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Research Article

Research on Grid-Connected Optimal Operation Mode between Renewable Energy Cluster and Shared Energy Storage on Power Supply Side

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The renewable energy cluster can reduce the total power deviation of renewable energy stations and also bring cooperative benefits to renewable energy stations. Shared energy storage can assist in tracking the power generation plan of renewable energy and has advantages in the scale of investment, utilization rate, and other aspects. Therefore, this article proposes a study on the grid-connected optimal operation mode between renewable energy cluster and shared energy storage on the power supply side. Firstly, for the complementary characteristics blurring each member's contribution to the cluster power deviation, an improved Shapley value method is used to build a rational mechanism for apportioning the cluster power deviation penalty. Secondly, based on the Nash negotiation model and allocation mechanism, the revenue model of the renewable energy cluster is constructed, and an improved particle swarm optimization algorithm is proposed to solve the cluster operation strategy. Then, based on the charge and discharge demand of renewable energy cluster, with the goal of maximizing the benefits of shared energy storage, capacity pricing is optimized, as well as capacity allocation and participation in the frequency control auxiliary service market. Finally, the solving process of grid-connected optimal operation mode is proposed, and the rationality of the grid-connected optimal operation strategy between renewable energy cluster and shared energy storage is verified by example analysis. The results indicate that renewable energy cluster and shared energy storage can effectively increase both benefits, and a win-win situation for all parties can be realized. On the one hand, the cooperation mode and allocation mechanism can effectively guarantee the benefit of each renewable energy station. On the other hand, shared energy storage is beneficial for assisting in tracking the power generation plan of renewable energy and reducing the renewable energy power curtailment situation. There also has residual capacity in the shared energy storage system; it can participate in the frequency control ancillary service market, which can improve the capacity utilization rate and benefit of shared energy storage.

1. Introduction

With the growth of installed capacity of renewable energy power generation, it is necessary to develop towards high-quality goals in order to adapt to market competition mechanisms, such as in Ref. [1]. Renewable energy cluster can effectively control uncertainty risks through complementary characteristics, which can bring cooperative benefit and enhance market competitiveness, such as in Refs. [2, 3]. Renewable energy cluster with energy storage can further reduce uncertainty risks. At present, renewable energy station is mostly with its own energy storage, which faces a problem with resource utilization efficiency lower. Due to the uncontrollable quality and small capacity of such energy storage, Li et al. stated that there may be problems with the limitation of control in Ref. [4]. Shared energy storage has advantages in terms of investment scale and utilization rate, Song et al. stated that it can provide greater cooperative benefit for renewable energy cluster in Ref. [5]. Therefore, it is of great significance to study the grid-connected optimal operation mode between renewable energy cluster and shared energy storage that explicitly encompasses various aspects, such as renewable energy cluster based on a cooperative game, shared energy storage assisting in tracking the power generation plan of renewable energy, and shared energy storage participation in frequency control ancillary service market. It is the problem that my study endeavors to tackle, which helps to make renewable energy power generation develop towards high-quality goals in order to adapt to market competition mechanisms.

1.1. Deficiency of Current Research. Many papers have been conducted on the cooperative problem of renewable energy cluster. In terms of cost allocation, Zhang et al. use the nucleolus method and Shapley value method to allocate the cooperative benefit generated by wind farms and P2G participating in the electricity market, such as in Ref. [6]. Zheng and Jiang adopt the improved Shapley value method to allocate the fluctuation cost of wind farm cluster in Ref. [7], considering the impact of each wind farm power fluctuation on the cluster. On the grid-connected model, Zhao et al. exploit the potential flexibility in the district heating system for better wind power accommodation in Ref. [8], and a cost allocation strategy based on the Shapley value method is proposed, which can rationally allocate the benefit among multiple agents. Wang et al. proposed a dynamic coordinated scheduling model that combines wind, photovoltaic, and energy storage to optimize the profit of the energy complementary delivery system and verified the rationality of introducing a cooperative mode for benefit distribution and utilizing an enhanced Shapley value method to allocate the benefits of joint operation among the three parties, such as in Ref. [9]. But, it only aims to maximize the whole alliance benefit and neglects the interests of members. At present, researches on the cooperative problem of renewable energy cluster mostly aim to maximize the whole cluster benefit, such as in Ref. [10]. However, further research is needed on the cooperation mode among cluster members, which should stimulate their cooperation motivation by maximizing cooperative benefit of cluster member, in order to achieve the effect of improving cluster power curve.

Shared energy storage is a new type of energy storage trading mode. It can satisfy the stability requirements that are related to power networks, since this is a critical matter for the incorporation of more distributed and stochastic resources. Shared energy storage is also going to be increasingly present in the electrical grid in the next few years. Cervero et al. developed a solid-state transformer system to provide important advantages for shared energy storage, which can remove a high number of power transformers and achieve a more compact facility with lower power losses, such as in Ref. [11]. Meanwhile, with the development of digital technology, Zheng et al. stated that the control accuracy, conversion efficiency, and response speed of renewable energy inverter will gradually be better than the traditional generator and feeder equipment in Ref. [12]. The above research provides technical support for energy storage assisting in tracking the power output plan of renewable energy, or participation in frequency control ancillary service market. In Aug 2021, the National Energy Administration officially issued the "Operation Management Regulation of Grid-connected Entities" and the "Management Rules of Auxiliary Services in the Power System," which recognize that shared energy storage is an independent grid-connected entity and can participate in ancillary services in the electricity market to obtain profits. In Jun 2022, the National Development and Reform Commission and the National Energy Administration issued the "Notice on Further Promoting New Energy Storage Participating in Electricity Market," which enhances the compensation standards for shared energy storage and improves the profit mechanism for shared energy storage. At present, shared energy storage can participate in auxiliary services to alleviate the problem of peak load and frequency regulation based on some representative representational provinces of China, such as Shandong, Qinghai, and Gansu. According to shared energy storage making different degrees of response to AGC signals, frequency regulation auxiliary service is compensated with the mileage of frequency regulation, and the compensation coefficient ranges from 0.014 to 2.099 \$/MW. Taking a 100 MW/200 MWh energy storage power station as an example, during the operation period of the demonstration project in 2022, the shared energy storage power station in Shandong can get a profit of about 2.8 million dollars a year under the compensation mechanism of frequency regulation. In Qinghai, the shared energy storage power station can receive 3.5 million dollars a year. In Gansu, the shared energy storage power station can receive 1.4 million dollars a year. The above content illustrates the validity of shared energy storage participating auxiliary services in the electricity market, and the main approach of shared energy storage obtaining frequency regulation profit. Meanwhile, Qiu et al. stated that the shared energy storage involved in the electricity market has contributed to the enhancement of the capacity utilization rate, such as in Ref. [13].

Scholars at home and abroad have conducted extensive research on the issue of energy storage assisting in tracking the power output plan of renewable energy, or participation in frequency control ancillary service market. However, there is less research on the optimal operation of shared energy storage, simultaneously considering the tracking of power output plans across multiple renewable energy stations and participation in the frequency control ancillary service market. Li et al. proposed a control strategy for shared energy storage to assist in tracking the power generation plan of renewable energy in Ref. [14], but did not effectively consider the cooperative mode of renewable energy stations. Ma et al. studied the strategy of shared energy storage to meet the primary frequency regulation needs of multiple renewable energy power generations and providing secondary frequency regulation services, such as in Ref. [15]. However, the demand for primary frequency regulation has little impact on the state of charge (SOC) of energy storage. Wu et al. analyzed the complementary characteristics during the operation of renewable energy stations in Ref. [16] but did not consider the application of assisting in tracking the power generation plan of renewable energy. Therefore, there is currently little research on the operation strategies for shared energy storage on the power supply side, which should simultaneously assist in tracking the power generation plan across multiple renewable energy stations and participate in the frequency control ancillary service market.

The sharing mode and benefit of energy storage need to consider the fairness and economy of cooperative parties, such as in Refs. [17, 18]. Jo and Park propose a new sharing mode based on virtual energy storage in Ref. [19], which can reduce physical energy storage capacity and investment cost. Yang et al. focus on the shared energy storage on the user side in Ref. [20], and Cui et al. achieve fair allocation of benefits based on game theory in Ref. [21]. Li et al. propose an improved Shapley value method to solve the capacity and cost issues of shared energy storage in Ref. [22], considering the different line losses caused by different positions of members in the alliance. However, the existing research on the sharing modes and benefit issues of energy storage mostly focuses on the user side, and there is less research on this on the power supply side.

1.2. Structure of Thesis. To sum up, researches on the cooperative problem of renewable energy cluster mostly aims to maximize the whole cluster benefit. Further research is needed on the cooperation mode among cluster members, which should stimulate their cooperation motivation by promoting the maximization of cluster member benefit, in order to achieve the effect of improving cluster power curve. Shared energy storage, as a new type of energy storage trading mode, is an effective means to reduce the uncertainty of renewable energy power generation. There is less research on the optimal operation of shared energy storage, simultaneously considering the tracking of power output plans across multiple renewable energy stations and participation in the frequency control ancillary service market. It does not fully utilize the function of shared energy storage. The sharing mode and benefit of energy storage need to consider the fairness and economy of cooperative parties, the existing research on the sharing modes and benefit issues of energy storage mostly focuses on the user side, and there is less research about this on the power supply side.

In response to the above issues, this article proposes a grid-connected optimal operation mode between renewable energy cluster and shared energy storage on the power supply side that explicitly encompasses various aspects, such as renewable energy cluster based on cooperative game, shared energy storage assisting in tracking the power generation plan of renewable energy, and shared energy storage participation in frequency control ancillary service market. Firstly, a framework for the grid-connected operation relationship between renewable energy cluster and shared energy storage was proposed in Part II, and an overall model for grid-connected optimal operation mode was built. Secondly, for the complementary characteristic blurring each member's contribution to the cluster power deviation, an improved Shapley value method is used to build a rational mechanism for apportioning the cluster power deviation penalty in Part III. Thirdly, based on the Nash negotiation framework and allocation mechanism, a benefit model for renewable energy cluster is established, and an improved particle swarm optimization method is proposed to solve the operation strategy for renewable energy cluster. Fourthly, based on the charge and discharge demand of renewable energy cluster, with the goal of maximizing the benefit of shared energy storage, capacity pricing of shared energy storage capacity is optimized in Part IV, as well as the capacity allocation and power declaration of participating in frequency control auxiliary service market. Fifthly, the solving process of the grid-connected optimal operation mode is proposed in Part V. Finally, the effectiveness of the grid-connected optimal operation mode between renewable energy cluster and shared energy storage on the power supply side is verified by example analysis in Part VI. Shared energy storage leasing helps to ensure that the benefit of each member in the cluster is higher than the benefit of the member with self-built energy storage. Shared energy storage and the cooperation mode among members help to reduce the power deviation penalty of the cluster, which can achieve a win-win situation for all parties.

1.3. Main Innovation of Paper. This paper conducts a detailed analysis of the cooperation mode of renewable energy cluster, shared energy storage capacity pricing, and shared energy storage participating in the frequency control ancillary service market. On the one hand, the cooperation mode of renewable energy cluster can effectively reduce power deviation and generate certain cooperative benefits. On the other hand, under the same energy storage rated capacity, shared energy storage can better assist in tracking the power generation plan of renewable energy than self-built energy storage and has residual capacity participating in the frequency control ancillary service market to obtain higher economic benefits. The main innovations are as follows.

(1) The optimal operation model of the renewable energy cluster is built under the cooperative mode. Adopting the Nash negotiation theory, its objective function is set as the product of the cooperation benefits of each station in the cluster, which can ensure the fairness of operational strategy for the cluster members

(2) The improved Shapley value method is used to build a rational mechanism for apportioning cluster power deviation penalty, reflects the impact of each station on the cluster power deviation, and can stimulate cluster members' cooperation motivation by maximizing the cooperative benefit of cluster member. Improved particle swarm optimization algorithm can help the population jump from local optimization solution and find global optimal solution

(3) The capacity price model of shared energy storage is established based on the charge and discharge demand of renewable energy cluster and can help shared energy storage to assist in tracking the power generation plan of renewable energy. The residual capacity of shared energy storage system can participate in the frequency control ancillary service market and can help shorten its cost-recovery cycle

(4) A two-layer energy management framework is proposed, the upper layer is a capacity-pricing model for shared energy storage, and the lower level is a cooperative game model for renewable energy cluster. It realizes the grid-connected coordinated operation between renewable energy cluster and shared energy storage

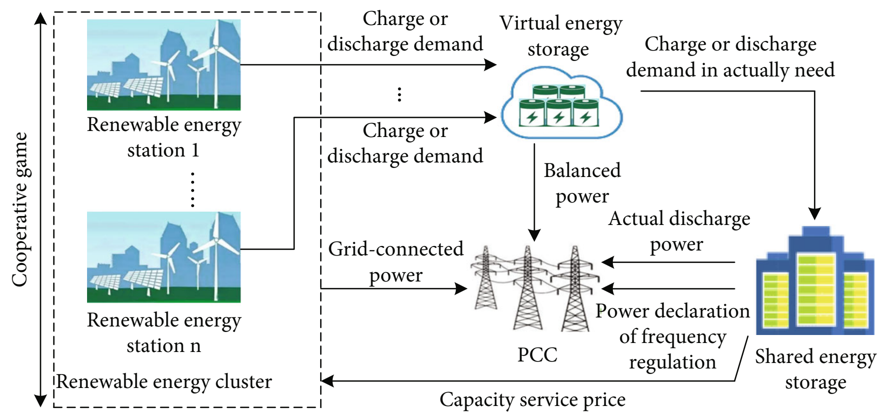


Figure 1: Relationship framework of the grid-connected operation mode between renewable energy cluster and shared energy storage.

2. Relationship Framework of the Grid-Connected Operation Mode

The relationship framework for the grid-connected operation mode between renewable energy cluster and shared energy storage is shown in Figure 1. The renewable energy cluster adopts a cooperative game model among multiple renewable energy stations, and the Nash negotiation model is used to fairly allocate the cooperative benefit among multiple renewable energy stations. Each renewable energy station can directly connect to the grid through a point of common coupling (PCC) or use shared energy storage for charging and discharging. For shared energy storage, the charging and discharging demands from multiple renewable energy stations will balance each other at some times. The balanced amount can be directly exchanged among renewable energy stations without operating losses, which is defined as virtual energy storage in this paper. From the above definition, the virtual energy storage in this paper temporarily does not consider charging and discharging losses. The emergence of virtual energy storage can avoid the frequent occurrence of the phenomenon of shared energy storage charging and discharging. The actual discharge power of shared energy storage is only the surplus power after balance.

Based on the life cycle cost of energy storage, shared energy storage sets initial capacity prices for renewable energy cluster, and each station purchases initial energy storage capacity services according to their own needs. Based on the operation strategy of the renewable energy cluster in the scheduling period, capacity price is optimized to encourage renewable energy cluster using shared energy storage to assist in tracking the power generation plan. When there is residual capacity in the shared energy storage, it can participate in the frequency control ancillary service market and gain revenue. The frequency regulation effectiveness of energy storage is much higher than that of conventional units, such as in Refs. [23, 24]. Therefore, energy storage has a clear competitive advantage in the frequency control auxiliary service market.

The grid-connected operation between renewable energy cluster and shared energy storage can enable the power grid to obtain relatively centralized, effective, and controllable adjusting resources, and more efficiently achieve supply-demand balance in the novel power system. All parties can achieve a win-win situation.

By analyzing the grid-connected operation mode between renewable energy cluster and shared energy storage, a model can be built as shown in Eq. (4) to achieve optimal operation for renewable energy cluster and shared energy storage. The subsequent chapters of this paper will focus on theoretical research and example analysis of this model.

$$x = \left(P_{\mathrm{RE}}^{R}(t), P_{\mathrm{BAT}}^{c,re}(t), P_{\mathrm{BAT}}^{d,re}(t), P_{\mathrm{RE}}^{\mathrm{vbat}}(t)\right), \tag{1}$$

$$y_1 = \left(p_{s,1}, \cdots, p_{s,i}, \cdots, p_{s,n_{\mathrm{RE}}}\right), \tag{2}$$

$$y_2 = \left(P_{\mathrm{BAT}}^{c,\mathrm{re}}(t), P_{\mathrm{BAT}}^{d,\mathrm{re}}(t), P_{\mathrm{BAT}}^{\mathrm{fr}}(t)\right), \tag{3}$$

$$\max \prod_{i=1}^{n_{\mathrm{RE}}} \left(F_{\mathrm{RE},i}(x) - F_{\mathrm{RE},i,0}(x)\right), \quad \text{s.t.}(x) \in \Omega_{\mathrm{RE}}, \tag{4}$$

$$\max F_{\mathrm{BAT}}(y_1, y_2), \quad \text{s.t.}(y_1, y_2) \in \Omega_{\mathrm{BAT}}. \tag{5}$$

In formula, x represents the operation strategy set of the renewable energy cluster. $P_{\mathrm{RE},i}^{R}(t)$ represents the grid-connected power of renewable energy station i at time t. $P_{\mathrm{BAT}}^{c,\mathrm{re}}(t)$ and $P_{\mathrm{BAT}}^{d,\mathrm{re}}(t)$ are the charge and discharge power provided by shared energy storage to renewable energy cluster at time t. $P_{\mathrm{RE}}^{\mathrm{vbat}}(t)$ is the discharge power provided by virtual energy storage for renewable energy cluster at time t. y_1 and y_2 are the operation strategy sets of shared energy storage. $p_{s,i}$ is the capacity price of shared energy storage corresponding to renewable energy station i. n_{RE} is the number of stations in the renewable energy cluster. $P_{\mathrm{BAT}}^{\mathrm{fr}}(t)$ is the power declaration of frequency regulation for shared energy storage at time t in the frequency control auxiliary service market. $F_{\mathrm{RE},i}$ is the benefit of renewable energy station in a cooperation model, while $F_{\mathrm{RE},i,0}$ is this in a noncooperative model. F_{BAT} is the benefit of shared energy storage. Ω_{RE} and Ω_{BAT} are the constraints for operation strategy sets of renewable energy cluster and shared energy storage.

3. Operation Model of Renewable Energy Cluster

Renewable energy station does not need to have self-build energy storage, which can reduce project construction investment. By leasing capacity from shared energy storage, it is possible to improve renewable energy power curtailment situation and achieve tracking the power generation plan of renewable energy. After aggregating renewable energy stations into renewable energy cluster, the power grid will assess the renewable energy cluster as a whole, according to corresponding rules.

3.1. Cooperative Game Model. At present, researches on the cooperative problem of renewable energy cluster mostly aim to maximize the whole cluster benefit. However, further research is needed on the cooperation mode among cluster members, which can stimulate their cooperation motivation by maximizing the cooperative benefit of cluster member, in order to achieve the effect of improving the cluster power curve. Therefore, the operation model of the renewable energy cluster in this paper considers the case, where multiple renewable energy stations purchase capacity services provided by shared energy storage, and the renewable energy cluster adopts a cooperative game mode among multiple renewable energy stations. Nash negotiation, as a type of cooperative game model, has an objective function that is the product of the cooperation benefits of each station in the cluster. The constraint is that the cooperation benefits of each station are greater than zero, and its optimal solution can enable each station to obtain Pareto optimal benefits, such as in Ref. [10]. The grid-connected renewable energy cluster model is built based on the Nash negotiation model and the rational mechanism for apportioning cluster power deviation penalty, which can fully ensure the fairness of operation strategies for each station. The objective function for the operation strategy of the renewable energy cluster is shown in Eq. (6), and Yuan et al. analyze the effectiveness of Eq. (6) in solving problems in Ref. [25], which is not described in this paper. An optimal operation strategy can achieve a benefit balance among stations and maximize the cooperation benefit of each station. The revenue model for the renewable energy cluster is shown in Eq. (7), which consists of power selling revenue, the using cost of shared energy storage, and the penalty of power deviation for each renewable energy station.

$$\max \prod_{i=1}^{n_{\mathrm{RE}}} \left(F_{\mathrm{RE},i} - F_{\mathrm{RE},i,0}\right), \tag{6}$$

$$F_{\mathrm{RE},i} = C_{\mathrm{RE},i}^{\mathrm{sale}} - C_{\mathrm{RE},i}^{\mathrm{bat}} - C_{\mathrm{RE},i}^{d}. \tag{7}$$

In the formula, $F_{\mathrm{RE},i}$ is the benefit of renewable energy station i under the cooperative mode. $F_{\mathrm{RE},i,0}$ is the benefit of renewable energy station i under the noncooperative mode. $F_{\mathrm{RE},i} - F_{\mathrm{RE},i,0}$ is the cooperation benefit of each station. $C_{\mathrm{RE},i}^{\mathrm{sale}}$ represents the power selling revenue of renewable energy station i. $C_{\mathrm{RE},i}^{\mathrm{bat}}$ is the using cost of shared energy storage for renewable energy station i. $C_{\mathrm{RE},i}^{d}$ is the penalty of power deviation for renewable energy station i.

3.1.1. Power Selling Revenue. Power selling revenue includes two parts, such as direct power selling revenue and indirect power selling revenue. The direct power selling revenue comes from the grid-connected power of each renewable energy station, as shown in the following:

$$C'^{\mathrm{sale}}_{\mathrm{RE},i} = \sum_{t=1}^{T} \left[p_e(t) P_{\mathrm{RE},i}^{R}(t) \Delta t\right]. \tag{8}$$

In the formula, $C'^{\mathrm{sale}}_{\mathrm{RE},i}$ is the direct power selling revenue. t is the scheduling time. T is the number of scheduling time in a scheduling period. $p_e(t)$ is the electricity price at time t. $P_{\mathrm{RE},i}^{R}(t)$ represents the grid-connected power of renewable energy station i at time t. Δt is the time interval.

Indirect power selling revenue can be obtained by using virtual energy storage and shared energy storage, as shown in the following:

$$C''^{\mathrm{sale}}_{\mathrm{RE},i} = \sum_{t=1}^{T} \left[p_e(t) \left(P_{\mathrm{RE},i}^{\mathrm{bat},d}(t) + P_{\mathrm{RE},i}^{\mathrm{vbat}}(t)\right) \Delta t\right]. \tag{9}$$

In the formula, $C''^{\mathrm{sale}}_{\mathrm{RE},i}$ represents the indirect power selling revenue. $P_{\mathrm{RE},i}^{\mathrm{bat},d}(t)$ is the discharge power provided by shared energy storage to renewable energy station i at time t. $P_{\mathrm{RE},i}^{\mathrm{vbat}}(t)$ is the discharge power provided by virtual energy storage to renewable energy station i at time t.

3.1.2. Using Cost of Shared Energy Storage. The using cost of shared energy storage for renewable energy station i is shown in the following:

$$C_{\mathrm{RE},i}^{\mathrm{bat}} = p_{s,i} \sum_{t=1}^{T} \left[\left(\frac{P_{\mathrm{RE},i}^{\mathrm{bat},d}(t)}{\eta_d + \eta_c P_{\mathrm{RE},i}^{\mathrm{bat},c}(t)}\right) \Delta t\right]. \tag{10}$$

In the formula, $p_{s,i}$ is the capacity price of shared energy storage corresponding to renewable energy station i, as shown in Eq. (32). $P_{\mathrm{RE},i}^{\mathrm{bat},c}(t)$ is the charge power provided by shared energy storage to renewable energy station i at time t. η_c and η_d are the charging and discharging efficiency of shared energy storage, respectively.

3.2. Power Deviation Penalty. When the actual grid-connected power of a renewable energy cluster deviates from the prediction power, it will be punished according to the power deviation, as shown in Eq. (11). By leasing shared energy storage to assist in tracking the power generation plan of renewable energy, the penalty of power deviation for renewable energy cluster can be reduced.

$$C_{\mathrm{RE}}^{d} = p_d \sum_{t=1}^{T} P_{\mathrm{RE}}^{d}(t) \Delta t, \tag{11}$$

$$\begin{aligned} P_{\mathrm{RE}}^{d}(t) &= P_{\mathrm{RE}}^{R}(t) - P_{\mathrm{RE}}^{D}(t) + P_{\mathrm{RE}}^{\mathrm{vbat}}(t) \\ &\quad - u_{\mathrm{BAT}}^{\mathrm{re}}(t) P_{\mathrm{BAT}}^{c,\mathrm{re}}(t) - \left[u_{\mathrm{BAT}}^{\mathrm{re}}(t) - 1\right] P_{\mathrm{BAT}}^{d,\mathrm{re}}(t), \end{aligned} \tag{12}$$

$$P_{\mathrm{RE}}^{R}(t)=\sum_{i=1}^{n_{\mathrm{RE}}}P_{\mathrm{RE},i}^{R}(t), \tag{13}$$

$$P_{\mathrm{RE}}^{\mathrm{vbat}}(t)=\sum_{i=1}^{n_{\mathrm{RE}}}P_{\mathrm{RE},i}^{\mathrm{vbat}}(t), \tag{14}$$

$$P_{\mathrm{BAT}}^{c,\mathrm{re}}(t)=\sum_{i=1}^{n_{\mathrm{RE}}}P_{\mathrm{RE},i}^{\mathrm{bat},c}(t), \tag{15}$$

$$P_{\mathrm{BAT}}^{d,\mathrm{re}}(t)=\sum_{i=1}^{n_{\mathrm{RE}}}P_{RE,i}^{\mathrm{bat},d}(t). \tag{16}$$

In the formula, p_d is the power deviation penalty coefficient. $Q_{\mathrm{RE}}^{d}(t)$ represents the power deviation of the renewable energy cluster at time t. $P_{\mathrm{RE}}^{R}(t)$ indicates the grid-connected power of renewable energy cluster at time t. $P_{\mathrm{RE}}^{D}(t)$ represents the prediction power of the renewable energy cluster at time t. $P_{\mathrm{RE}}^{\mathrm{vbat}}(t)$ represents the discharge power provided by virtual energy storage to renewable energy cluster. $P_{\mathrm{BAT}}^{c,\mathrm{re}}(t)$ and $P_{\mathrm{BAT}}^{d,\mathrm{re}}(t)$ are the charge and discharge power provided by shared energy storage to renewable energy cluster at time t. $u_{\mathrm{BAT}}^{\mathrm{re}}(t)$ is the charge and discharge status of shared energy storage leased by renewable energy cluster, which is a 0-1 variable. $u_{\mathrm{BAT}}^{\mathrm{re}}(t)=1$ represents shared energy storage charging. $u_{\mathrm{BAT}}^{\mathrm{re}}(t)=0$ indicates shared energy storage discharge.

In view of the cooperative problem of renewable energy cluster, it is necessary to rationally allocate the cooperative benefit among multiple cluster members. The complementary characteristics of renewable energy power generation will help the positive and negative grid-connected power deviation of each station cancel out, leading to a decrease in the power deviation penalty of renewable energy cluster. However, the complementary characteristics are blurring each member's contribution to the cluster power deviation. Moreover, there is often a situation in a cluster where the power deviation of a certain station is significant, but in the opposite direction to the power deviation of other stations. It can decrease the power deviation of other stations and has the effect of reducing the power deviation penalty of the cluster and generating cooperation benefits. At this point, if the cluster deviation penalty is allocated based on the power output of each station or according to the size of the deviation, it is unfair for the station that plays a role like the above. The Shapley value method can implement allocation based on the marginal deviation penalty of each station, reflecting the enhanced effect of each station joining the cluster on complementary characteristics. Meanwhile, the rational mechanism for apportioning cluster power deviation penalty is needed to generate operation strategy, and the Shapley value method used for allocation can also motivate the cooperation enthusiasm of each station. Zheng and Jiang and Quan et al. discussed the effectiveness of the Shapley value method in cost allocation of wind power fluctuations in Refs. ([7, 26] and presented a mathematical framework or algorithm used to illustrate the above content, which is not repeatedly described in this paper. This section extends its application to the scenario of renewable energy cluster and shared energy storage. The calculation method for the Shapley value is shown in Eq. (18).

$$W(|S|)=\frac{(n-|S|)!(|S|-1)!}{n!}, \tag{17}$$

$$X_i=\sum_{S_i\in S}W(|S|)[C(S)-C(S-i)] \quad i=1,2,\cdots,n_{\mathrm{RE}}. \tag{18}$$

In the formula, $W(|S|)$ is the weighting factor. n is the number of renewable energy stations. S_i is all subclusters of renewable energy cluster S including station i. $C(S)$ is the deviation penalty of subcluster including station i. $C(S-i)$ is the deviation penalty of subcluster after removing station i. X_i represents the Shapley value that station i should be allocated in the cluster deviation penalty.

The larger the grid-connected power of renewable energy station, the greater their proportion in the cluster power output, and their power deviation is more likely to affect the cluster. Therefore, to fully demonstrate the impact of each station power output on the power deviation of the cluster, it is necessary to adjust the Shapley value based on the grid-connected power of each station to improve the grid-connected power quality of the cluster. The power deviation penalty for renewable energy station i based on the improved Shapley value method is shown in the following:

$$\begin{aligned}&C_{\mathrm{RE},i}^{d}=X_i+\delta\Delta K_i C_{\mathrm{RE}}^{d},\\&\Delta K_i=Q_{\mathrm{RE},i}\left(\sum_{i=1}^{n_{\mathrm{RE}}}Q_{\mathrm{RE},i}\right)^{-1}-(n_{\mathrm{RE}})^{-1}.\end{aligned} \tag{19}$$

In the formula, δ is the adjustment coefficient for reallocation. ΔK_i is the correction factor for reallocation. $Q_{RE,i}$ is the power quantity of renewable energy station i.

3.3. Constraints

3.3.1. Power Constraint of Renewable Energy Station.

$$\begin{aligned}&0\le P_{\mathrm{RE},i}^{R}(t)+P_{\mathrm{RE},i}^{\mathrm{vbat}}(t)-u_{\mathrm{BAT}}^{\mathrm{re}}(t)P_{\mathrm{RE},i}^{\mathrm{bat},c}(t)-[u_{\mathrm{BAT}}^{\mathrm{re}}(t)-1]P_{\mathrm{RE},i}^{\mathrm{bat},d}(t)\le P_{\mathrm{RE},i}^{\max},\\&\sum_{i=1}^{n_{\mathrm{RE}}}\left[P_{\mathrm{RE},i}^{R}(t)+P_{\mathrm{RE},i}^{\mathrm{vbat}}(t)-u_{\mathrm{BAT}}^{\mathrm{re}}(t)P_{\mathrm{RE},i}^{\mathrm{bat},c}(t)-[u_{\mathrm{BAT}}^{\mathrm{re}}(t)-1]P_{\mathrm{RE},i}^{\mathrm{bat},d}(t)\right]\le P_{\mathrm{PCC}}^{\max},\\&0\le\left|P_{\mathrm{RE},i}^{R}(t)-P_{\mathrm{RE},i}^{R}(t-1)-u_{\mathrm{BAT}}^{\mathrm{re}}(t)P_{\mathrm{RE},i}^{\mathrm{bat},c}(t)-[u_{\mathrm{BAT}}^{\mathrm{re}}(t)-1]P_{\mathrm{RE},i}^{\mathrm{bat},d}(t)\right.\\&\qquad\left.+P_{\mathrm{RE},i}^{\mathrm{vbat}}(t)\right|\le\Delta P_{\mathrm{RE}}^{\max}.\end{aligned} \tag{20}$$

In the formula, $P_{\mathrm{RE},i}^{\max}$ is the installed capacity of renewable energy station i. $P_{\mathrm{PCC}}^{\max}$ is the power limit of PCC. $\Delta P_{\mathrm{RE}}^{\max}$ is the output fluctuation limit of renewable energy station, which is influenced by the installed capacity of renewable energy station, such as in Ref. [27].

3.4. Power Constraint of Shared Energy Storage.

$$0 \le \sum_{i=1}^{n_{RE}} P_{RE,i}^{bat,c}(t) \le P_{BAT}^{max}, \quad 0 \le \sum_{i=1}^{n_{RE}} P_{RE,i}^{bat,d}(t) \le P_{BAT}^{max}. \tag{21}$$

In the formula, P_{BAT}^{max} is the upper limit of the charge and discharge power for shared energy storage.

3.4.1. Cooperation Mode Constraint of Renewable Energy Cluster. In the cooperative game model, the operation benefit of renewable energy station i in cooperation mode must not be lower than this in the noncooperative model, as shown in Eq. (22). It is a precondition for the survival of a cluster.

$$F_{RE,i} \ge F_{RE,i,0}. \tag{22}$$

3.5. Operation Benefit in Noncooperative Mode.

$$F_{RE,i,0} = C_{RE,i,0}^{sale} - C_{RE,i,0}^{bat} - C_{RE,i,0}^{d}. \tag{23}$$

In the formula, $C_{RE,i,0}^{sale}$ represents the power selling revenue of renewable energy station i in noncooperative mode. $C_{RE,i,0}^{bat}$ is the using cost of shared energy storage for renewable energy station i in noncooperative mode. $C_{RE,i,0}^{d}$ is the penalty of power deviation for renewable energy station i in noncooperative mode.

3.5.1. Power Selling Revenue.

$$\begin{aligned} C_{RE,i,0}^{sale} &= C'^{sale}_{RE,i,0} + C''^{sale}_{RE,i,0}, \\ C'^{sale}_{RE,i,0} &= \sum_{t=1}^{T} \left[p_e(t) P_{RE,i,0}^{R}(t) \Delta t \right], \\ C''^{sale}_{RE,i,0} &= \sum_{t=1}^{T} \left[p_e(t) P_{RE,i,0}^{bat,d}(t) \Delta t \right]. \end{aligned} \tag{24}$$

In the formula, $C'^{sale}_{RE,i,0}$ is the direct power selling revenue in noncooperative mode. $P_{RE,i,0}^{R}(t)$ represents the grid-connected power of renewable energy station i in noncooperative mode at time t. $P_{RE,i,0}^{bat,d}(t)$ is the discharge power provided by self-build energy storage to renewable energy station i in noncooperative mode at time t. $C''^{sale}_{RE,i,0}$ is the indirect power selling revenue in noncooperative mode.

3.5.2. Using Cost of Shared Energy Storage.

$$C_{RE,i}^{bat} = \sum_{t=1}^{T} \left[\left(\frac{p_{s,d}(t) P_{RE,i,0}^{bat,d}(t)}{\eta_d + p_{s,c}(t) \eta_c P_{RE,i,0}^{bat,c}(t)} \right) \Delta t \right], \tag{25}$$

In the formula, $P_{RE,i,0}^{bat,c}(t)$ is the charge power provided by self-build energy storage to renewable energy station i in noncooperative mode at time t.

3.5.3. Power Deviation Penalty.

$$\begin{aligned} C_{RE,i,0}^{d} &= p_d \sum_{t=1}^{T} P_{RE,i,0}^{d}(t) \Delta t, \\ P_{RE,i,0}^{d}(t) &= P_{RE,i,0}^{R}(t) - P_{RE,i,0}^{D}(t) - u_{BAT}^{re}(t) P_{RE,i,0}^{bat,c}(t) \\ &\quad - \left[u_{BAT}^{re}(t) - 1 \right] P_{RE,i,0}^{bat,d}(t). \end{aligned} \tag{26}$$

In the formula, $C_{RE,i,0}^{d}$ is the power deviation penalty for renewable energy station i in noncooperative mode. $P_{RE,i,0}^{d}(t)$ is the power deviation of renewable energy station i in noncooperative mode. $P_{RE,i,0}^{D}(t)$ represents the prediction power of the renewable energy station i in noncooperative mode.

3.6. Improved Particle Swarm Optimization Algorithm. The renewable energy cluster model contains complex nonlinear parts, which can be solved by an improved particle swarm optimization algorithm. The particle swarm optimization algorithm is simple and easy to operate, but it is easy to get stuck at a locally optimal value. Local convergence estimate coefficient can be used to improve particle swarm optimization algorithm, in order to improve the quality and diversification of solutions and promote the solving efficiency. Jiang et al. proposed a local convergence estimate coefficient in Ref. [28] and made a discussion about the parameters employed in the algorithm and their respective significance. It will not be described in this paper, but only existing achievement as Eq. (27) is used to obtain the whole optimal solution of the target problem.

$$L_{ce} = \sqrt{\frac{\sum_{j=1}^{m} \left(f_j - f_{best} \right)^2}{m}}. \tag{27}$$

In the formula, L_{ce} is the local convergence estimate coefficient. m is the number of iterations. f_j is the optimal population fitness value in the jth iteration. f_{best} is the fitness of the global optimal particle during the iteration.

When the population after a certain number of iterations and L_{ce} is too small, it indicates that the population optimization process is blocked after m iterations and the population converges to the local optimum or obtains the whole optimal solution. When L_{ce} is less than the set value, the algorithm randomly mutates population velocity within the range. If the population has found the whole optimal solution, the mutation has no effect on the optimization results. If the population converges to the local optimum, the algorithm randomly mutates population velocity can help the population jump from the local optimization solution and find better particles.

4. Operation Model of Shared Energy Storage

Due to the renewable energy cluster adopting a cooperative model among renewable energy stations, the capacity of shared energy storage to meet the charge or discharge demand of the renewable energy cluster will be less than the capacity sum of each renewable energy station self-build energy storage. Therefore, shared energy storage has advantages in terms of investment scale and utilization rate.

The initial capacity price can be designed based on the life cycle cost of shared energy storage. After the end of a scheduling period, the power deviation penalty difference between the cooperation mode and the noncooperative mode is calculated, and this difference is refunded according to the contribution ratio of each renewable energy station to optimize the initial capacity price. Finally, fully considering the differentiated demand for shared energy storage among renewable energy stations, it can achieve the effect that the benefit of station leasing shared energy storage is higher than the benefit of the station with self-built energy storage.

4.1. Optimal Benefit Model. The revenue of shared energy storage comes from the renting capacity to renewable energy cluster and participating frequency control ancillary service market. The cost of shared energy storage is mainly the life expenditure. Equation (28) can be established with the goal of maximizing the benefit of shared energy storage.

$$F_{\mathrm{BAT}} = C_{\mathrm{BAT}}^{\mathrm{re}} + C_{\mathrm{BAT}}^{\mathrm{fr}} - C_{\mathrm{BAT}}^{\mathrm{life}}. \tag{28}$$

In the formula, F_{BAT} represents the benefit of shared energy storage. $C_{\mathrm{BAT}}^{\mathrm{re}}$ is using cost of shared energy storage paid by renewable energy cluster. $C_{\mathrm{BAT}}^{\mathrm{fr}}$ is the revenue of participating frequency control ancillary service market. $C_{\mathrm{BAT}}^{\mathrm{life}}$ is the cost of life expenditure.

$$\begin{aligned} C_{\mathrm{BAT}}^{\mathrm{re}} &= \sum_{i=1}^{n_{\mathrm{RE}}} C_{\mathrm{RE},i}^{\mathrm{bat}} = \sum_{i=1}^{n_{\mathrm{RE}}} \sum_{t=1}^{T} \left[p_{s,i} \left(\frac{P_{\mathrm{RE},i}^{\mathrm{bat},d}(t)}{\eta_d + \eta_c P_{\mathrm{RE},i}^{\mathrm{bat},c}(t)} \right) \Delta t \right], \\ C_{\mathrm{BAT}}^{\mathrm{life}} &= p_{\mathrm{life}} \sum_{t=1}^{T} \left[\left(P_{\mathrm{BAT}}^{c,\mathrm{re}}(t) + P_{\mathrm{BAT}}^{d,\mathrm{re}}(t) \right) \Delta t + 2\beta P_{\mathrm{BAT}}^{\mathrm{fr}}(t) \right]. \end{aligned} \tag{29}$$

In the formula, p_{life} is the life expenditure cost coefficient. β is the ratio of the actual power quantity consumption to the power declaration when shared energy storage participating in frequency regulation during Δt, which can be calculated from historical AGC signals. $P_{\mathrm{BAT}}^{\mathrm{fr}}(t)$ is the power declaration for shared energy storage at time t in the frequency control ancillary service market.

4.2. Capacity Pricing Model. The construction condition of shared energy storage power stations on the power supply side is convenient, and the energy storage power station has excellent regulation performance. For now, China's policymakers are indicating that shared energy storage participates in the electricity market as much as possible for profit. On the one hand, it is to provide energy storage leasing services for renewable energy cluster and obtain an interest in leasing, which is currently the core source of revenues for shared energy storage. On the other hand, by being dispatched to participating frequency control auxiliary service in the electricity market, shared energy storage can obtain service fee, which mainly takes provinces such as Shandong, Qinghai, and Gansu as representatives. This section refers to Refs. [29, 30] and develops a capacity pricing model for shared energy storage leasing service. Based on the life cycle cost of energy storage, shared energy storage sets initial capacity prices for renewable energy cluster, and each station purchases initial energy storage capacity services according to their own needs. The leasing service should be provided by shared energy storage to renewable energy cluster accordingly. For shared energy storage, the revenue of renting capacity to renewable energy cluster can ensure the recovery of investment cost. Based on the operation strategy of the renewable energy cluster in the scheduling period, capacity price is optimized to encourage renewable energy cluster using shared energy storage to assist in tracking the power generation plan. This is to shorten the payback period of shared energy storage investment through price advantages. The initial capacity price and its optimization process ensure the willingness in shared energy storage investment and renewable energy cluster using shared energy storage and can maintain a healthy development of the supply and demand relationship between shared energy storage and renewable energy cluster. The comprehensive explanation of the technique employed to optimize capacity pricing and allocation can refer to Refs. [29, 30], and the process of building the capacity pricing model is as follows.

As the purchaser of capacity services, the renewable energy cluster needs to evaluate the life cycle cost of energy storage before determining the purchase price of capacity services. According to parameters such as kinds of energy storage, charge and discharge power, and installed capacity, the annual investment cost of energy storage is shown in the following:

$$C_{\mathrm{BAT},0}^{\mathrm{ic}} = \frac{\left(p_{\mathrm{bat},p} P_{\mathrm{BAT}}^{\max} + p_{\mathrm{bat},e} E_{\mathrm{BAT}}^{\max} \right) \tau (1+\tau)^{y}}{\left[(1+\tau)^{y} - 1 \right]}. \tag{30}$$

In the formula, $C_{\mathrm{BAT},0}^{\mathrm{ic}}$ is the annual investment cost of energy storage. $p_{\mathrm{bat},p}$ is the cost coefficient of energy storage power, taken as 0.11 to 0.206 million dollars/MW. $P_{\mathrm{BAT}}^{\max}$ is the upper limit of charge and discharge power for shared energy storage. $p_{\mathrm{bat},e}$ is the cost coefficient of energy storage capacity, taking 0.206 to 0.315 million dollars/MW. $E_{\mathrm{BAT}}^{\max}$ indicates the installed capacity of shared energy storage. τ is the annual discount rate. y is the service life of energy storage.

For shared energy storage, the revenue of renting capacity to renewable energy cluster should cover the investment cost of energy storage. Therefore, Eq. (30) is used to calculate the initial capacity price of shared energy storage corresponding to renewable energy station i, as shown in the following:

$$\begin{aligned} p_{s,i,0} &= \frac{p_{s,\mathrm{re}} P_{RE,i}^{\max}}{\sum_{i=1}^{n_{\mathrm{RE}}} P_{\mathrm{RE},i}^{\max}}, \\ p_{s,\mathrm{re}} &= \frac{C_{\mathrm{BAT},0}^{\mathrm{ic}}}{T_0}. \end{aligned} \tag{31}$$

In the formula, $p_{s,\mathrm{re}}$ is the initial capacity price designed by shared energy storage for renewable energy cluster. T_0 is the annual operating hours for shared energy storage.

For renewable energy station, the using cost of shared energy storage should be lower than the cost of self-built energy storage. On the basis of the initial capacity price, fully considering the difference between cooperation mode and noncooperative mode, the reduction value of the deviation penalty is returned to each station according to the Shapley value model shown in Eq. (18). It can ensure that the benefit exceeds the self-built energy storage, reflect the principle of distribution according to work, and help to promote the cooperation enthusiasm of each station.

The capacity price of shared energy storage corresponding to renewable energy station i during the scheduling period is shown in the following:

$$p_{s,i} = p_{s,i,0} - \left(\frac{X_i^{-1}}{\sum_{i=1}^{n_{\mathrm{RE}}} X_i^{-1}} \right) \sum_{i=1}^{n_{\mathrm{RE}}} \left(C_{\mathrm{RE},i}^{d} - C_{\mathrm{RE},i,0}^{d} \right). \tag{32}$$

4.3. Revenue Model of Frequency Regulation. Shared energy storage participating in the frequency control ancillary service market not only fully utilizes energy storage capacity to improve the frequency regulation effect of the power grid but also can increase its own benefit. When energy storage participates in frequency regulation, frequent actions can affect the operation life of shared energy storage. Therefore, shared energy storage makes power declaration hourly in the frequency control ancillary service market, as shown in the following:

$$\begin{aligned}
P_{\mathrm{BAT}}^{\mathrm{fr}}(t) &= \min\left(P_{\mathrm{BAT}}^{m1}(t), P_{\mathrm{BAT}}^{m2}(t), P_{\mathrm{BAT}}^{m3}(t) \right) \times (1-q), \\
P_{\mathrm{BAT}}^{m1}(t) &= P_{\mathrm{BAT}}^{\max} - \max\left(\left| \tilde{P}_{\mathrm{BAT}}(t) \right| \right), \\
P_{\mathrm{BAT}}^{m2}(t) &= \left(S_{\mathrm{BAT}}^{\max} - \max\left(\left| \tilde{K}_S(t) \right| \right) \right) \frac{E_{\mathrm{BAT}}^{\max}}{\Delta t_{\mathrm{fr}}}, \\
P_{\mathrm{BAT}}^{m3}(t) &= \left(\min\left(\left| \tilde{K}_S(t) \right| \right) - S_{\mathrm{BAT}}^{\min} \right) \frac{E_{\mathrm{BAT}}^{\max}}{\Delta t_{\mathrm{fr}}}.
\end{aligned} \tag{33}$$

In the formula, $P_{\mathrm{BAT}}^{\mathrm{fr}}(t)$ is power declaration of shared energy storage in the frequency control ancillary service market at time t. $P_{\mathrm{BAT}}^{m1}(t)$ is the upper limit of shared energy storage charging and discharging power at time t based on $P_{\mathrm{BAT}}^{\max}$. $P_{\mathrm{BAT}}^{m2}(t)$ is the upper limit of shared energy storage charging and discharging power at time t based on $S_{\mathrm{BAT}}^{\max}$. $P_{\mathrm{BAT}}^{m3}(t)$ is the upper limit of shared energy storage charging and discharging power at time t based on $S_{\mathrm{BAT}}^{\min}$. q is the reserved ratio, taken as 5%. $P_{\mathrm{BAT}}^{\max}$ is the upper limit of shared energy storage charging and discharging power. $S_{\mathrm{BAT}}^{\max}$ and $S_{\mathrm{BAT}}^{\min}$ represent the upper and lower limits of shared energy storage SOC, respectively. $\tilde{P}_{\mathrm{BAT}}(t)$ is the optimization results of the shared energy storage power sequence at time t. $\tilde{K}_S(t)$ is the optimization result of the SOC sequence at time t. $E_{\mathrm{BAT}}^{\max}$ is the installed capacity of shared energy storage. Δt_{fr} is the time interval of power declaration of frequency regulation.

Revenue of shared energy storage participating in the frequency control ancillary service market is shown in Eq. (34), such as in Ref. [15] and Refs. [31, 32].

$$C_{\mathrm{BAT}}^{\mathrm{fr}} = \sum_{t=1}^{T} \left[\left(c_{\mathrm{ic}} + c_{\mathrm{ip}} d_{\mathrm{AGC}} \right) P_{\mathrm{BAT}}^{\mathrm{fr}}(t) \right]. \tag{34}$$

In the formula, c_{ic} is the capacity price. c_{ip} is the mileage price. d_{AGC} is the mileage coefficient, which is the hourly historical average of mileage, calculated from historical AGC signals.

4.4. Constraints

4.4.1. Energy Storage Capacity Constraints. The charging and discharging power constraints and residual capacity constraints of energy storage are shown in Eqs. (35)–(40). In the sharing mode, Papaefthymiou and Dragoon proposed the shared energy storage power and installed capacity constraints in Ref. [33], which are shown in Eq. (42). Equation (44) described the charging power equal to the discharging power during the scheduling period, which can ensure that the shared energy storage can still return to its initial SOC at the beginning of the next scheduling period.

$$P_{\mathrm{BAT}}^{c,\mathrm{total}}(t) = \frac{P_{\mathrm{BAT}}^{c,\mathrm{re}}(t) + \beta P_{\mathrm{BAT}}^{\mathrm{fr}}(t)}{\Delta t}, \tag{35}$$

$$P_{\mathrm{BAT}}^{d,\mathrm{total}}(t) = \frac{P_{\mathrm{BAT}}^{d,\mathrm{re}}(t) + \beta P_{\mathrm{BAT}}^{\mathrm{fr}}(t)}{\Delta t}, \tag{36}$$

$$0 \le P_{\mathrm{BAT}}^{c,\mathrm{total}}(t) \le P_{\mathrm{BAT}}^{\max}, \tag{37}$$

$$0 \le P_{\mathrm{BAT}}^{d,\mathrm{total}}(t) \le P_{\mathrm{BAT}}^{\max}, \tag{38}$$

$$E_{\mathrm{BAT}}(t) = \frac{E_{\mathrm{BAT}}(t-1) + u_{\mathrm{BAT}}(t)\eta_c P_{\mathrm{BAT}}^{c,\mathrm{total}}(t) + \left[u_{\mathrm{BAT}}(t) - 1\right] P_{\mathrm{BAT}}^{d,\mathrm{total}}(t)}{\eta_d}, \tag{39}$$

$$S_{\mathrm{BAT}}(t) = \frac{E_{\mathrm{BAT}}(t)}{E_{\mathrm{BAT}}^{\max}}, \tag{40}$$

$$0.1 \le S_{\mathrm{BAT}}(t) \le 0.9, \tag{41}$$

$$P_{\mathrm{BAT}}^{\max} = \gamma \sum_{i=1}^{n_{\mathrm{RE}}} P_{\mathrm{RE},i}^{\max}, \tag{42}$$

$$\frac{E_{\mathrm{BAT}}^{\max}}{P_{\mathrm{BAT}}^{\max}} = 2, \tag{43}$$

$$\sum_{t=1}^{T} P_{\mathrm{BAT}}^{d,\mathrm{total}}(t) = \sum_{t=1}^{T} P_{\mathrm{BAT}}^{c,\mathrm{total}}(t). \tag{44}$$

In the formula, $P_{\mathrm{BAT}}^{c,\mathrm{total}}(t)$ represents the total charging power of shared energy storage. $P_{\mathrm{BAT}}^{d,\mathrm{total}}(t)$ is the total discharge power for shared energy storage. $E_{\mathrm{BAT}}(t)$ is the residual capacity of shared energy storage at time t. $u_{\mathrm{BAT}}(t)$ is the

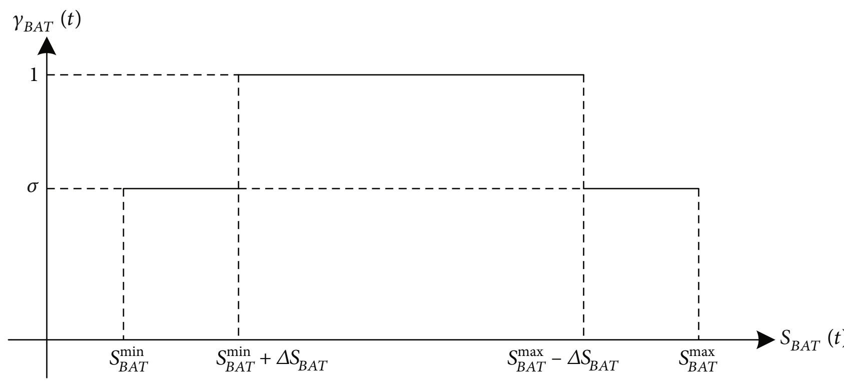


Figure 2: Relationship between frequency regulation performance index and shared energy storage SOC.

charging and discharging state of shared energy storage, which is a 0-1 variable. $u_{\mathrm{BAT}}(t) = 1$ represents shared energy storage charging. $u_{\mathrm{BAT}}(t) = 0$ indicates shared energy storage discharge. $S_{\mathrm{BAT}}(t)$ is the SOC of shared energy storage at time t. $E_{\mathrm{BAT}}^{\max}$ indicates the installed capacity of shared energy storage. γ is the capacity proportion of energy storage, which gives service to renewable energy cluster, taken as 10%, and the duration of energy storage charging and discharging is set at 2 hours.

4.4.2. Energy Storage Frequency Regulation Performance Constraints. When energy storage is participating in frequency regulation, a high or low value of SOC for shared energy storage may result in energy storage not being able to respond to the frequency regulation instruction in a timely manner. Therefore, the frequency regulation performance index of shared energy storage can be expressed as a segmented function of SOC variation, as shown in Figure 2.

The frequency regulation performance index of shared energy storage at time t is shown in the following:

$$\gamma_{\mathrm{BAT}}(t) = \begin{cases} 1, & S_{\mathrm{BAT}}^{\min} + \Delta S_{\mathrm{BAT}} \le S_{\mathrm{BAT}}(t) \le S_{\mathrm{BAT}}^{\max} - \Delta S_{\mathrm{BAT}} \\ \sigma, & \text{others} \end{cases},$$
$$\Delta S_{\mathrm{BAT}} = \left(S_{\mathrm{BAT}}^{\max} - S_{\mathrm{BAT}}^{\min}\right)h. \tag{45}$$

In the formula, $\gamma_{\mathrm{BAT}}(t)$ is the shared energy storage frequency regulation performance index at time t. ΔS_{BAT} is the allowable deviation SOC value. σ is the frequency regulation performance coefficient, taken as 0.5. When SOC is at the median value, $\sigma = 1$. h is the allowable deviation percentage of SOC from the median value.

In order to maintain the efficiency and performance of shared energy storage participating in frequency regulation, this model takes the average value of $\gamma_{\mathrm{BAT}}(t)$ during the frequency regulation period as the indicator for measuring the frequency regulation performance of energy storage in the operation model, as shown in the following:

$$\gamma_{\mathrm{BAT}} = \mathrm{mean}\{\gamma_{\mathrm{BAT}}(t) | u_{\mathrm{BAT}}(t) = 1\},$$
$$\gamma_{\mathrm{BAT}}(t) \ge \gamma_{\mathrm{BAT}}^{\min}. \tag{46}$$

In the formula, γ_{BAT} is the average value of $\gamma_{\mathrm{BAT}}(t)$. $\gamma_{\mathrm{BAT}}^{\min}$ is the lower limit of γ_{BAT}.

5. Solution of Grid-Connected Operation Model

This paper conducts research on the grid-connected operation mode between renewable energy cluster and shared energy storage and builds a two-layer energy management framework. The upper layer is a capacity pricing model for shared energy storage, with the goal of maximizing the benefit of shared energy storage. The lower level is a cooperative game model for renewable energy cluster, which optimizes the operation strategy of renewable energy cluster and uses the Nash negotiation model to allocate cooperative benefit among renewable energy stations. This section uses a combination of YALMIP+ CPLEX+ MOSEK to solve the grid-connected operation model. Among them, YALMIP is mainly used to define the standard form of the optimization model, CPLEX is mainly used to solve the optimization model, and MOSEK is mainly used to verify and analyze the solution results. The solution process of the grid-connected operation model is shown in Figure 3, which is briefly described as follows.

Step 1. Input known parameters define the operation decision variables of all parties as Eq. (1), calculate the initial capacity price of shared energy storage, and set the maximum number of iterations Z and the current number of iterations $z = 1$.

Step 2. Based on the initial capacity price of shared energy storage, the benefit model of renewable energy cluster is constructed based on the Nash negotiation model, considering the power selling revenue, using the cost of shared energy storage, power deviation penalty, and a rational mechanism for apportioning cluster power deviation penalty, as shown in Eq. (6). By using the improved particle swarm optimization algorithm in Section 3.5 to solve the benefit model, the optimal operation strategy for renewable energy cluster can be obtained.

Step 3. Based on the charge and discharge demand of renewable energy cluster, with the goal of maximizing the benefit of shared energy storage as shown in Eq. (28), optimize operation strategies such as energy storage capacity pricing, capacity allocation, and participation in frequency regulation auxiliary service market.

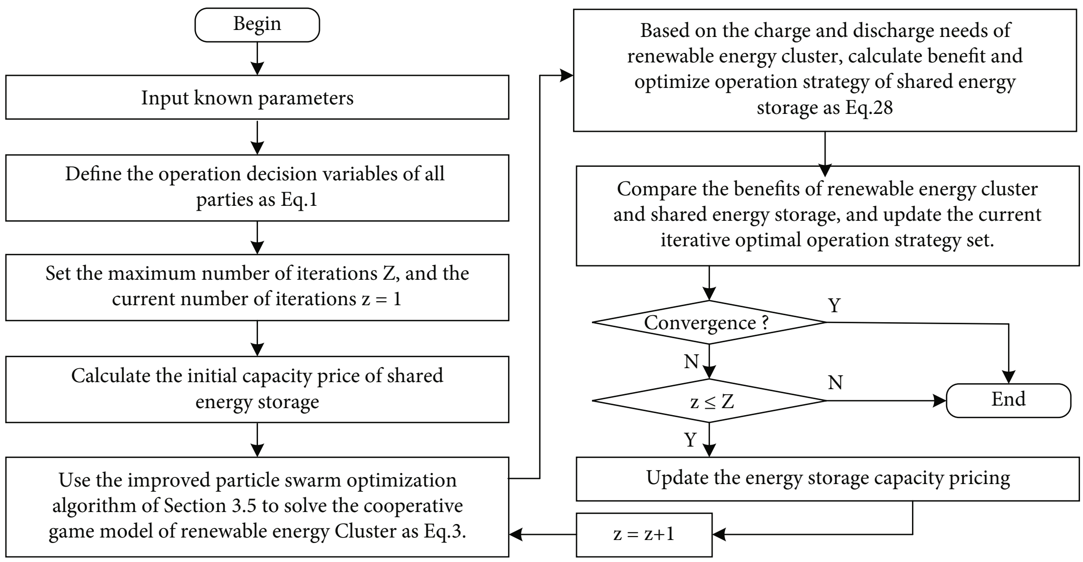


Figure 3: Solution process of grid-connected operation model.

Step 4. Compare the benefits of renewable energy cluster and shared energy storage and update the current iterative optimal operation strategy set. As the shared energy storage and renewable energy cluster interact and respond in order, the convergence of their operation strategies can be achieved.

Step 5. Before achieving convergence, it is also necessary to determine whether z is less than the maximum number of iterations Z. If $z \leq Z$, let $z = z + 1$ and update the energy storage capacity pricing to return to Step 2. The renewable energy cluster will be optimized with the new energy storage capacity pricing to calculate another round of charge and discharge demand. If $z > Z$, end the iteration and output the grid-connected optimal operation strategy between renewable energy cluster and shared energy storage.

The laboratory computer configuration is shown as follows. CPU: Intel Core i7-13700KF; main-board: ASUS PRIME Z790M-PLUS D4; internal storage: KLEVV 32GB DDR4 3600; graphics card: NVIDIA RTX4070Ti 8G; and power supply: 800 W.

The duration of each simulation in the algorithm is closely related to the iterations of the improved particle swarm optimization algorithm, the convergence accuracy of the grid-connected operation model, and other settings. According to the initial parameters of the example analysis in this paper, the duration of each simulation is at the minute level, not reaching the hour level.

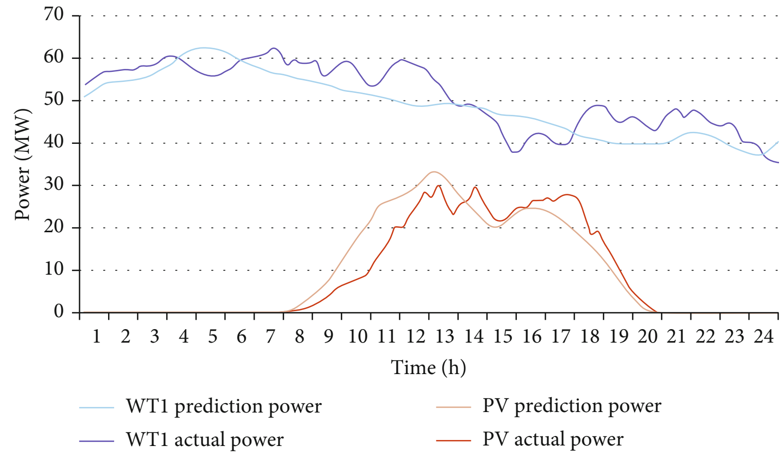
6. Example Analysis

Due to the impact of the construction progress of the demonstration project, this paper contains two examples, striving to reflect the most authentic data to readers. Example 1 uses wind farm WT_1 and photovoltaic power station PV in northwest China to form a renewable energy cluster REC_1 in Section 6.1 in order to illustrate the impact of complementary characteristics and shared energy storage on cluster power deviation. Example 2 uses three wind farms WT_2, WT_3, and WT_4 in northwest China to form a renewable energy cluster REC_2 in Sections 6.2–6.4 in order to illustrate the operation strategy of renewable energy cluster and shared energy storage. The proportion of self-built energy storage capacity for renewable energy stations is 10%, and the charging and discharging time is 2 hours.

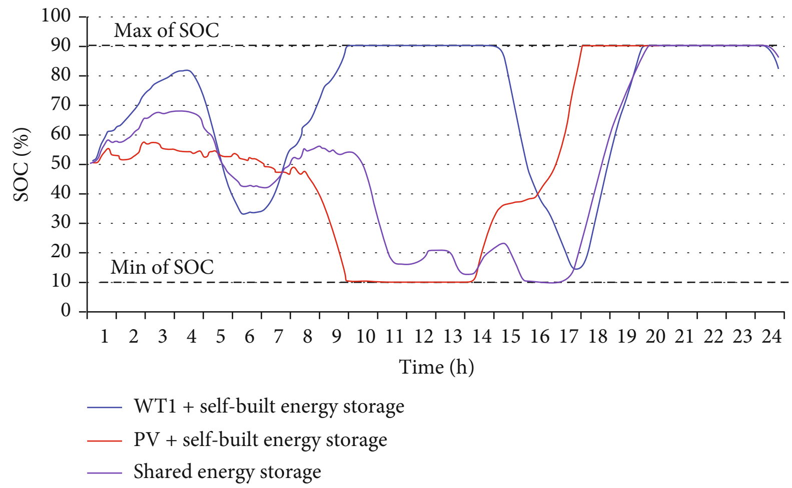
6.1. Power Deviation Analysis in Renewable Energy Cluster. The renewable energy cluster REC_1 includes the wind farm WT_1 with a rated capacity of 100 MW and the photovoltaic power station PV with a rated capacity of 100 MW. Based on this, this section simulated and analyzed the complementary characteristics of renewable energy station and the impact of complementary characteristics and shared energy storage on the power deviation of renewable energy cluster. Under the same energy storage rated capacity, the complementary characteristics between renewable energy stations help RE C_1 improve energy storage utilization rate, increase energy storage usage time, and reduce power deviation of renewable energy cluster.

The complementary characteristics of WT_1 and PV are shown in Figure 4(a), and the mean absolute percentage error (MAPE) is used to evaluate the accuracy of prediction. The MAPE of WT_1, PV, and WT_1 + PV are 5.56%, 6.15%, and 4.26%, respectively. WT_1 has a high-power output at night and in the morning, but actual power often exceeds the prediction power, which results in significant power deviation. PV do not generate power at night, and actual power may exceed the prediction power in the afternoon, which also results in significant power deviation. Therefore, WT_1 and PV have a certain degree of complementarity, the power deviation will significantly decrease after WT_1 and PV form a cluster, and the charge and discharge demand for energy storage will also decrease.

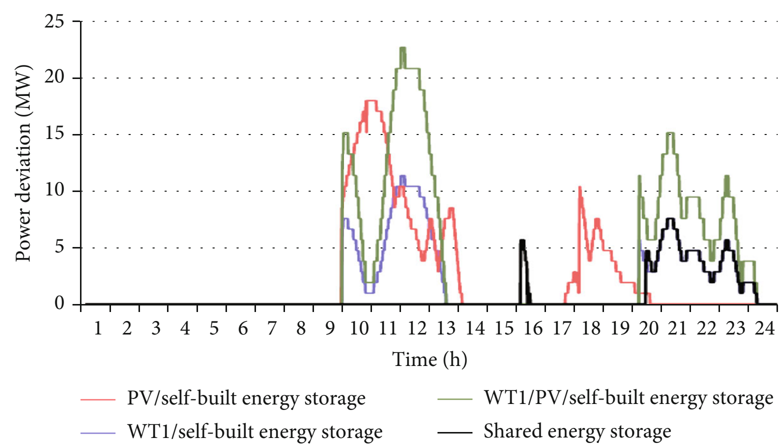
In the case of self-built energy storage 10 MW/20 MWh, the energy storage is charged when the renewable energy station actual power exceeds the prediction power and discharged when the renewable energy station actual power is



(a) Prediction power and actual power of WT_1 and PV

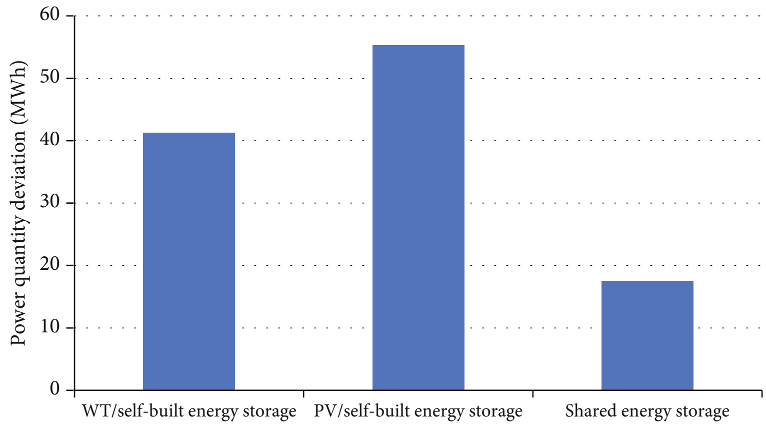


(b) SOC comparison between self-built energy storage and shared energy storage



(c) Power deviation comparison between self-built energy storage and shared energy storage

Figure 4: Continued.



(d) Power quantity deviation comparison between self-built energy storage and shared energy storage

Figure 4: Power deviation analysis of renewable energy cluster.

lower than the prediction power. Energy storage can assist in tracking the power generation plan of renewable energy. The energy storage SOC comparison between self-built energy storage and shared energy storage is shown in Figure 4(b). The time of reaching the SOC limit for self-built energy storage is much longer than that of shared energy storage, indicating that the complementary characteristics of renewable energy stations can help improve the energy storage utilization rate and achieve positive interaction to decrease the power deviation of renewable energy cluster.

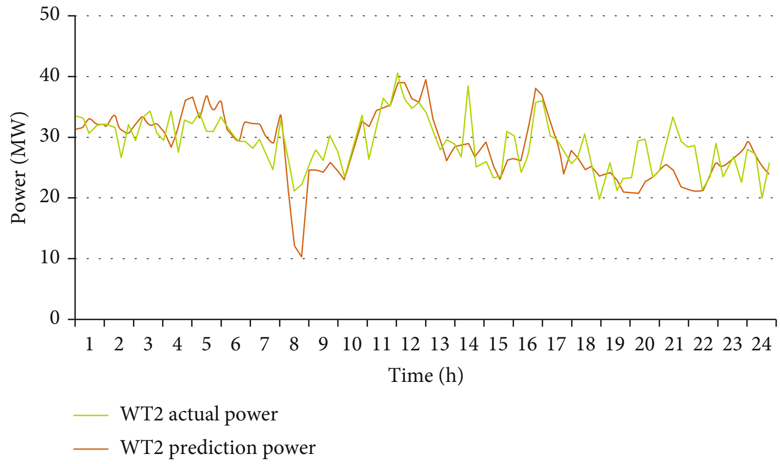
Under the same operation strategy, the power deviation comparison between self-built energy storage and shared energy storage is shown in Figure 4(c). The black curve represents the power deviation in shared energy storage mode with the MAPE of 1.89%, which considers the complementary characteristics of WT_1 and PV. The red and blue curves represent the power deviation in self-built energy storage mode for WT_1 and PV, and the MAPE of both are 2.18% and 4.33%, respectively. The green curve represents the superposition of the WT_1 and PV power deviation in self-built energy storage mode, and the MAPE is 3.69%. Compared with self-built energy storage, shared energy storage effectively reduces power deviation, thereby reducing the power quantity deviation penalty. The power quantity deviation comparison between self-built energy storage and shared energy storage is shown in Figure 4(d). Therefore, based on shared energy storage and the complementary characteristics of renewable energy stations, it can effectively reduce the power deviation of renewable energy cluster and power quantity deviation penalty.

6.2. Optimal Operation Analysis of Renewable Energy Cluster and Shared Energy Storage. The renewable energy cluster REC_2 consists of wind farms WT_2, WT_3, and WT_4, with installed capacities of 45 MW, 64 MW, and 70 MW, respectively. The power curves of WT_2, WT_3, and WT_4 are shown in Figures 5(a)–5(c). Refer to the electricity price in northwest China, as shown in Figure 5(d). Taking 1 hour as the scheduling time, and $T = 24$. When the renewable energy cluster is connected to the grid, the power deviation penalty coefficient is 63.12 \$/MWh, and the adjustment coefficient of the improved Shapley method is taken as 2. The initial capacity pricing for shared energy storage is 57.63 \$/MWh, the energy storage charging and discharging efficiency is 0.9, and the upper and lower limits of SOC are 0.9 and 0.1, respectively. The capacity price of frequency regulation is 1.37 \$/MW, and the mileage price is 1.1 \$/MW. The mileage coefficient is the hourly historical average of mileage calculated from historical AGC signals, such as in Ref. [31]. The life expenditure cost coefficient is taken as 6.86 \$/MW.

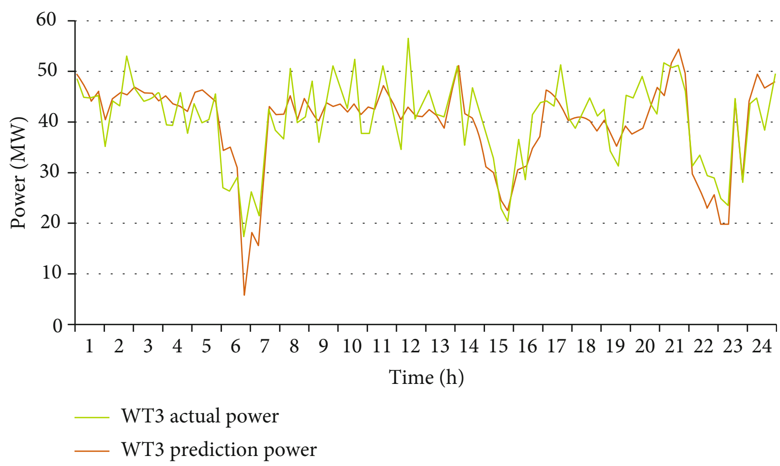
The convergence curve for solving the operation strategy of the renewable energy cluster is shown in Figure 6. The improved particle swarm optimization algorithm sets the maximum number of iterations for local convergence judgment to 30 and the local convergence estimate coefficient to 0.1. As shown in Figure 6, in iterations of 80-120, 250-280, and others, the particle swarm falls into a local optimum. By using the speed update mechanism to jump from the local optimization solution, the next better population can be found, and the fitness gradually increases. On the latter day of the solving process, the population occurs multiple velocity mutation, but no better solution has been found, and the final result stabilizes at the maximum value.

The prediction power of the renewable energy cluster is shown in Figure 7(a). The actual power of the renewable energy cluster includes the grid-connected power of each wind farm and charge and discharge power provided by virtual energy storage and shared energy storage. The convergence results of actual power for renewable energy cluster and wind farms are shown in Figure 7(b).

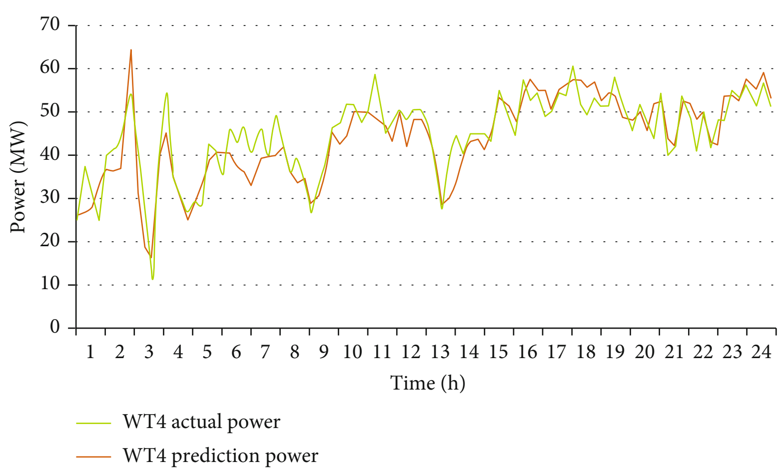
The self-built energy storage rated power of WT_2, WT_3, and WT_4 of the renewable energy cluster in noncooperative mode is 4.5, 6.4, and 6.9 MW, respectively, and the charging and discharging time is 2 hours. The renewable energy power curtailment situations of cooperation mode and noncooperative mode are shown in Figure 8. As shown in Figure 7(a), the prediction power of the renewable energy cluster during this period is greater than the power limit of



(a) WT_2

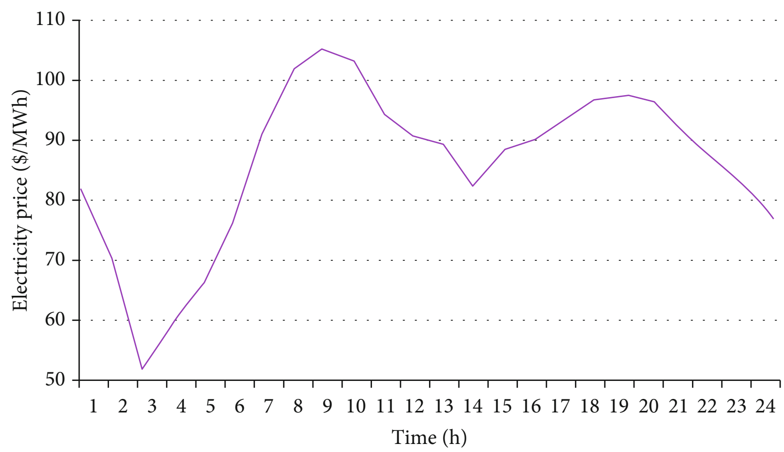


(b) WT_3



(c) WT_4

Figure 5: Continued.



(d) Electricity price

Figure 5: Power curve and electricity price curve of wind farms.

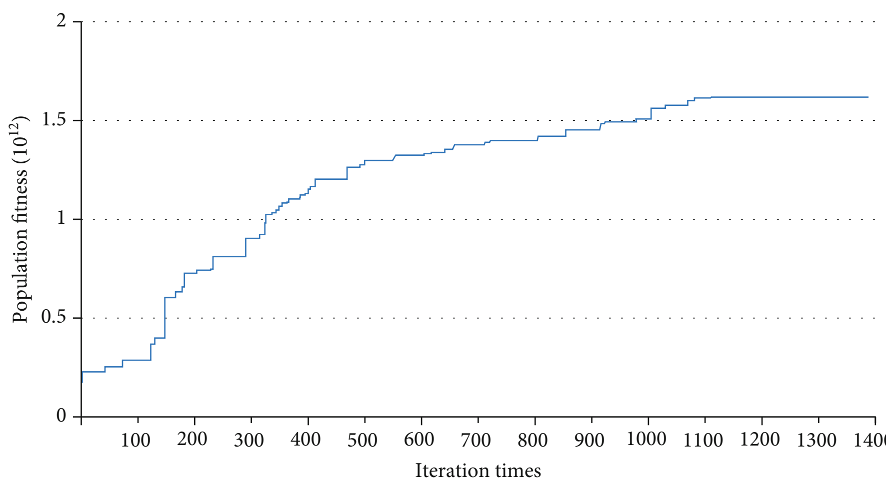


Figure 6: Convergence curve of improved particle swarm optimization algorithm.

PCC. Therefore, the wind power curtailment condition occurs frequently between 1:00 and 8:00. Figure 7(b) shows the actual power of the renewable energy cluster in the optimal operation, which is consistent with the power limit of PCC during 1:00-8:00 and in line with the actual situation. In the cooperation mode, each wind farm actively utilizes shared energy storage, and compared to noncooperative mode, the wind power curtailment decreases by 19.2%.

The charging power of energy storage is positive, and the discharge power is negative. The charging and discharging histogram and SOC curve of shared energy storage in the optimal operation are shown in Figure 9(a). The scheduling trend of shared energy storage is to charge first and then discharge, and finally, the SOC recovers to 0.5. As shown in Figure 9(a), during the period of wind power curtailment, shared energy storage is charged. When the actual output of the renewable energy cluster is less than the prediction power, the energy storage is discharged, which assists in tracking the power generation plan of renewable energy. In the optimal operation, the variation range of shared energy storage SOC is 0.45-0.9, indicating that the shared energy storage capacity actual required by renewable energy cluster is less than the rated capacity. Therefore, there is residual capacity in the shared energy storage system, it can participate in the frequency control ancillary service market.

As shown in Figure 9(b), the charging and discharging demands from multiple renewable energy stations will balance each other at some times. The balanced amount can be directly interconnected through virtual energy storage, with no operating losses. Compared to Figure 9(b), the actual charging and discharging power of shared energy storage is smaller in Figure 9(a). The charge and discharge power of virtual energy storage is much greater than the actual charge and discharge power of shared energy storage. The balanced power is not provided by shared energy storage but directly provided and used by wind farms, greatly reducing the power loss and operating cost of shared energy storage. At the same time, the balanced power between multiple renewable energy stations has to some extent reduced

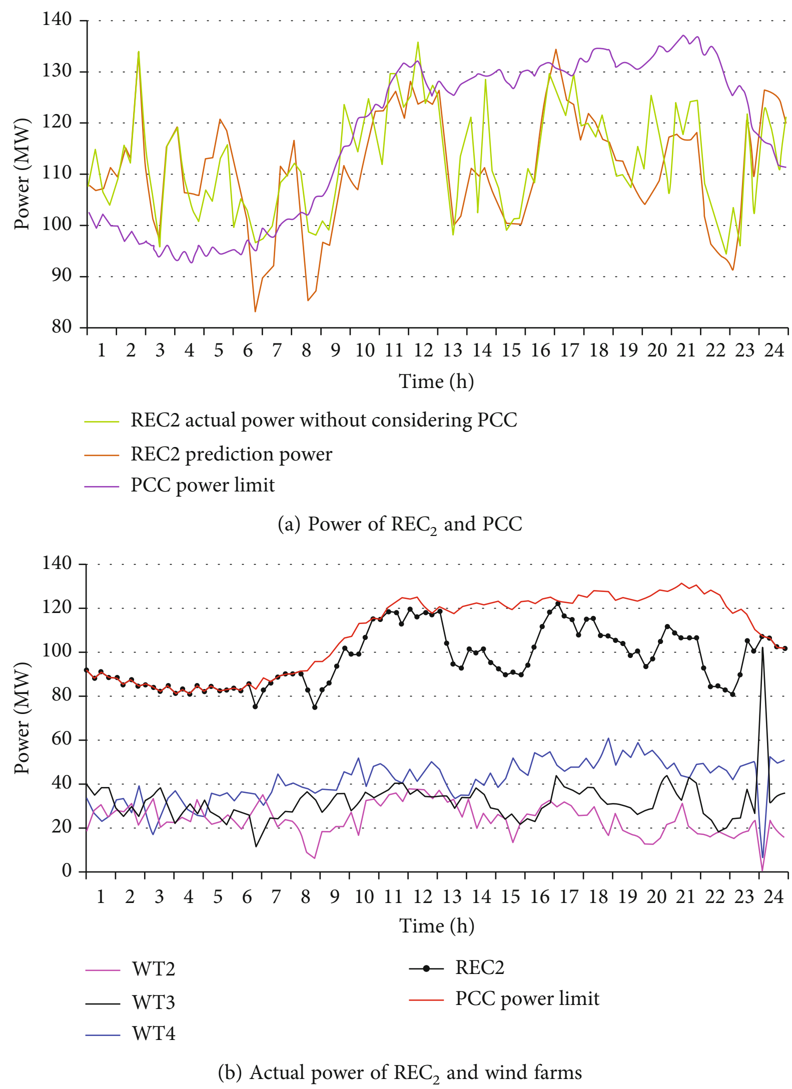


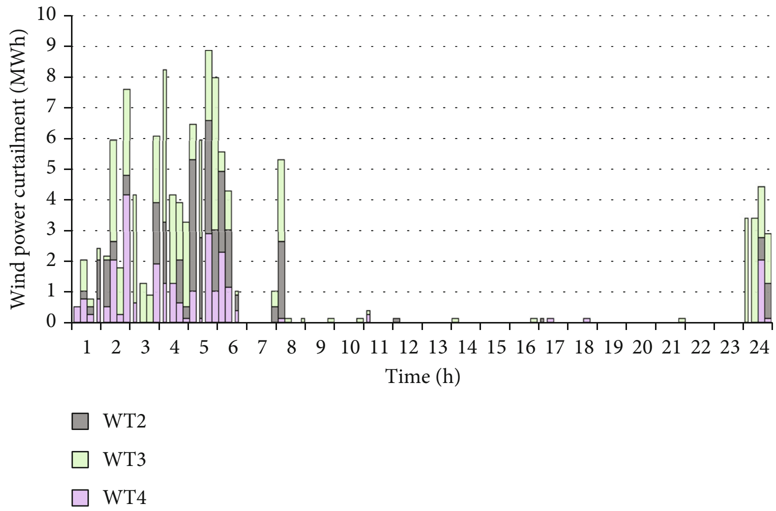
Figure 7: Power curve of renewable energy cluster in optimal operation.

the capacity demand for shared energy storage, which helps to reduce the using cost of shared energy storage capacity paid by renewable energy cluster.

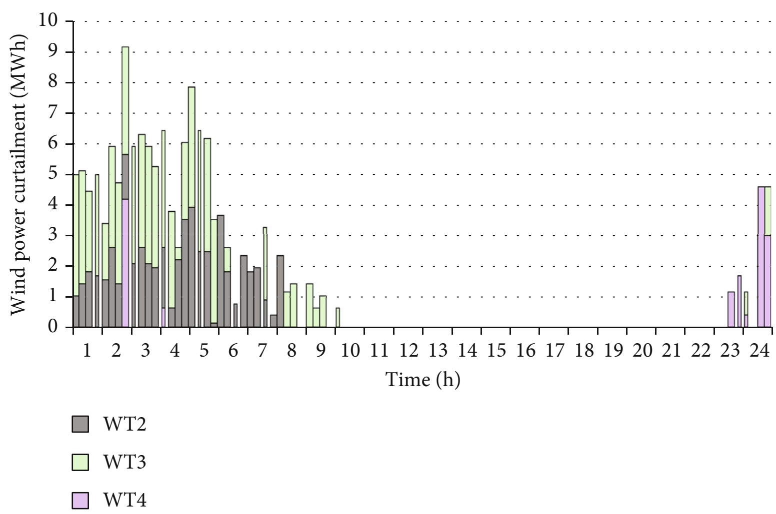
6.3. Benefit Analysis of Renewable Energy Cluster. The direct power selling revenue, indirect power selling revenue, and using cost of shared energy storage for each station of the renewable energy cluster in the optimal operation can be directly calculated, according to the grid-connected power, as well as the charge and discharge power of shared energy storage and virtual energy storage. The improved Shapley value method is used to build a rational mechanism for apportioning cluster power deviation penalty, and the power deviation penalty of each station can be calculated. The benefits of the cluster and each wind farm in the optimal operation are shown in Table 1.

As shown in Table 2, compared with the noncooperative mode, the benefit of each wind farm in cooperation mode has been effectively improved. In terms of various revenue, the direct power-selling revenue of each wind farm in the noncooperative mode is slightly higher than that of the cooperation mode, but the total power-selling revenue in the cooperation mode is higher. In the cooperation mode, each wind farm actively utilizes energy storage assisting in tracking the power generation plan of renewable energy, and the charging and discharging demands from multiple wind farms will balance each other through virtual energy storage, which can effectively improve the indirect power selling revenue of each wind farm. Among them, WT_4 has the highest rated capacity, with higher prediction power and power selling revenue than other WT_2 and WT_3. The benefits of WT_2 and WT_3 are still higher than those of noncooperative mode, and they can also benefit from the cluster.

The improved Shapley value method is used to build a rational mechanism for apportioning cluster power deviation penalty, and the power deviation penalty of each wind farm is shown in Table 3. Because WT_4 has the minimum power uncertainty, and its power deviation and other wind farms are weakly positively correlation, the power deviation



(a) Cooperation mode



(b) Noncooperative mode

Figure 8: Wind power curtailment condition of wind farms in the optimal operation.

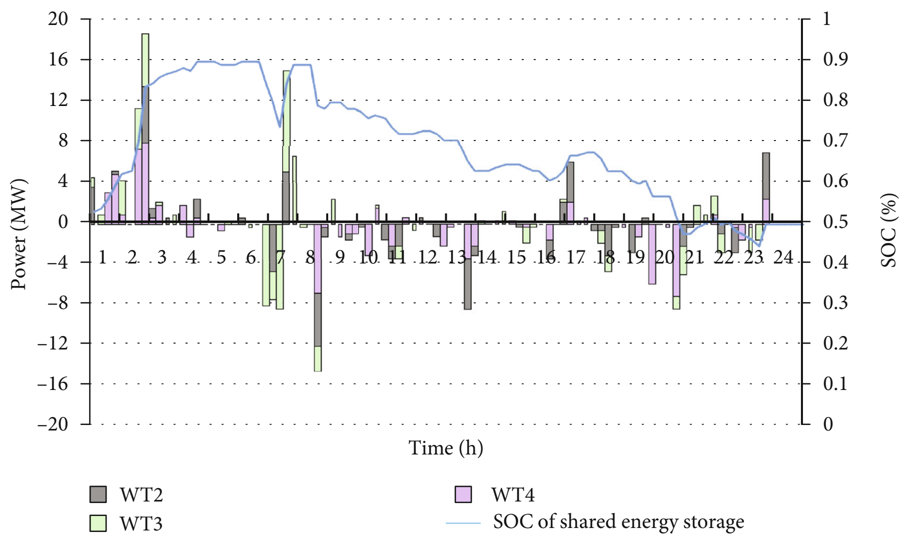
penalty received by WT_4 is also the smallest, which is in line with objective reality.

As shown in Table 1, the indirect power-selling revenue of the cluster is generated by the discharge of virtual energy storage and shared energy storage leased by each wind farm. The using cost of shared energy storage is much lower than the indirect power selling revenue. The benefits obtained from the cluster in the cooperation mode are mainly reflected in the following two points.

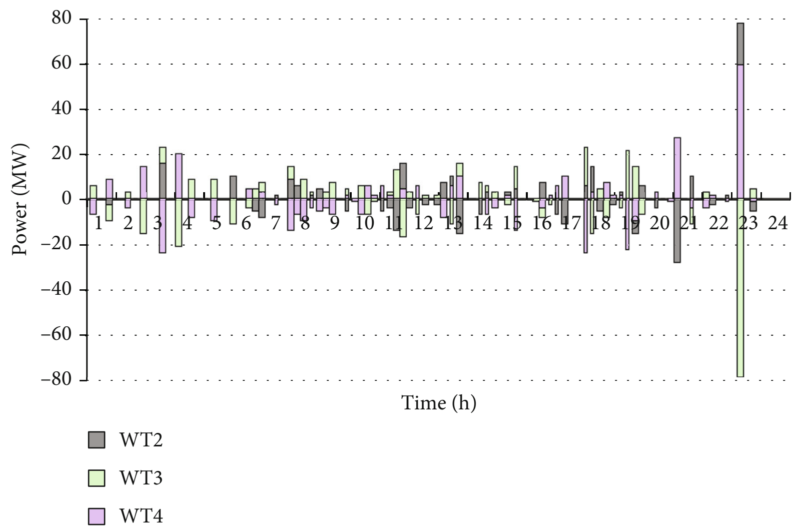
Firstly, the charging and discharging demands from multiple renewable energy stations can balance each other through virtual energy storage. Balanced power does not need to consider the power loss and operation cost of shared energy storage. Compared to the self-built energy storage by each wind farm, the using cost of shared energy storage has significantly decreased, and the benefits obtained from shared energy storage have significantly increased, as shown in Table 2. From Table 2, it also can be seen that each wind farm does not consider the balanced power in noncooperative mode, each wind farm rarely uses energy storage, in order to control the using cost of energy storage. Compared with the noncooperative mode, the using cost of energy storage in cooperation mode decreased by 51.26%, and the indirect power selling revenue of the cluster increased by 141.3% by using virtual energy storage.

Secondly, when the renewable energy cluster is connected to the grid, the charging and discharging demands from multiple renewable energy stations will balance each other at some times. As shown in Table 2, the power deviation penalty of the cluster has been reduced by 18.44% compared to the noncooperative mode, and the effect of tracking the power generation plan of renewable energy has been effectively improved.

6.4. Benefit Analysis of Shared Energy Storage. Shared energy storage can cover the life cycle cost by renting capacity to renewable energy cluster and generate benefits. As shown in Figure 9(a) of Section 6.2, the shared energy storage



(a) Shared energy storage



(b) Virtual energy storage

Figure 9: Charge and discharge curve of energy storage.

Table 1: Revenue of each wind farm and renewable energy cluster.

Name	Direct power selling revenue	Indirect power selling revenue	Using cost of shared energy storage	Power deviation penalty	Benefit
WT_2	59053.06	3153.32	1194.14	496.30	60515.94
WT_3	77413.35	4133.73	522.35	149.44	80875.29
WT_4	100387.47	5360.5	568.97	-112.42	105291.42
REC_2	236853.88	12647.55	2285.46	533.32	246682.65

capacity actual required by renewable energy cluster is less than the rated capacity. Therefore, there is residual capacity in the shared energy storage system, and it can participate in the frequency control ancillary service market. It can increase the benefit of shared energy storage and can help shorten its cost-recovery cycle. Shared energy storage makes power declaration hourly in the frequency control ancillary service market, as shown in Figure 10. It can be calculated that the mileage revenue of frequency regulation for the day is $3779.38, and the capacity revenue is $256.58. The total revenue obtained from the frequency control ancillary service market was $4035.96. As shown in Table 1, it can be seen that shared energy storage renting capacity to renewable energy cluster can generate a revenue of $2285.46.

Table 2: Benefit comparison of wind farms between cooperation mode and noncooperative mode.

Operation mode	Member of cluster	Direct power selling revenue	Indirect power selling revenue	Using cost of shared energy storage	Power deviation penalty	Benefit
Cooperation mode	WT_2	59053.06	3153.32	1194.14	496.30	60515.94
	WT_3	77413.35	4133.73	522.35	149.44	80875.29
	WT_4	100387.47	5360.5	568.97	-112.42	105291.42
Noncooperative mode	WT_2	59171.24	987.12	1629.29	261.78	58267.29
	WT_3	78304.38	1499.87	1096.80	392.11	78315.34
	WT_4	101925.62	2754.34	1963.27	0.00	102716.69

Table 3: Marginal deviation penalty of wind farms.

Name	Description	C(S)	C(S-i)	C(S)-C(S-i)
Cluster containing WT_2	WT_2	1895.54	0.00	1895.54
	WT_2 and WT_3	1707.44	1471.63	235.81
	WT_2 and WT_4	1351.53	1301.76	49.77
	REC_2	533.32	1081.31	-547.99
Cluster containing WT_3	WT_3	1471.63	0	1471.63
	WT_2 and WT_3	1707.44	1895.54	-188.1
	WT_3 and WT_4	1081.44	1301.76	-220.32
	REC_2	533.32	1351.4	-818.08
Cluster containing WT_4	WT_4	1296.83	0	1296.83
	WT_2 and WT_4	1351.53	1895.54	-544.01
	WT_3 and WT_4	1081.44	1471.63	-390.19
	REC_2	533.32	1707.31	-1173.99

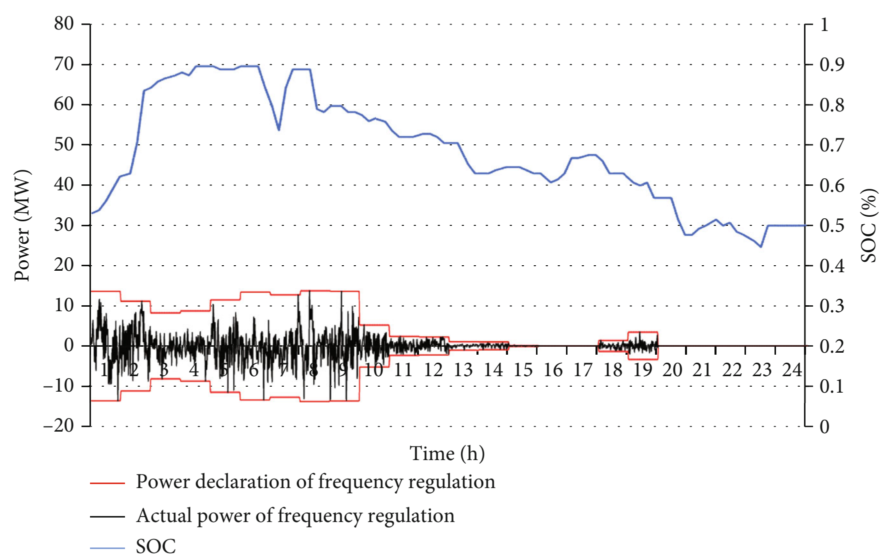


Figure 10: Shared energy storage participating in the frequency control ancillary service market.

Taking into account both providing capacity services and participating in the frequency control ancillary service market, the life expenditure cost of shared energy storage is \$1176.28. According to Eq. (28), the benefit of shared energy storage can be calculated as \$5145.14. Therefore, in addition to providing capacity services to cover the life cycle cost, shared energy storage can also have certain frequency regulation revenue to improve the economy.

7. Conclusions

In response to the development difficulties, such as power uncertainty of renewable energy, high life cycle cost of energy storage on the power supply side, and long cost-recovery cycle, the research on the grid-connected optimal operation mode between renewable energy cluster and shared energy storage was proposed in this paper. The cooperative game model based on the Nash negotiation can achieve a benefit balance among stations and maximize the cooperation benefit of each station. The improved Shapley value method can rationally allocate the cooperative benefit among multiple cluster members. Improved particle swarm optimization algorithm helps to skip the local optimum and achieve the global maximum of cooperation benefit for renewable energy cluster. The capacity pricing and frequency regulation revenue can ensure the willingness in shared energy storage investment and renewable energy cluster using shared energy storage and maintain a healthy development of the supply and demand relationship between shared energy storage and renewable energy cluster. A two-layer energy management framework is built in Part V, the upper layer is a capacity pricing model for shared energy storage, and the lower level is a cooperative game model for renewable energy cluster. When the iteration ends, the grid-connected optimal operation strategy between renewable energy cluster and shared energy storage can be output. The above research methods ensure the rationality of the strategies proposed. Results of Sections 6.2–6.4 can be employed for evaluating the performance and efficacy of the strategies proposed, and the quantitative analysis of the examples ensures the effectiveness of the strategies proposed accordingly. The main conclusions are as follows.

(1) The Nash negotiation model is introduced into the optimal operation model of the renewable energy cluster, the objective function is the maximum of the product of cooperation benefits among each station in the renewable energy cluster, in order to ensure that the revenue of each renewable energy station is higher than that of noncooperative mode. For the complementary characteristics blurring each member's contribution to the cluster power deviation, an improved Shapley value method is used to build a rational mechanism for apportioning cluster power deviation penalty, in order to reflect the impact of each station on the cluster power deviation. An improved particle swarm optimization algorithm is used to solve the problem in order to obtain the optimal equilibrium point of renewable energy cluster benefit

(2) Compared to the self-built energy storage in noncooperative mode among renewable energy stations, the renewable energy cluster reduces the frequency of using shared energy storage by virtual energy storage, which can reduce the using cost of shared energy storage by 51.26% and increase indirect power selling revenue by 141.3%. In addition to reducing the energy storage capacity actual required by renewable energy cluster, the cooperation mode can effectively encourage each station to fully utilize shared energy storage, which can reduce the wind power curtailment by 19.2% and reduce the cluster power deviation penalty by 18.44%. It enables the renewable energy cluster to track the power generation plan while obtaining cooperation benefits

(3) Shared energy storage can optimize capacity prices based on the charge and discharge demand of renewable energy cluster and can effectively assist in tracking the power generation plan of renewable energy in order to reduce the power deviation penalty. In addition, under the same energy storage rated capacity, the variation range of shared energy storage SOC is 0.45-0.9, indicating that the shared energy storage capacity actual required by renewable energy cluster is less than the rated capacity. Therefore, there is residual capacity in the shared energy storage system, and it can participate in the frequency control ancillary service market. Therefore, it is more conducive to improving the shared energy storage utilization rate, increasing shared energy storage revenue, and shortening the cost-recovery cycle of shared

Further research will be conducted around capacity planning, investment efficiency, and capacity price optimization of shared energy storage. For the renewable energy cluster, the Shapley value approach will be improved, simplified, and extended applied for the purpose of allocating cooperation benefit more efficiently, and further improvement of the Nash negotiation model and swarm intelligence algorithm will be carried out. This operation strategy will be optimized to be suitable for the case that the object to be solved is complicated and can accelerate the optimization process and save calculation time but cannot influence precision.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author has no conflicts to disclose.

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