applied sciences

MDPI

Article

Joint Operation of Renewable Energy and Battery Switch Station Considering the Benefits of Different Subjects

Zhe Jiang [1], Wendong Li [2,*], Changhui Ma [1], Linlin Ma [3], Bing Zhang [3], and Kuan Lu [1]

[1] Electric Power Research Institute, State Grid Shandong Electric Power Company, Jinan 250003, China; jiangzhe_edu@hotmail.com(Z. J.); machanghui@163.com (C.M.); lk83@163.com (K.L.)

[2] Shandong Energy Regulatory Office of National Energy Administration，Jinan 250004，China; leewbush@163.com

[3] Shandong Electric Power Dispatching and Control Center, Jinan 250001, China; bzhang007@126.com (B.Z.); 13791054820@163.com (L.M.)

* Correspondence: leewbush@163.com; Tel.: +86-134-759-11051

Received: 19 February 2019; Accepted: date; Published: date

Abstract: In the context of the rapid development of renewable energy and electric vehicles, the collaborative optimization problem of the two is studied. A cooperative operation mode of renewable energy and battery switch station belonging to different investors is put forward. By analyzing the relationship of cooperation and competition between them, their pursuit of maximizing their own interests is modeled as a Stackelberg game model in which the renewable energy company is the leader and the battery switch station is the follower. By comparing and analyzing the characteristics of strong Stackelberg equilibrium and weak Stackelberg equilibrium of the game model, a solution method combining backward-induction method and genetic algorithm is proposed. The simulation results show that the proposed model can automatically achieve the optimal allocation of resources and achieve win-win in the process of renewable energy company and battery switch station pursuing their own interest maximization.

Keywords: power system; battery switch station; renewable energy; Stackelberg game

1. Introduction

With the rapid development of renewable energy (RE), its uncontrollability and volatility have caused a series of problems to the grid [1-4]. Cooperation with controllable resources to enhance the controllability of RE has become a consensus [5-7]. With the help of battery to grid (B2G) technology [8], the electric vehicle battery switch station (BSS) could achieve multiple benefits. In addition to providing electric vehicle users with battery swapping services, the BSS can also serve as an energy storage station or controllable load [9]. Therefore, the cooperation between RE and BSS could not only benefit the power grid, but also promote the development of RE industry and electric vehicle industry.

In [10], an economic dispatch model of microgrid including RE and BSS is established, and the economy of microgrid operation is improved through the cooperative optimization of RE and BSS. The uncertainty of RE generation and battery swapping demand is further considered in [11]. A stochastic optimization model of microgrid including RE and BSS is established based on the chance-constrained programming. In [12], a multi-objective cooperative optimizing model of BSS and RE is established by fully considering the randomness. By adjusting the charging and discharging power of BSS in coordination with RE, the load fluctuation and network loss is reduced effectively, and the planning penetration of RE is improved as well. However, these studies need the grid company as a coordinating body to coordinate and control a variety of dispatchable resources. Because of this, these studies are based on the interests of grid companies, while the interests of RE and BSS are not fully considered.

In the interest of RE and BSS, a collaborative operation pattern is proposed in [13], in which the electric vehicle battery are charged by wind and photovoltaic energy in BSS. References [14] and [15] suggested that wind farms and BSS should be combined into a joint system and operate as an independent enterprise in power system. With a unified coordinated control of wind farms and BSS, the whole benefit of the joint system is maximized. The simulation results showed that this operation mode can achieve a win-win situation for wind farms and BSS. However, there is a prerequisite for the above research, that is, RE and BSS belong to the same investment subject or they have the will to form a joint system.

With the development of the electricity market reform in China, the investors in the electricity market are becoming more and more diversified and complicated. Generally, RE and BSS belong to different investors [16]， thus it is difficult to popularize the operation mode of the joint system mentioned above. In fact， in a deregulated electricity market, RE and BSS are market signal-oriented and only pay attention to their own interests. Therefore, their generation and consumption are highly subjective, and it is difficult to coordinate and manage them effectively.

In recent years, game theory has been widely used in power system [17-20]. Game theory is a theory to study how to optimize the decision-making strategy of each decision-making body which has interest correlation or conflict. This theory provides a new means to solve the cooperative optimization problem among the different investment entities mentioned above.

In this paper, the co-optimization of RE and BSS is studied. The innovation points are as follows. (1) Aiming at the situation that RE and BSS belong to different investment subjects, a cooperation mode is proposed. Different from the previous research, this cooperation mode no longer requires the two partners to belong to a same investment body, so this mode is more feasible in an electricity market where the investors are diversified. (2) Based on game theory, a Stackelberg model is established, in which RE company is the leader and BSS is the follower. The model could reflect the co-existence relationship of competition and cooperation between RE and BSS effectively. (3) In the model proposed in this paper, it is no longer needed of a unified coordinated control for RE and BSS. In fact, an optimal resources allocation and a win-win situation could be automatically achieved in the course of RE and BSS pursuit of maximizing their own interests respectively.

The organization of this paper is as follows. Section 2 introduces the framework of the joint operation of RE and BSS. The proposed Stackelberg game model is described in Section 3. In section 4 we analyze the two kinds of game equilibrium solutions and propose the corresponding algorithm. Simulation analysis is given in Section 5. Finally, the conclusions are drawn in Section 6.

2. Joint Operation Mode of RE and BSS

The RE company signs a cooperation agreement with the BSS. RE company would aggregate distributed wind power, photovoltaic and other renewable energy resources in their jurisdiction. On the one hand, the RE company provides charging services for BSS, on the other hand, RE company sells electricity to the distribution company. In addition to meeting the battery swapping demand, BSS can also sell the surplus power stored back to the RE company. A block diagram of the cooperation between the two is shown in Figure 1.

Since RE company and BSS belong to different investors, there is no subordinate relationship between them. Although the RE company has no right to directly control the charging and discharging behavior of the BSS, it can indirectly affect the charging and discharging decision of the BSS by adjusting the charge/discharge price. After obtaining the next day's generation price from distribution company, the RE company will set the charge/discharge price for each period of the next day. On the one hand, it could guide the BSS to operate as controllable load to promote the consumption of RE. On the other hand, the BSS would be regarded as a special energy storage station, which is allowed to discharge in reverse in order to increase the electricity sales revenue of the RE company by load shifting.

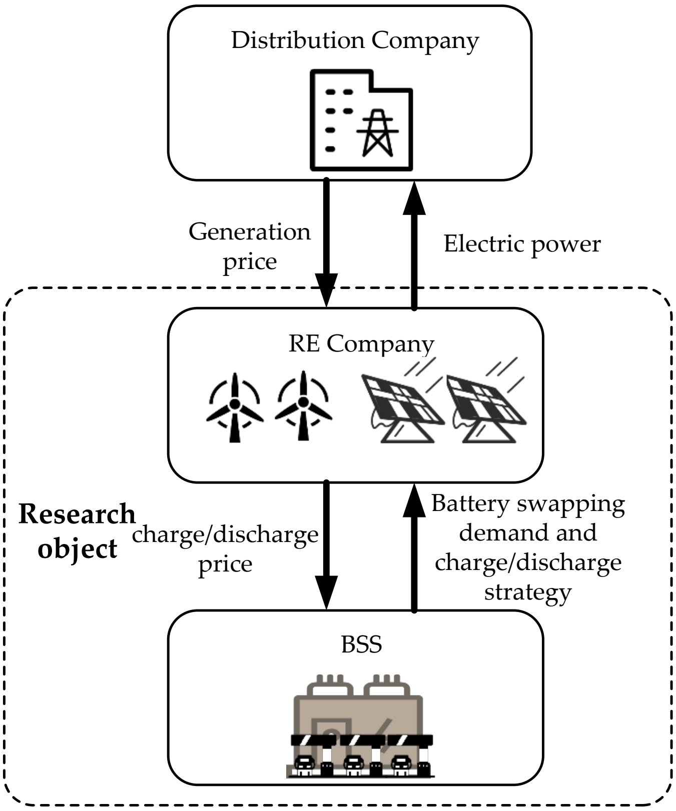

Figure 1. Block diagram of cooperation between RE company and BSS.

The BSS will set the charge/discharge schedule according to the battery swapping demand after the charge/discharge price is obtained. BSS will charge the battery as cheaply as possible, on the one hand to meet the battery swapping demand with low charging costs and, on the other hand, to store RE and sell it at high prices to increase its revenue through such "low-price charging and high-price discharging".

Under the framework of this cooperation, the distribution company does not obtain economic benefits through direct participation in the cooperation. In fact, its benefits lie in the increased controllability of RE generation through the collaboration of RE company and BSS. Since the distribution company could indirectly adjust the output power of RE by setting the generation price, the impact of randomness and uncontrollable characteristics of RE on the grid could be reduced.

3. Mathematical Modeling

3.1. Leader (RE company) model

In order to maximize its own revenue, the RE company guide the charging and discharging power of the BSS by optimizing the charge/discharge prices. The RE company's revenue is expressed as Equation (1) below:

$$\sum_{t=1}^{N_t}(P_{\mathrm{RE}}^t - P_{\mathrm{c}}^t + P_{\mathrm{d}}^t)\rho_{\mathrm{RE}}^t \Delta t + \sum_{t=1}^{N_t} P_{\mathrm{c}}^t \rho^t \Delta t - \sum_{t=1}^{N_t} P_{\mathrm{d}}^t \rho^t \Delta t \tag{1}$$

Equation (1) consists of three parts: the first part is the income from the sale of electricity to the distribution company, the second part is the income from the sale of electricity to BSS, and the third part is the cost of purchasing electricity from the BSS. Under the condition that the forecast value of renewable energy is known, the income from the sale of this part of the electricity is fixed. Therefore, the payoff function of the RE company can be expressed as Equation (2).

$$\max \sum_{t=1}^{N_t}(P_{\mathrm{c}}^t - P_{\mathrm{d}}^t)\rho^t \Delta t - \sum_{t=1}^{N_t}(P_{\mathrm{c}}^t - P_{\mathrm{d}}^t)\rho_{\mathrm{RE}}^t \Delta t \tag{2}$$

The strategy space is defined by the following constraints:

(1) Charge/discharge price constraint

$$\rho_{\min}^t \le \rho^t \le \rho_{\max}^t \tag{3}$$

(2) Average Charge/discharge price constraint

$$\frac{1}{N_t}\sum_{t=1}^{N_t}\rho^t \le \overline{\rho} \tag{4}$$

In order to restrain the market power of the RE company, the average charge/discharge price constraint is introduced. The upper limit of the average charge/discharge price is set to protect the benefits of BSS. When the RE company raises the charge/discharge price of some time periods, it needs to lower the prices of others, and uses the price differences in different time periods to guide the charging and discharging behavior of BSS.

3.2. Follower (BSS) Model

After obtaining the charge/discharge price from the RE company, the BSS will optimize the charging and discharging power based on the battery swapping demand in order to maximize its own benefit. The revenue of BSS is shown in Equation (5).

$$\sum_{t=1}^{N_t} sW^t + \sum_{t=1}^{N_t} P_{\mathrm{d}}^t \rho^t \Delta t - \sum_{t=1}^{N_t} P_{\mathrm{c}}^t \rho^t \Delta t \tag{5}$$

The Equation (5) consists of three parts: the first part is the income of the battery swapping service, the second part is the income from the sale of electricity, and the third part is the cost of purchasing electricity to charge the battery. When the battery swapping demand is known, the income of battery swapping service is fixed, so the payoff function of the BSS can be expressed as Equation (6).

$$\max \sum_{t=1}^{N_t}(P_{\mathrm{d}}^t - P_{\mathrm{c}}^t)\ \rho^t \Delta t \tag{6}$$

The decision variable is the charging and discharging power in each period of the next day. The strategy space is defined by the following constraints:

(1) Charge/discharge power constraint

$$0 \le P_{\mathrm{c}}^t \le P_{\mathrm{cmax}}^t \tag{7}$$

$$0 \le P_{\mathrm{d}}^t \le P_{\mathrm{dmax}}^t \tag{8}$$

(2) Capacity constraint of the batteries in BSS

$$Q^t \le Q_{\max} \tag{9}$$

$$Q^t = Q_0 + \sum_{i=1}^{t}\left(P_{\mathrm{c}}^i \eta_{\mathrm{c}} \Delta t - P_{\mathrm{d}}^i \Delta t / \eta_{\mathrm{d}} - W^i\right) \tag{10}$$

(3) BSS energy storage constraint at the end of a decision-making cycle

$$Q^{N_t} \ge Q_{\mathrm{end}} \tag{11}$$

Without prejudice to the battery swapping services at the next decision-making cycle, Q_{end} is usually equal to Q_0.

(4) Battery swapping demand reserve constraint

$$Q^t \geq Q_{\min} + (1+\alpha)W^{t+1} \tag{12}$$

(5) Zero emission constraint over EVs

$$P_{\text{c}}^t \leq P_{\text{RE}}^t \tag{13}$$

According to the contract between BSS and the RE company, BSS can only charge the battery by the power from renewable energy in order to realize zero emissions of EVs.

3.3. Stackelberg game model

Stackelberg game, also known as master-slave game, is a non-cooperative dynamic game, and the status of the players is different. One is the leader, who makes the decision first, and the other is the follower, who needs to make the optimal response to the leader's decision. The optimal response strategy of the follower is predictable to the leader, therefore, the leader will consider the possible response of the follower and make the decision which is most beneficial to his own interests. The cooperative relationship between RE company and BSS described in the previous section constitutes a typical Stackelberg game.

The RE company and BSS cannot directly control each other's decisions, but can indirectly affect the other party's payoff through their own strategies and ultimately affect each other's strategy. For example, on the one hand, RE company sets charge/discharge price to guide the charging and discharging behavior of BSS, on the other hand, the charging and discharging strategies of BSS can affect the revenue of RE company, and that will prompt RE company to adjust his charge/discharge price accordingly. Therefore, the pursuit of maximizing their respective interests can be modeled as a Stackelberg game model.

The RE company and BSS do not make the decision at the same time. In fact, the RE company, as the leader, sets the charge/discharge price first, and its payoff function is to maximize its own benefits. In order to maximize its own revenue, as the follower, the strategy of BSS is to optimize the charging and discharging power according to the charge/discharge price set by the RE company. In addition, since the RE company can predict the possible optimal response strategy of BSS, the strategy of the RE company will be dynamically revised accordingly to maximize its own payoff.

According to the above analysis, the Stackelberg game model of RE company and BSS can be modeled as Equation (14).

$$\begin{array}{ll} \text{Leader} & \left\{ \begin{array}{l} \max \quad \sum_{t=1}^{N_t} (P_{\text{c}}^t - P_{\text{d}}^t)\rho^t \Delta t - \sum_{t=1}^{N_t} (P_{\text{c}}^t - P_{\text{d}}^t)\rho_{\text{RE}}^t \Delta t \\ \qquad \text{s.t.} \;\; (3)\sim(4) \end{array} \right. \\ \text{Fol l ower} & \left\{ \begin{array}{l} \left\{P_{\text{c}}^t, P_{\text{d}}^t\right\} \in \arg\max \quad \sum_{t=1}^{N_t} (P_{\text{d}}^t - P_{\text{c}}^t) \;\; \rho^t \Delta t \\ \qquad \text{s.t.} \;\; (7)\sim(13) \end{array} \right. \end{array} \tag{14}$$

As can be seen from Equation (14), the follower's game model acts as a constraint of the leader's game model.

4. Stackelberg equilibrium

Stackelberg equilibrium is a refinement of Nash equilibrium, which belongs to a kind of sub-game perfect equilibrium [21]. For the same strategy of the leader, the follower may have more than one optimal response strategy, that is to say, the follower's payoff is the same under different strategies. However, the payoff is different for the leader. In [22], Leitmann extends the Stackelberg equilibrium and proposed the concept of generalized Stackelberg equilibrium, which can guarantee the leader's minimum profit. On this basis, Berton et al. divided Stackelberg equilibrium into strong Stackelberg equilibrium and weak Stackelberg equilibrium according to the different preference of follower strategy [23]. When the follower has multiple optimal response strategies, in the strong Stackelberg equilibrium, the follower will choose the strategy that is most favorable to the leader; and in the weak Stackelberg equilibrium, the follower will choose the strategy that is the most unfavorable to the leader.

At the strong Stackelberg equilibrium point, if the BSS refuses to choose the strategy most favorable to the RE company, then the payoff of the RE company will be reduced. In other words, the strategy at the strong Stackelberg equilibrium is an optimistic decision for the RE company, because there is a risk of less than its expected payoff. It should be noted that in the Stackelberg game model proposed in this paper, the RE company and BSS belong to different stakeholders, and there is no subordinate relationship between them. Although the RE company is in the leading status in the game, he cannot directly control the behavior of BSS. As a rational decision-maker, the BSS has no incentive to choose the strategy which is more favorable to the RE company when BSS's payoff is the same under a variety of strategies. In order to guarantee the RE company's minimum revenue, the weak Stackelberg equilibrium is more suitable to the game model in this paper.

At present, the common methods to solve Stackelberg equilibrium include KKT conditions method [24], penalty function method [25], intelligent algorithm [26] and so on.

In the strong Stackelberg equilibrium, when BSS has multiple optimal response strategies, it will choose the strategy that is most favorable to the RE company. In other words, the BSS and the RE company have the same optimization goal. As a result, the bi-level programming model can be converted to a single layer programming model to be solved directly. However, for the weak Stackelberg equilibrium solution, the BSS will choose the strategy that is most unfavorable to the RE company. In this case, the above method is no longer applicable. In this paper, an intelligent algorithm based on the backward induction method is used to solve the weak Stackelberg equilibrium.

The backward induction method starts from the last stage of a dynamic game, and gradually deduces the optimal strategy of the decision-makers in each stage.

In the last game stage, for a given charge/discharge price strategy $\{\pi^t, t=1,2,...,N_t\}$ of RE company, the follower's model is a linear programming model, and the optimal strategy of BSS and its maximum payoff f_{BSS} can be obtained by solving the model. f_{BSS} can be expressed as Equation (15):

$$\sum_{t=1}^{N_t}(P_{\mathrm{d}}^t - P_{\mathrm{c}}^t)\ \rho^t \Delta t = f_{\mathrm{BSS}} \tag{15}$$

Adding Equation (15) as an equality constraint and a new BSS model is proposed, which is expressed as Equation (16). In this model, BSS could minimize RE company's payoff while ensuring that its own payoff remain the same.

$$\begin{aligned} &\min\ \sum_{t=1}^{N_t}(P_{\mathrm{c}}^t - P_{\mathrm{d}}^t)\rho^t \Delta t - \sum_{t=1}^{N_t}(P_{\mathrm{c}}^t - P_{\mathrm{d}}^t)\rho_{\mathrm{RE}}^t \Delta t \\ &\text{s.t. Equation (7)\sim(13),(15)} \end{aligned} \tag{16}$$

The Equation (16) is a linear programming model, which can be solved by CPLEX to obtain the optimal strategy of BSS $\{P_c^t, P_d^t,\ t=1,2,...,N_t\}$. Furthermore, the RE company's revenue can be calculated by Equation (1). The backward induction method can be solved by genetic algorithm, where its objective function is maximizing the revenue of the RE company and the decision variables are the charge/discharge price in different time periods.

5. Simulation Analysis

5.1. Simulation Parameter Setting

According to the data of an actual BSS in Shandong Province, the parameters of BSS is set as Table 1. Select the actual battery swapping demand of the BSS for a certain day as the forecast values, which are shown in Figure 2.

Table 1. Parameters of the BSS.

No.	Parameters	Quantity [1]
1	$Q_{\max}$	55 MWh
2	$Q_{\min}$	5.5 MWh
3	Q_0	16.5 MW
4	Q_{end}	16.5 MW
5	P_{cmax}	11 MW
6	P_{dmax}	7 MW
7	s	1,300 ¥/MWh
8	η_{c}	95%
9	η_{d}	92%
10	α	10%

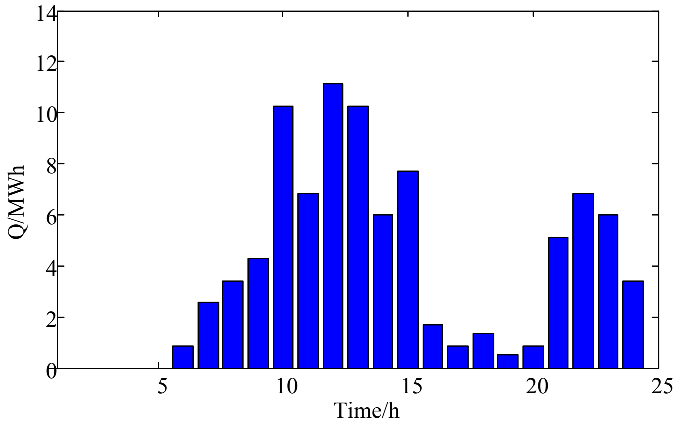

Figure 2. Prediction of battery swapping demand.

Suppose the RE company owns wind power and photovoltaic power. The predicted power of the RE company are taken from the actual wind power and photovoltaic power of a certain area in Shandong Province, as shown in Figure 3. The decision-making period is 24 hours of the next day.

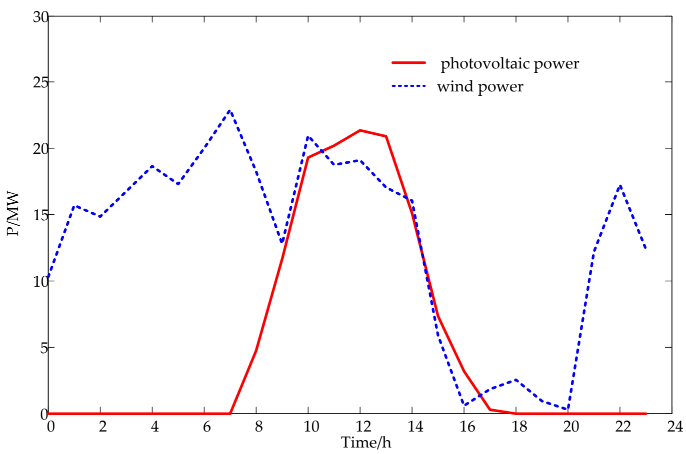

Figure 3. Prediction of wind power and photovoltaic power.

The distribution company purchases price of electricity is known, and the peak-valley price was adopted as shown in figure 4. The upper limit of charge/discharge price shall be 1.5 times of the electricity purchase price of the distribution company, and the lower limit shall be 50% of the electricity purchase price of the distribution company. If the BSS directly charging the battery from the distribution company, the contract price ρ_{DC} is 720 ¥/MWh. In order to ensure the cooperative motivation of BSS, the average charge/discharge price $\overline{\rho}$ is the same as ρ_{DC}.

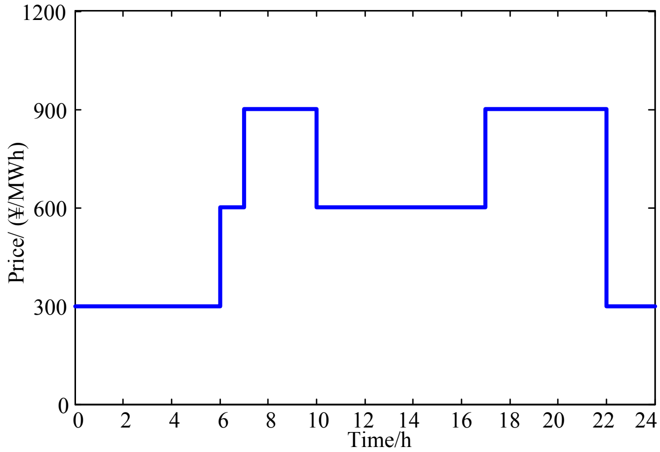

Figure 4. Price of electricity purchased by the distribution company.

5.2. Optimization Result Analysis

- Analysis of the weak Stackelberg equilibrium solution

Based on the above conditions, the weak Stackelberg equilibrium of the game are obtained as shown in Figure 5. The payoff of RE company and BSS at the weak Stackelberg equilibrium is ￥276,480 and ￥58,671, respectively. When RE company adopts the strategy at the weak Stackelberg equilibrium point, no matter what kind of rational strategy BSS adopts, the income of RE company will not be lower than ￥276,480. Therefore, the weak Stackelberg equilibrium solution is a conservative decision for the RE company, and the payoff at the equilibrium point is the minimum of its payoff.

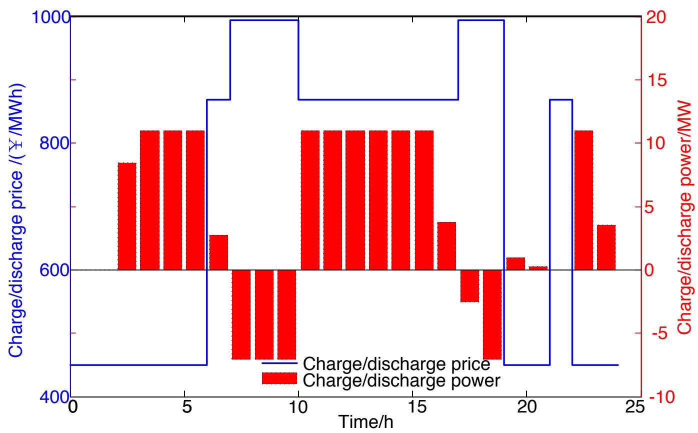

Figure 5. The weak Stackelberg equilibrium.

Comparing figure 4 and figure 5, it can be seen that the changing trend of charge/discharge price is basically consistent with that of the electricity purchase price of the distribution company. During periods of low electricity purchase price of distribution company, such as period 0-6, the RE company sets a low charge/discharge price, directs the BSS to charge, and to store power. During the period of high electricity purchase price of the distribution company, such as period 20-21, RE company sets a high charge/discharge price to attract BSS to discharge, so as to increase the revenue of electricity sale of the RE company.

Table 2 compares the revenue of RE and BSS under the cooperative and non-cooperative models. In the non-cooperative mode, BSS buys electricity directly from the distribution network company in accordance with the contract price ρ_{DC}, and does not consider the sale of electricity to the power grid by BSS.

Table 2. The revenue of both sides in different scenario.

Scenario	RE company	BSS
Cooperative scenario	￥276,480	￥58,671
Non-cooperative scenario	￥252,054	￥52,200

As shown in Table 2, compared to the case of non-cooperation, in the game model proposed in this paper, the revenue of both RE and BSS has increased. Therefore, both of them have the motive of cooperation.

- Sensitivity analysis of the average charge/discharge price

In the Stackelberg game, the RE company, as the leader, sets the charge/discharge price first, which has the first-mover advantage. If it is not restricted, the fairness of the game may be reduced. In this situation, the participation enthusiasm of BSS would be reduced or BSS might even refuse to cooperate. Table 3 shows the effect of the average charge/discharge price on the revenue of both sides in the game.

Table 3. The revenue of both sides with different average Charge/discharge price.

Average Charge/discharge price ￥/MWh	RE company ￥	BSS ￥
750	277,911	57,240
720	276,480	58,671
650	27,2196	62,955
600	26,9136	66,015
550	26,6076	69,075

As can be seen from Table 3, as the average charge/discharge price $\bar{\rho}$ declines, revenue of the RE company continues to decrease, while BSS's revenue continues to increase. It can be predicted that with the continuous decline of $\bar{\rho}$, when the revenue of RE is less than ￥252,054 (its revenue under the non-cooperative mode given in Table 2), the RE company will not have the motivation to participate in the game. Similarly, with the increasing of $\bar{\rho}$, when the revenue of BSS is less than ￥58,671 (its revenue under the non-cooperative mode given in Table 2), BSS will not have the motivation to participate in the cooperation. Therefore, the average charge/discharge price should be reasonably set to mobilize the enthusiasm of both sides of the game.

- Benefit of the distribution company

Although the cooperation between RE company and BSS does not bring direct economic revenue to the distribution company, the controllability of renewable energy is improved by the cooperation, which can reduce the adverse impact of renewable energy on the power grid. As a result, the distribution company can guide the output power of renewable energy by adjusting the purchase price, so as to reduce the peak-valley difference of the power grid and reduce the peak-shaving pressure.

Figure 6 shows a comparison of the peak-valley difference of the power grid load under different conditions. As can be seen from figure 6, when there is no renewable energy, the peak-valley difference of the power grid load is 61MW. When renewable energy is directly connected to the grid, the peak-valley difference of the equivalent load taking the renewable energy output into account is increases to 76MW. However, when RE company and BSS work together, the peak-valley difference could be reduced to 67MW by adjusting the output of different time intervals in response to the purchase price of the distribution company.

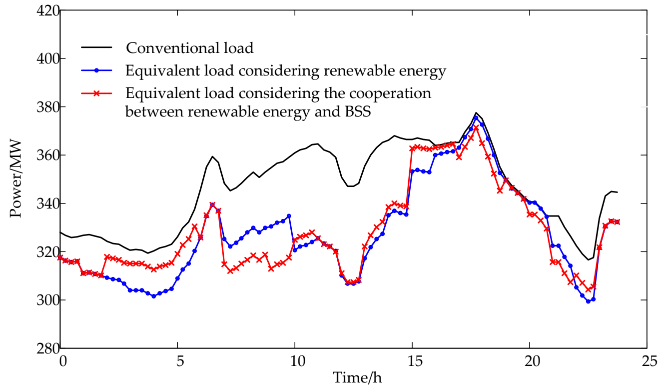

Figure 6. The load curve under different conditions.

6. Conclusions

In this paper, the cooperative mechanism of RE and BSS to achieve win-win results is studied when they belong to different investment subjects and do not want to form a joint system. The main conclusions are as follows:

(1) A Stackelberg game model with RE company as leader and BSS as follower is proposed, which can simulate the interaction between RE company and BSS well. On the one hand, RE company does not need to directly control the charge/discharge behavior of BSS, but only needs to optimize the charge/discharge price of each period to guide the charge/discharge behavior of BSS. On the other hand，BSS is not only a passive recipient of the price. BSS could affect the revenue of the RE company by adjusting its own charge/discharge strategy, so as to urge RE company to adjust the charge/discharge price.

(2) The proposed model no longer requires that the RE company and BSS belong to a same interest subject, and there is no need for unified coordinated control between them. While pursuing the maximization of their own interests, RE company and BSS could automatically realize the optimal allocation of resources, and a win-win situation is achieve as well.

(3) The comparative analysis of the two Stackelberg equilibrium shows that the weak Stackelberg equilibrium is more in line with the cooperation mechanism proposed in this paper. In addition, the simulation results show that the revenue of RE company and BSS in the model proposed in this paper is higher than their revenue when they operate alone, which proves that both of them have the motivation to participate in the game.

In this paper, the randomness of battery swapping demand is only roughly considered by a pattern of fixed reserve ratio. In order to precisely consider the randomness both of battery swapping demand and RE power, it is necessary to extend the proposed pure-strategy game model to a mixed-strategy game model. And this will be our next research direction.

Author Contributions: Zhe Jiang completed major research tasks and wrote the paper. Wendong Li gave important suggestion and participated in the writing work as well. Changhui Ma, Bing Zhang and Linlin Ma contributed to the simulation analysis. Kuan Lu revised the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

N_t Number of time intervals

Δt Length of a single time interval

P_{RE}^{t} Active power output of renewable energy at time t
ρ_{RE}^{t} Pool purchase price of RE generation at time t
P_{c}^{t} Charging power of BSS at time t
P_{d}^{t} Discharging power of BSS at time t
ρ^{t} Charge/discharge price of BSS at time t
$\rho_{\min}^{t}$ Minimum Charge/discharge price of BSS at time t
$\rho_{\max}^{t}$ Maximum Charge/discharge price of BSS at time t
$\overline{\rho}$ Average Charge/discharge price
ρ_{DC} Contract price for the direct charging of BSS from the distribution company
s Unit price of battery swapping
W^{t} Battery swapping demand at time t
P_{cmax} Maximum charging power of BSS
P_{dmax} Maximum discharging power of BSS
Q^{t} Energy storage of BSS at time t
$Q_{\max}$ Rated capacity of BSS
$Q_{\min}$ Minimum energy storage of the BSS
Q_{0} Initial energy storage of BSS
Q_{end} Energy storage at the end of a decision-making cycle
η_{c} Charge efficiency of BSS
η_{d} Discharge efficiency of BSS
α Reserve ratio of the battery swapping demand

References

1. Min, C.-G. Analyzing the Impact of Variability and Uncertainty on Power System Flexibility. Appl. Sci. 2019, 9, 561.
2. Golovanov, N.; Lazaroiu, G.C.; Roscia, M.; Zaninelli, D. Power Quality Assessment in Small Scale Renewable Energy Sources Supplying Distribution Systems. Energies 2013, 6, 634-645.
3. Bizuayehu, A.; Nieta, A.; Contreras, J.; Catalao, J. Impacts of stochastic wind power and storage participation on economic dispatch in distribution systems. IEEE Transactions on Sustainable Energy, 2017, 7, 1336-1345.
4. Lu, S.-D.; Wang, M.-H.; Kuo, M.-T.; Tsou, M.-C.; Liao, R.-M. Optimal Unit Commitment by Considering High Penetration of Renewable Energy and Ramp Rate of Thermal Units-A case study in Taiwan. *Appl. Sci.* 2019, *9*, 421.
5. Zhao, H.; Wu, Q.; Hu, S.; Xu, H.; Rasmussen, C. Review of energy storage system for wind power integration support. Applied Energy, 137, 545-553.
6. Torres-Moreno, J.L.; Gimenez-Fernandez, A.; Perez-Garcia, M.; Rodriguez, F. Energy Management Strategy for Micro-Grids with PV-Battery Systems and Electric Vehicles. Energies 2018, 11, 522.
7. Chan, K.; Luo, X.; Qin, M.; Wu, T.; Chung, C. Optimal planning and operation of energy storage systems in radial networks for wind power integration with reserve support. IET Generation, Transmission & Distribution, 2016, 10, 2019-2025.
8. Xue, F.; Lei, X.; Zhang, Y.; Liu, H.; Gao, C. A Brand-New Approach of Connecting Electrical Vehicles With Smart Grid From Vehicle-to-Grid Mode to Battery-to-Grid Mode. Power System Technology, 2012, 36, 29-34.
9. Jiang, Z.; Han, X.; Li, Z.; Li, W. Dependent Chance Goal Programming of Wind-EVBSS Considering its Multiple Benefits. Power System Technology, 2016, 40, 1134-1139.
10. Miao， Y.; Jiang, Q.; Cao, Y. Operation Strategy for Battery Swap Station of Electric Vehicles Based on Microgrid. Automation of Electric Power Systems, 2012, 36, 33-38.

11. Liu, F.; Yang, X.; Shi, S.; Zhang, M.; Deng, H.; Guo, P. Economic Operation of Microgrid Containing Charging-Swapping-Storage Integrated Station Under Uncertain Factors of Wind Farm and Photovoltaic Generation. Power System Technology, 2015, 39, 669-676.
12. Tian, Y.; Liao, Q.; Xue, Y.; Chen, Y. Multi-scenario coordinated planning method of EV battery-swapping station and distributed generation based on coordinated charging strategy. Electric Power Automation Equipment, 2017, 37, 62-69.
13. Fu, H.; Liu, M.; Chen, Z. Multi-objective Optimization of Battery Swapping Station with Wind Photovoltaic and Energy Storage. Proceedings of the CSU-EPSA, 2016, 28, 38-43.
14. Jiang, Z.; Han, X.; Li, Z.; Wang, M.; Liu, G.; Wang, M.; Li, W.; Ollis, T.B. Capacity Optimization of a Centralized Charging Station in Joint Operation with a Wind Farm. Energies 2018, 11, 1164.
15. Jiang, Z.; Han, X.; Li, Z.; Li, W.; Wang, M.; Wang, M. Two-Stage Multi-Objective Collaborative Scheduling for Wind Farm and Battery Switch Station. Energies 2016, 9, 886.
16. Suo, L.; Xiang, C.; Tang, W.; Liu, Z.; Zhao, H. Multi-objective Bi-level Programming of Centralized Charging Station Considering Benefits Balance for Different Subjects. Automation of Electric Power Systems, 2016, 40, 100-107.
17. Wang, K.; Ouyang, Z.; Krishnan, R.; Shu, L.; He, L. A game theory based energy management system using price elasticity for smart grids. IEEE Transactions on Industrial Informatics, 2015, 11, 1607-1616.
18. Lu, Q.; Chen, L.; Mei, S. Typical Applications and Prospects of Game Theory in Power System. Proceedings of the CSEE, 2014, 34, 5009-5017.
19. Schneider, I.; Roozbehani, M. Energy market design for renewable resources: imbalance settlements and efficiency-robustness tradeoffs. IEEE Transactions on Power Systems, 2017, 3757-3767.
20. Mei, S.; Wang, Y.; Liu, F.; Zhang, X.; Sun, Z. Game approaches for hybrid power system planning. IEEE Transactions on Sustainable Energy, 2012, 3, 506-517.
21. Wang, Z.; Yuan, Y.; An, B.; Li, M.; Wang, F. An Overview of Security Games. Journal of Command and Control, 2015, 1, 121-149.
22. Leitmann, G. On generalized Stackelberg strategies. Journal of Optimization Theory & Applications, 1978, 26, 637-643.
23. Breton, M.; Alj, A.; Haurie, A. Sequential stackelberg equilibria in two-person games. Journal of Optimization Theory & Applications, 1988, 59, 71-97.
24. Wei, W.; Chen, Y.; Liu, F.; Mei, S.; Tian, F.; Zhang, X. Stackelberg Game Based Retailer Pricing Scheme and EV Charging Management in Smart Residential Area. Power System Technology, 2015, 39, 939-945.
25. Anandalingam, G.; White, D. A solution method for the linear static stackelberg problem using penalty functions. IEEE Transactions on Automatic Control, 1990, 35, 1170-1173.
26. Song, Y.; Zhang, J. Multi-objective CuckooSearch Algorithm for Bi-level Programming Problems. Opeations Reseach and Management Science, 2017, 26, 1-10