market do not show much difference for different parameter combinations. The reason is that, with equation (14) considered, the maximum wind power outputs available, $P_{k,\max}^{\text{wind}}$, limits the power outputs of the hydropower and lead to reduced revenue of the hydropower.

As shown in Figure 12, with different σ, the revenue of hydropower differs. Take periods 29–36 and 81–84, for example, the revenue for hydropower in Case 3.2 is lower than it is in Case 3.1. In periods 41–48 and 69–72, the revenue for hydropower in Case 3.2 is greater than it is in Case 3.1. In periods 37–40 and 77–80, great imbalance charges occur for the hydropower. In Table 3, the total net revenue of the hydropower is 2,131.1$ and 235.64 in Case 3.1 and Case 3.2 in the intrahour market, respectively. When it comes to the wind power, with the help of the hydropower, more revenue is achieved by settling the generation deviation. However, for Case 3.2, when $\sigma = 0.85$, the revenue is same as in Case 3.1, while the revenue of the hydropower is much lower than in Case 3.1. This is because the generation plan submitted by the hydropower is limited by parameter σ in the day-ahead market, and then the generation dispatched from the hydropower in the intrahour market will be limited too.

As shown in Table 3, with the coordination operation, imbalance charges can be partly settled. However, if the DM prefers more revenue from the wind-hydro alliance, the relaxation of the volume in the intrahour market is an option without considering the scheduling plan for the next scheduling horizon. Therefore, hydropower plays an important role in the wind-hydro alliance, and the hydropower undertakes a risk of losing revenue while coordinating with the wind power.

By comparing the cases presented above, it can be concluded that the introduction of σ and ρ helps control the operation of the hydropower in the day-ahead market and the intrahour market, respectively. It also provides the DM with a tool to balance the interests of both power plants. For

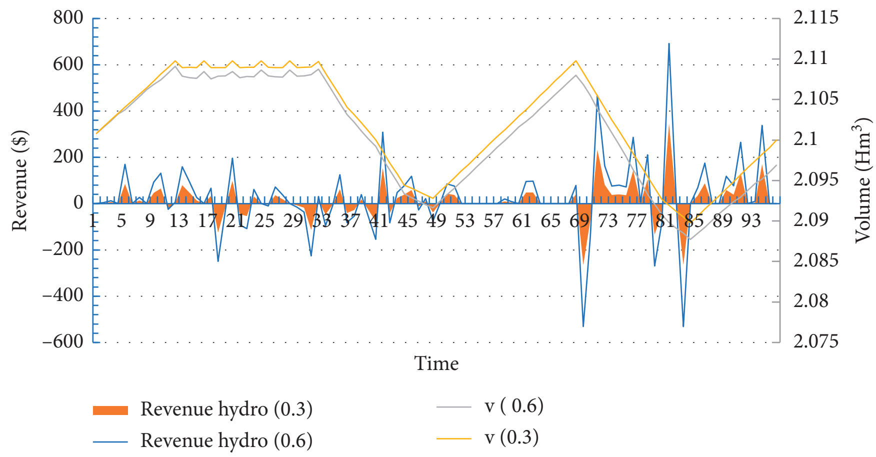

FIGURE 15: Revenue of hydropower plant in the intrahour market when δ is 0.6 and 0.3 when $\sigma = 0.85$ and $\rho = 0.95$.

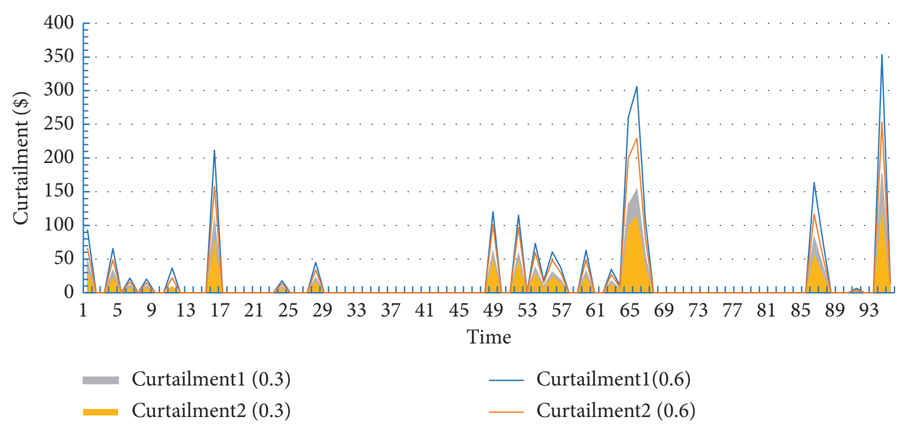

FIGURE 16: Curtailment in the intrahour market when δ is 0.6 and 0.3.

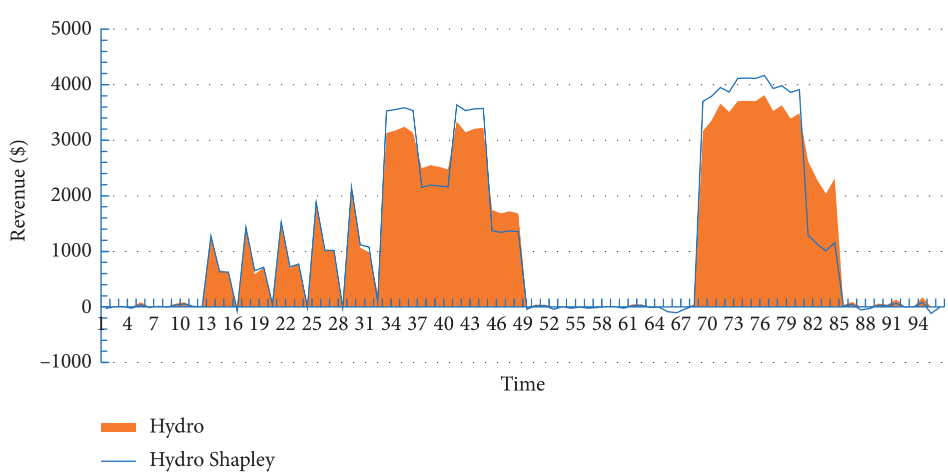

FIGURE 17: Shapley value of the revenue of hydropower in the intrahour market when $\delta = 0.3$.

example, when the DM puts the revenue of the wind power in the first place, the hydropower can operate like an SR unit by setting σ lower than 1. As in Case 3.1 and Case 3.2, hydropower utilizes the water resources to coordinate the deviation of the wind power at the cost of the revenue in the day-ahead market. Furthermore, in some extreme cases in Case 2.2, extra reservoir volume can be used to coordinate with the wind power deviation in the intrahour market.

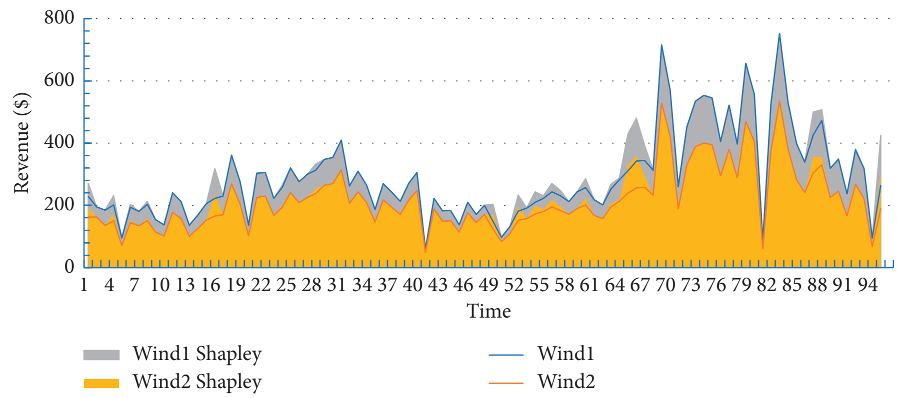

Figure 18: Shapley value of the revenue of hydropower in the intrahour market when $\delta = 0.3$.

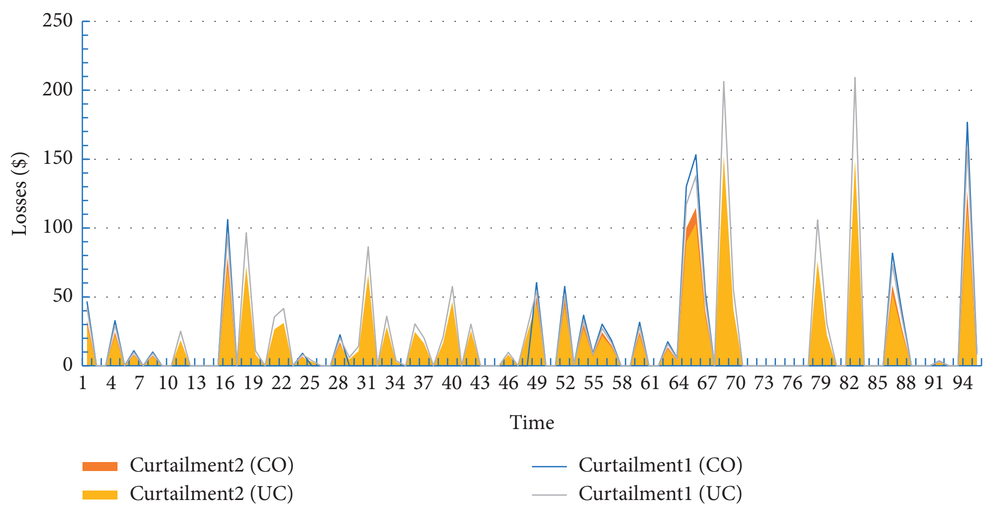

Figure 19: The curtailment of wind farms in the intrahour market when $\delta = 0.3$.

Therefore, the DM can arrange the scheduling plan by choosing the preferred parameter combinations.

For the wind-hydro alliance, if the volume of the reservoir can be dispatched at will, more revenue can be expected, but this will make the next scheduling horizon less operational and the hydropower will face great risk in the alliance. On the contrary, the introduction of σ enables the hydropower to allocate the water resources in the day-ahead market without overusing the reservoir volume in the intrahour market.

3.2.4. Case 4: Distribution of the Revenue for Both Power Plants using the Shapley Value Method. As discussed in Section 2.1.3, to apply the Shapley Value method, an important condition is that the total water utilization should be the same for both coordinated and uncoordinated cases. Therefore, the calculation of the Shapley Value is based on an uncoordinated (Case 4.1) case and a coordinated case (Case 4.2). Case 4.2 proposes the problem that the total water utilization is determined by solving the case when the lower bound of volume at the end of the scheduling horizon is set as the initial volume of 2.1 Hm^3. Then, Case 4.1 is solved based on the water utilization. As a result, total water utilization is 0.081153734 Hm^3. The relevant parameters discussed in Case 4 are set in Table 5.

Figure 13 shows that, with the same water consumption, the spillage in Case 4.1, in which the hydropower runs alone, is much greater than in Case 4.2 when both power plants ally. For example, spillage happens only in periods 9 and 25 for Case 4.1, and periods 1–4, 30, 53, and 87–96 for Case 4.2. The same happens when it comes to the wind power in which the wind curtailment happens in almost every time period in Case 4.2, but only half of the time for Case 4.1 and the amount of curtailment for Case 4.1 can be neglected compared to Case 4.1. That means the cooperation help reduces both the curtailment and the spillage in the intrahour market for both power plants. Both power plants benefit from the coordination with higher revenue and lower discard of resources.

Table 5 shows the overall losses and revenue for both power plants in Case 4. Without coordination in Case 4.1, both power plants incur significant losses from discarding resources which are not calculated in revenue or imbalance charges, but apparently has a great influence on the overall revenue and optimal operation in the next scheduling horizon. With coordination operation in Case 4.2, the spillage losses for hydropower and curtailment losses for wind power are almost neglectable compared to the uncoordinated Case 4.1.

Compared to Case 4.1, Case 4.2 has a magnificent decrease in losses. As a result, in Case 4.2, the revenue of the wind power increases, but that of the hydropower decreases.

With its contribution, the hydropower coordinates to compensate for the deviation and cut back the curtailment of the wind power. Eventually, it increases the revenue of wind power and the wind-hydro alliance.

Within the Shapley Value method, the characteristic of coordination operation is obviously shown in Figure 14. If the wind power revenue declines, the hydropower will catch up and fulfill the revenue of the alliance. In time periods 21, 35, and 40, the Shapley Value for wind power is negative; this means hydropower helps to diminish the curtailment by losing revenue greatly as −1893.6$, −4530.0$, and −2957.6$, respectively. In such periods, wind power should compensate the hydropower for its contribution to the diminishment of the curtailment. The same happens when the hydropower needs help from the alliance. Therefore, the wind-hydro alliance indeed can obtain more revenue from the market and diminish the curtailment and the spillage, as presented in Table 6.

In Table 7, by considering the Shapley Value, the hydropower will get more revenue from the alliance than when the revenue is distributed using the normal way. The marginal contribution is considered, and it is fairer for hydropower because it undertakes the risk of losing revenue to help reduce the generation deviation.

3.2.5. Case 5: Distribution of the Revenue for Three Power Plants Using the Shapley Value Method. In Case 5, the hydropower plant must compensate for two wind farms at the same time. This leads to more frequently unscheduled operations by hydropower plants, and ultimately to a greater loss of generation revenue. To better study this problem, the author applies a wind scale parameter δ which corresponds to the reduction of the wind power size and observe how the benefits of the alliance vary under different parameter choices.

In the last part of Case 5, the author evaluates the revenue under different δ and applies the Sharpe Value method for the revenue distribution.

With other conditions unchanged ($\sigma = 0.85$ and $\rho = 0.95$), when the parameter δ sets as one, the optimal problem is infeasible. However, after reducing the parameter, the optimal problem again reaches an optimal solution.

Take δ to correspond to 0.6 and 0.3, for example, as shown in Figure 15, the greater the wind scale is, the more the water consumed is and revenue of the hydropower plant increases as well. In some periods such as 61, 62, 73, 74, and 75, hydropower gains much more profit than it does when $\delta = 0.3$.

For wind farms, the proportion of the curtailment of both wind farms almost doubled which equals to the proportion of the two parameter combinations. As shown in Figure 16, while taking wind farm 1, for example, when $\delta = 0.3$, the curtailment is cut significantly in most of the periods, especially no curtailment is observed in period 11. This is apparently due to the scheduling operation of the reservoir.

Table 8: Shapley value for the revenue of both power plants in Case 5.

	Wind 1	Wind 2	Hydro	Overall
Case 5 (UC)	27374.19	20592.37	111552.89	159519.46
Case 5 (CO)	28360.59	20095.85	112204.48	160606.92
Shapley value	28612.68	20796.69	111197.55	160606.92

To investigate how to distribute revenue for three power plants using the Shapley Value method, the author chooses $\delta = 0.3$ as our initial condition.

The Figures 15 and 16 show the Shapley Value curve of the hydropower plant and two wind farms. In Figure 17, in several periods such as 34–37 and 70–80, the hydropower plant will acquire more profits for its greater contribution to the alliance. However, in periods such as 46–59, wind power plants also contribute to the alliance in Figure 18. In periods 52–57 and 63–67, the hydropower will lose money for wind farms coordinate to help (Figures 15–18).

Figure 19 shows that the curtailment of wind drops in almost every period when three power plants coordinate. The coordination operation helps better exploiting wind resources.

In Table 8, the total revenue for the three-partner alliance is 160606.92$, but when they operate independently, the revenue is 159519.46$. The coordination only gains an extra 1087.46$ from the market which is relatively lower than other Cases in this paper because the wind power scale is much smaller.

To sum up, applying the Shapley Value to distributing the revenue in a three-partner alliance can better reflect the contribution of each partner. Moreover, it also helps us better understand the inner connection of partners. Therefore, it can distribute the revenue with perfect equity.

4. Conclusions

This paper focuses on three main issues. First, based on the operational policy in the PJM power market, a model is established to maximize the expected profit sum of the day-ahead and the intrahour of the wind-hydro alliance. The water inflow is scenario-based, and the deviation charges policy of wind power and hydropower are subject to the operating policies in power market. Second, to allocate the resources that hydropower can provide in both markets during coordination operation, three parameters are introduced. Those two parameters can help better analyze the possibilities and the performance of coordination operation. Third, the allocation of the profit for the wind-hydro alliance is discussed by using the Shapley Value method.

According to the research, the independent operation of the wind power may lose money which arises from the volatility of wind speed. Meanwhile, the operation of the reservoir is flexible and can compensate for the generation deviation of the wind power. When the reservoir is used as SR units for the wind power, the wind power will acquire more revenue than when it operates individually. The coordination of both power plants is at the volume consumption or the revenue loss of the hydropower. It is because the performance of the coordination depends on the reservoir volume put to use, and the unscheduled operations of reservoir cause balance charges.

However, if the reservoir can reserve some potential generation ability in the day-ahead market and coordinate with the wind power in the intrahour market, the wind-hydro alliance can obtain more revenue without overusing the reservoir volume. Therefore, if the volume can be dispatched properly, there is no risk of volume shortage in the intrahour market when both power plants coordinate. Besides, for more than two players in the alliance, one reservoir may not be able to compensate for other plants. Therefore, the scales of the wind farms and reservoir will have influence on the effectiveness of the coordination. In the implementation of joint scheduling, in order to make better use of wind and hydropower resources and at the same time obtain the maximum generation benefits, the proportional relationship between the two scales needs to be reasonably chosen. Due to the intense coordination operations, the division of interests among the players of the alliance is highly contested. To this end, the author introduces the Shapley Value method, which proposes a more equitable division of profits between players while conducting an in-depth analysis of the marginal contribution of the players.

Nomenclature

A. Abbreviations

DA: The day-ahead market
RT: The intrahour market
ISO: Independent system operator
UC: Uncoordinated
CO: Coordinated
HP: Hydropower
WP: Wind power

B. Indexes

t: Index for the day-ahead periods
k: Index for the intrahour periods
S: Index for scenarios

C. Scalar

σ: Parameter to calibrate the generation potential for the day-ahead generation
ρ: Parameter to calibrate the reservoir volume for the intrahour generation

D. Constants

Scene: Number of scenarios
T: Number of periods
v_{ini}: Reservoir's initial volume in the intrahour market (Hm^3)
inflow_t: Inflow in the day-ahead market in t period (m^3/s)
$\underline{q_t}, \underline{q_k}$: Lower limit of hydropower discharge rate in both markets (m^3/s)
$\overline{q_t}, \overline{q_k}$: Upper limit of hydropower discharge rate in both markets (m^3/s)
$\underline{P_t^{\text{hydro}}}, \underline{P_k^{\text{hydro}}}$: Lower limit of hydropower in both markets (MW)
$\overline{P_t^{\text{hydro}}}, \overline{P_k^{\text{hydro}}}$: Upper limit of hydropower in both markets (MW)
$\underline{q\text{loss}_t}, \underline{q\text{loss}_k}$: Lower limit of spillage in both markets (m^3/s)
$\overline{q\text{loss}_t}, \overline{q\text{loss}_k}$: Upper limit of spillage in both markets (m^3/s)
$\underline{v_t}, \underline{v_k}$: Lower limit of reservoir volume in both markets (Hm^3)
$\overline{v_t}, \overline{v_k}$: Upper limit of reservoir volume in both markets (Hm^3)
$\text{Pr}_t^{\text{wind}}$: The day-ahead wind energy price ($/MWh)
P_t^{wind}: The day-ahead wind power (MW)
$\text{Pr}_t^{\text{hydro}}$: The day-ahead hydroenergy price ($/MWh)
P_t^{hydro}: The day-ahead hydropower generation (MW)
$\text{Penalty}_k^{\text{wind}}$: Energy balancing price for wind power ($/MWh)
$\text{Penalty}_k^{\text{hydro}}$: Energy balancing price for hydropower ($/MWh)
$P_{k,f}^{\text{wind}}$: Forecasted wind power outputs in the intrahour market (MW)
$P_{k,\max}^{\text{wind}}$: Maximum power outputs of wind power in the intrahour market (MW)
Δt: Time elapse for a single time period

E. Variables

$\text{inflow}_{k,s}$: Reservoir inflow in the intrahour market at period k in scenario s (m^3/s)
q_t: Decision variable of hydropower discharge in the day-ahead market (m^3/s)
$q_{k,s}$: Decision variable of hydropower discharge in the intrahour market in scenario s (m^3/s)
$q\text{loss}_t$: Decision variable of hydropower spillage in the day-ahead market (m^3/s)
$q\text{loss}_{k,s}$: Decision variable of hydropower spillage in the intrahour market in scenario s (m^3/s)
$q_{all\text{co}}$: Water consumption for hydropower when both power plants coordinate (Hm^3).
$q_{\text{all uc}}$: Water consumption for hydropower when both power plants operate alone (Hm^3)
$P_{\text{t}}^{\text{hydro}}$: The power outputs of reservoir in the day-ahead market (MW)
$P_{\text{k}}^{\text{hydro}}$: The power outputs of reservoir in the intrahour market without coordination (MW)
$P_{\text{k,s}}^{\text{hydro}}$:

The power outputs of reservoir in the intrahour market with coordination (MW)
h_t: Head of the reservoir at period t (m)
$h_{k,s}$: Head of the reservoir at period k in scenario s (m)
v_t: Reservoir volume in the day-ahead market (Hm^3)
$v_{k,s}$: Reservoir volume in the intrahour market in scenario s (Hm^3)
$v_{T,s}^{end}$: Reservoir volume at the end of schedule horizon in the intrahour market in scenario s (Hm^3)
W_{DA}: Total water used in the day-ahead market (Hm^3)
W_{RT}^s: Total water used in the intrahour market (Hm^3)
P_k^{wind}: Decision variable of wind power outputs in the intrahour market without coordination (MW)
P_k^{wind}: Decision variable of wind power outputs in the intrahour market with coordination (MW)
$|\Delta P_k^{wind}|$: The deviation of wind power in the intrahour market (MW)
$\Delta P_{k,s}^{hydro}$: The deviation of hydropower outputs in the intrahour market in scenario s (MW)
$\text{Profit}_{DA}^{hydro\cdot uc}$: The revenue of hydropower in the day-ahead market when uncoordinated ($)
$\text{Profit}_{RT}^{hydro\cdot uc}$: The revenue of hydropower in the intrahour market when uncoordinated ($).
$\text{Profit}_{DA}^{hydro\cdot co}$: The revenue of hydropower in the day-ahead market when coordinated ($)
$\text{Profit}_{RT}^{hydro\cdot co}$: The revenue of hydropower in the intrahour market when coordinated ($)
$\text{Profit}_{DA}^{wind\cdot co}$: The revenue of wind power in the day-ahead market when uncoordinated ($)
$\text{Profit}_{RT}^{wind\cdot co}$: The revenue of wind power in the intrahour market when uncoordinated ($)
$\text{Profit}_{DA}^{wind\cdot co}$: The revenue of wind power in the day-ahead market when coordinated ($)
$\text{Profit}_{RT}^{wind\cdot co}$: The revenue of wind power in the intrahour market when coordinated ($)
profit_{DA}^{uc}: The revenue of both power plants in day-ahead market when uncoordinated ($)
profit_{RT}^{uc}: The revenue of both power plants in intrahour market when uncoordinated ($)
profit_{DA}^{co}: The revenue of both power plants in day-ahead market when coordinated ($)
profit_{RT}^{co}: The revenue of both power plants in intrahour market when coordinated ($)
$\text{profit}_{DA}^{hydro\cdot co1}$: The revenue of hydropower in the day-ahead market when coordinate with wind farm 1($)
$\text{profit}_{RT}^{hydro\cdot co1}$: The revenue of hydropower in the intrahour market when coordinate with wind farm 1($)
$\text{profit}_{DA}^{hydro\cdot co2}$: The revenue of hydropower in the day-ahead market when coordinate with wind farm 2($)
$\text{profit}_{RT}^{hydro\cdot co2}$: The revenue of hydropower in the intrahour market when coordinate with wind farm 2($)
$\text{profit}_{DA}^{hydro\cdot co'}$: The revenue of hydropower in the day-ahead market when coordinate with two wind farms ($)
$\text{profit}_{RT}^{hydro\cdot co'}$: The revenue of hydropower in the intrahour market when coordinate with two wind farms ($)
$\text{Profit}_{DA}^{wind1\cdot co}$: The revenue of wind farm 1 in the day-ahead market when coordinate with hydropower ($)
$\text{Profit}_{RT}^{wind1\cdot co}$: The revenue of wind farm 1 in the intrahour market when coordinate with hydropower ($)
$\text{Profit}_{DA}^{wind1\cdot uc}$: The revenue of wind farm 1 in the day-ahead market when it operates alone ($)
$\text{Profit}_{RT}^{wind1\cdot uc}$: The revenue of wind farm 1 in the intrahour market when it operates alone ($)
$\text{Profit}_{DA}^{wind2\cdot co}$: The revenue of wind farm 2 in the day-ahead market when coordinate with hydropower ($)
$\text{Profit}_{RT}^{wind2\cdot co}$: The revenue of wind farm 2 in the intrahour market when coordinate with hydropower ($)
$\text{Profit}_{RT}^{wind2\cdot co}$: The revenue of wind farm 2 in the day-ahead market when it operates alone ($)
$\text{Profit}_{RT}^{wind2\cdot uc}$: The revenue of wind farm 2 in the intrahour market when it operates alone ($)
$\text{Profit}_{DA}^{wind1\cdot co'}$: The revenue of wind farm 1 in the day-ahead market when coordinate with hydropower and wind farm 2 ($)
$\text{Profit}_{RT}^{wind1\cdot co'}$: The revenue of wind farm 1 in the intrahour market when coordinate with hydropower and wind farm 2 ($)
$\text{Profit}_{DA}^{wind2\cdot co'}$: The revenue of wind farm 2 in the day-ahead market when coordinate with hydropower and wind farm 2 ($)
$\text{Profit}_{RT}^{wind2\cdot co'}$: The revenue of wind farm 2 in the intrahour market when coordinate with hydropower and wind farm 2 ($)
$\sum \varphi(a)_{hydro}$: The Shapley value of hydropower ($)
$\sum \varphi(a)_{wind}$: The Shapley value of wind power ($).

Data Availability

The historical energy price data used to support the findings of this study are available online and can be obtained at https://www.pjm.com/markets-and-operations/energy.aspx.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] T. Ikegami, C. T. Urabe, T. Saitou, and K. Ogimoto, "Numerical definitions of wind power output fluctuations for power system operations," *Renewable Energy*, vol. 115, pp. 6–15, 2018.

[2] X. Yuan, Q. Tan, X. Lei, Y. Yuan, and X. Wu, "Wind power prediction using hybrid autoregressive fractionally integrated moving average and least square support vector machine," *Energy*, vol. 129, pp. 122–137, 2017.

[3] J. C. Smith, M. R. Milligan, E. A. DeMeo, and B. Parsons, "Utility wind integration and operating impact state of the art," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 900–908, 2007.

[4] A. Fabbri, T. GomezSanRoman, J. RivierAbbad, and V. H. MendezQuezada, "Assessment of the cost associated with wind generation prediction errors in a liberalized electricity market," *IEEE Transactions on Power Systems*, vol. 20, no. 3, pp. 1440–1446, 2005.

[5] X. Yuan, B. Ji, Y. Yuan, R. M. Ikram, X. Zhang, and Y. Huang, "An efficient chaos embedded hybrid approach for hydro-thermal unit commitment problem," *Energy Conversion and Management*, vol. 91, pp. 225–237, 2015.

[6] D. Barbosa de Alencar, C. De Mattos Affonso, R. Limão de Oliveira, J. Moya Rodríguez, J. Leite, and J. Reston Filho, "Different models for forecasting wind power generation: case study," *Energies*, vol. 10, no. 12, p. 1976, 2017.

[7] R. Billinton, H. Chen, and R. Ghajar, "Time-series models for reliability evaluation of power systems including wind energy," *Microelectronics Reliability*, vol. 36, no. 9, pp. 1253–1261, 1996.

[8] D. C. Hill, D. McMillan, K. R. Bell, and D. Infield, "Application of auto-regressive models to UK wind speed data for power system impact studies," *IEEE Transactions on Sustainable Energy*, vol. 3, pp. 134–141, 2011.

[9] A. Bizrah and M. Al-Muhaini, "The impact of seasonal ARMA wind speed modeling on the reliability of power distribution systems," in *Proceedings of 2017 IEEE Power & Energy Society General Meeting*, pp. 1–5, Chicago, IL, USA, July 2017.

[10] P.I. LLC, "PJM manual 11: energy & ancillary services market operations," Tech. Report, 2014, http://www.pjm.com/-/media/documents/manuals/m11.ashx.

[11] Z. Zhao, C. Wang, M. Nokleby, and C. Miller, "Improving short-term electricity price forecasting using day-ahead LMP with ARIMA models," in *Proceedings of 2017 IEEE Power & Energy Society General Meeting*, Chicago, IL, USA, July 2017.

[12] A. J. Conejo, M. A. Plazas, R. Espinola, and A. B. Molina, "Day-ahead electricity price forecasting using the wavelet transform and ARIMA models," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 1035–1042, 2005.

[13] L. V. L. Abreu, M. E. Khodayar, M. Shahidehpour, and L. Lei Wu, "Risk-constrained coordination of cascaded hydro units with variable wind power generation," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 3, pp. 359–368, 2012.

[14] Y. Quan, L. He, and M. He, "Short-term hydropower scheduling with gamma inflows using CVaR and Monte Carlo simulation," in *Proceedings of 2014 Seventh International Symposium on Computational Intelligence and Design*, pp. 108–111, Hangzhou, China, December 2014.

[15] X. Yuan, Y. Zhang, and Y. Yuan, "Improved self-adaptive chaotic genetic algorithm for hydrogeneration scheduling," *Journal of Water Resources Planning and Management*, vol. 134, no. 4, pp. 319–325, 2008.

[16] B. Hartmann and A. Dán, "Cooperation of a grid connected wind farm and an energy storage unit-demonstration of a simulation tool," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 1, pp. 49–56, 2012.

[17] X. Li, L. Yao, and D. Hui, "Optimal control and management of a large-scale battery energy storage system to mitigate fluctuation and intermittence of renewable generations," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 4, pp. 593–603, 2016.

[18] X. Yuan, Y. Wang, J. Xie, X. Qi, H. Nie, and A. Su, "Optimal self-scheduling of hydro producer in the electricity market," *Energy Conversion and Management*, vol. 51, no. 12, pp. 2523–2530, 2010.

[19] M. Korpaas, A. T. Holen, and R. Hildrum, "Operation and sizing of energy storage for wind power plants in a market system," *International Journal of Electrical Power & Energy Systems*, vol. 25, no. 8, pp. 599–606, 2003.

[20] M. Karami, H. A. Shayanfar, J. Aghaei, and A. Ahmadi, "Scenario-based security-constrained hydrothermal coordination with volatile wind power generation," *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 726–737, 2013.

[21] X. Yuan, Z. Chen, Y. Yuan, Y. Huang, X. Li, and W. Li, "Sliding mode controller of hydraulic generator regulating system based on the input/output feedback linearization method," *Mathematics and Computers in Simulation*, vol. 119, pp. 18–34, 2016.

[22] A. Oshiya and K. Lakshmi, "Interval optimization technique for the coordination of hydro units with wind power generation," in *Proceedings of International Conference on Advanced Computing & Communication Systems*, Coimbatore, India, January 2016.

[23] Y. Liu, C. Jiang, J. Shen, and J. Hu, "Coordination of hydro units with wind power generation using interval optimization," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 443–453, 2015.

[24] X. Yuan, H. Tian, S. Zhang, B. Ji, and Y. Hou, "Second-order cone programming for solving unit commitment strategy of thermal generators," *Energy Conversion and Management*, vol. 76, pp. 20–25, 2013.

[25] J. H. Dai and H. X. Xue, "The strategy of profit allocation among partners in dynamic alliance based on the Shapley value," *Chinese Journal of Management Science*, 2004.

[26] M. Maschler, G. Owen, and M. Maschler, *The Consistent Shapley Value for Games without Side Payments*, Springer Berlin Heidelberg, Berlin, Germany, 1992.

[27] U. Faigle and W. Kern, "The Shapley value for cooperative games under precedence constraints," *International Journal of Game Theory*, vol. 21, no. 3, pp. 249–266, 1992.

[28] R. Tian, L. F. Sun, B. Y. Li, and X. Y. Mi, "Collaborative logistics profit distribution model base on improved shapley value," *Applied Mechanics and Materials*, vol. 543–547, pp. 4404–4407, 2014.