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Optimal Dispatching of Microgrids with Development of Prosumers Sharing Energy Storage

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Abstract: The charge/discharge operation of the prosumer's energy storage and the energy interaction between prosumers and MGs are chaotic from the overall point of the MG's operation. It causes considerable resource waste and reduces the overall benefits of the MG with multi-prosumers. Therefore, a game theory-based optimal scheduling strategy for the MG with multi-prosumers combined into a PRCO is proposed in this paper. According to the prosumers' complementary characteristics of ES utilization and energy production, prosumers can be integrated into the PRCO to obtain energy reciprocity by sharing ES with an ordered charge–discharge operation. Meanwhile, to improve the collaboration of prosumers and the overall efficiency of the MG, a game scheduling model is established with the MG as the leader and the PRCO as the follower. The ToU price incentive policy is implemented in the MG to maximize the operational benefits and reduce the difference between the valley and peak load. Meanwhile, the PRCO responds to the price policy and implements an ordered charge–discharge strategy of ES to optimize each member's energy scheduling strategy and minimize the total costs. The PRCO revenues are distributed to prosumers based on the Shapley value method. The uniqueness and existence of Stackelberg equilibrium in the game model are proved. The simulations of a community MG show that the ordered charge–discharge operation of ES is achieved and the overall benefits of the system are improved.

Keywords: sharing energy storage; prosumer coalition; ordered charge–discharge; master–slave game; optimization

Citation: Li, F.; Su, K.; Li, X.; Zhang, B. Optimal Dispatching of Microgrids with Development of Prosumers Sharing Energy Storage. *Electronics* **2024**, *13*, 1899. https://doi.org/10.3390/electronics13101899

Academic Editor: Carlos Andrés García-Vázquez

Received: 6 April 2024
Revised: 2 May 2024
Accepted: 9 May 2024
Published: 12 May 2024

1. Introduction

A paradigm shift with the deepening of source–load interactions stimulates the active participation of users in demand response. Consequently, prosumers with PV, ES, and power load are constantly emerging, which brings new challenges to the optimal scheduling of MGs with prosumers [1–3]. The energy scheduling of multi-prosumers in the MG exhibits the two following characteristics: (1) the production and consumption capabilities of prosumers are different and complementary; (2) the charge–discharge behaviors for ES are also different and complementary. The prosumers participating in MG scheduling coordinate their PV, ES, and loads to maximize their interests independently without considering the above characteristics. No coordination may cause considerable resource waste and low effectiveness in the overall system. Therefore, multi-prosumers can be combined into a PRCO to participate in the scheduling of the MG. The integration promotes the utilization efficiency of resources and the overall benefits of the system. Moreover, game theory is introduced for building the optimization scheduling model [4,5], since the MG and PRCO belong to different entities with different operation objectives, to further maximize the overall benefits of the MG system.

To improve the utilization of energy generated in the microgrid, under the price incentives, the optimal dispatching of the MG system to prosumers, mainly considering demand-side response, has been studied extensively [6–10]. However, the studies usually focus on the master–slave game between the MG and prosumers without considering their collaboration [11,12]. According to C. O. Adika et al. [9], residential users effectively reduced their power consumption costs under the price incentives by optimizing the operation time of the equipment and the ES's schedule. L. Ma et al. [10] developed a model based on a non-cooperative game between the PV prosumer cluster and the MG operator without taking the contribution of ES prosumers. A bi-level optimization model based on Stackelberg game theory was proposed in [11,12], which set the MG managers as the upper leaders to formulate the ToU price and the users as followers to respond. Furthermore, the benefits distribution between the MG managers and the prosumers was studied in [11] without involving cooperation among the prosumers. Also, Özge Erol et al. [12] proposed a Stackelberg game approach for energy sharing management of a microgrid to increase the profits of the MG and reduce the dependency of the MG on the utility grid. Veniamin Boiarkin et al. [13] proposed a novel dynamic pricing model to maximize the utilization of energy generated in the microgrid and reduce the import of energy from the utility grid. However, the above studies mainly focused on maximizing the benefits to the whole coalition and its members, while the interaction and mutual usefulness gained by the coalition's energy sharing have not been explored fully under the grid's price incentives.

To develop energy sharing with efficient utilization of the participants in the MG's scheduling, cooperative game theory and a peer-to-peer trading mode was introduced to increase the energy utilization [14–21]. According to Y. Du et al. [14], a cost allocation method using cooperative game theory was proposed to ensure fairness among the members and the economic stability of the coalition. The cooperative game model of the photovoltaic microgrid group was proposed in [15,16] to promote the energy interaction among microgrid clusters and further improve the overall profits of the coalition. L. Han et al. [17] discussed the distribution schemes of the coalition's profits satisfying individual and overall rationality, where the coalition occurred with the prosumer clusters, including distributed ES systems. Moreover, Zibo Wang et al. [18] proposed a market power modeling and restraint method of aggregated prosumers with a game-theoretic approach to restrain market power abuse in energy trading. A novel energy cooperation framework for cooperative energy storage systems and prosumers was proposed with an energy cooperation platform in [19] to improve the energy economy and solution efficiency. A new energy storage sharing framework was proposed in [20] with energy storage allocation for prosumers, which can reduce the electricity costs of prosumers and improve the practical feasibility. In addition, Xianshan Li et al. [21] proposed a photovoltaic battery cost-bundling model and a battery load utility-bundling model to improve the power system's new energy consumption and reduction in energy storage investment. Bo Gu et al. [22] proposed a novel approach to optimize the charging–discharging schedule of battery energy storage systems in the microgrids with prosumers, which can improve the profit of each prosumer. According to Balakumar P. et al. [23], a distributed energy sharing program is proposed to share energy among PV prosumers to increase energy utilization and maximize PV prosumer's profit. Those studies rarely considered the initiative and collaboration of prosumers as decision-making subjects, to improve energy reciprocity and overall efficiency of the MG.

In this paper, an optimal scheduling strategy for MGs with multi-prosumers is developed. The proposed framework strengthens the demand-side response ability for the PRCO under the price incentives. Furthermore, the proposed model promotes the systematic charge–discharge scheduling of multi-prosumers sharing energy storage, and the outcomes improve the efficiency of resource utilization compared with the prosumers' individual optimization. The main contributions are as follows:

(1) According to the prosumers' complementary characteristics of ES utilization and energy production, prosumers can be integrated into a PRCO to obtain energy reciprocity and the ordered charge–discharge operation of ES.
(2) A model of master–slave game scheduling is established with the MG as the leader and the PRCO as the follower. A price incentive policy is implemented by the MG and

price strategy is optimized to maximize operational benefits. Afterward, the PRCO responds to the price policy and optimizes the energy scheduling strategy of each member, with the objective of minimizing electricity consumption costs.

(3) The additional benefit to each member in the PRCO is obtained by the SVM.

The framework of this paper is as follows:

The structure of the MG with a PRCO is developed in Section 2. The cooperative relationship of the game between the MG and PRCO is introduced in Section 3 and the prosumers' energy sharing mechanism is considered. Moreover, the mathematical game models of all players are described in detail in Section 4. The flow chart for solving the model of the Stackelberg game is discussed in Section 5, and the simulation analysis is presented in Section 6. Finally, the conclusions are provided in Section 7.

2. The Structure of the MG with a PRCO

The structure of the MG with a PRCO is shown in Figure 1 and it is composed of new energy generation units, controllable generation units, conventional loads, and prosumers. The controllable units contain gas turbines and diesel generators.

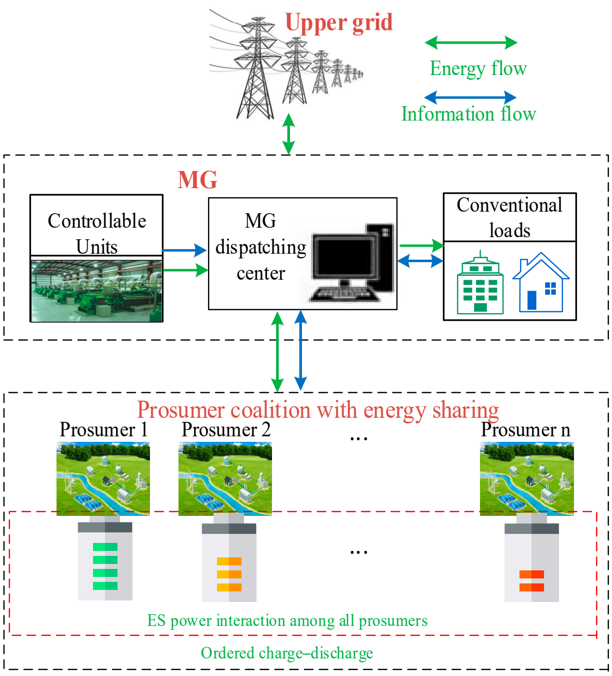

Figure 1. The MG system with a PRCO.

The operation objective of prosumers is to obtain the lowest cost of energy consumption by the coordination of PV power, ES, and its original load, and the power shortage is balanced by the interaction with the MG. According to the different characteristics of PV power, ES, and conventional loads among multi-prosumers, prosumers can be integrated into a PRCO for energy reciprocity, to obtain energy among prosumers and promote local consumption of new energy. The utilization efficiency of resources can be promoted through the prosumers' complementary behaviors while the PRCO participates in the MG's scheduling.

Meanwhile, the scheduling objective of the MG is to obtain peak cutting and valley filling and maximize its operation profits. Each prosumer has access to the MG at different locations. To reduce the peak–valley difference of the net load, the MG formulates the ToU price policy to encourage the active participation of multi-prosumers in demand-side response and adjust their power consumption strategies. The power shortage of the MG will be balanced by the interaction with the upper grid.

3. The Optimization Scheduling Strategy of the MG with a PRCO

3.1. Scenario Description of Photovoltaic Output Uncertainty

The actual photovoltaic output is composed of its predicted value and prediction deviation:

$$P_t^{\mathrm{PV}} = P_t^{\mathrm{PV},f} + \delta_t^{\mathrm{PV}} \quad (1)$$

When describing the uncertainty of photovoltaic output, the deviation of PV output can be regarded as a normal distribution random variable: the mean value is zero, and the variance is described as σ_{PV}^2. The variance is related to the predicted output and installed photovoltaic capacity, as shown in Equation (2):

$$\begin{cases} \delta_t^{\mathrm{PV}} \sim N\left(0, \sigma_{\mathrm{PV}}^2\right) \\ \sigma_{\mathrm{PV}}^2 = \left(\frac{1}{5} P_t^{\mathrm{PV,f}} + \frac{1}{50} P_{\mathrm{total}}^{\mathrm{PV}}\right)^2 \end{cases} \quad (2)$$

The probability density function corresponding to the normal distribution of Equation (3) is:

$$f_{\mathrm{PV}}(\delta_t^{\mathrm{PV}}) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{PV}}} \cdot \exp\left(\frac{(\delta_t^{\mathrm{PV}})^2}{2\sigma_{\mathrm{PV}}^2}\right) \quad (3)$$

To describe the uncertainty of PV output, the scenario analysis method is introduced to obtain typical scenarios of possible photovoltaic output, and scenario reduction is implemented to reduce the solution dimension for transforming various uncertainties into a combination of multiple certifying factors. According to the prediction model of PV output, a large quantity of data are sampled by the Monte Carlo method; the Monte Carlo method can conveniently deal with a large number of uncertain factors, and the calculation time does not increase with the increase in the system scale. Then, *K*-means clustering method is introduced to cluster actual photovoltaic output data and to form a sample set; finally, the typical scene and the probability of each scenario of photovoltaic output are obtained.

3.2. The Game Relationship between the MG and PRCO

During the scheduling periods, the electricity price is set in the MG according to the peak and valley periods of loads. Each prosumer responds to the price policy and coordinates with the MG scheduling while its load demands are fulfilled. The multi-prosumers can be integrated into a PRCO. To balance the interests of all players, a master–slave game relationship of MG with PRCO is established to maximize the benefits of both players since the MG and PRCO belong to different entities with different operation objectives.

On the one hand, the PRCO can realize the interconnection and mutual assistance by taking advantage of the energy production and consumption differences among the prosumers. On the other hand, the demand-side response ability of the prosumers can be improved by participating in the MG scheduling in the form of a PRCO to perform better for the operation of the MG.

Consequently, the master–slave game scheduling framework is built as shown in Figure 2. As the leader, the MG implements the ToU price policy to stimulate the PRCO to change the power consumption arrangement for peak load clipping and valley filling. As a follower, the PRCO responses to the price policy to obtain the minimum cost.

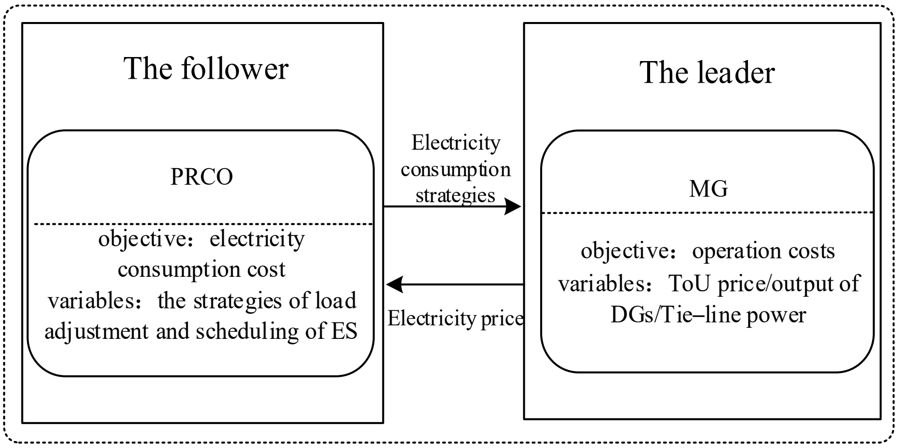

Figure 2. Game scheduling framework of MG with PRCO.

3.3. Ordered Charge and Discharge Strategy of PRCO

Ordered energy charging–discharging scheduling is introduced to improve the utilization rate of energy storage resources in the PRCO so that the energy reciprocity of the residual electric power among prosumers is promoted.

The amount of residual electric power is denoted in Equation (4) before the prosumer k executes mutual energy compensation:

$$\Delta P_{k,t}^{l} = l_{k,t} + P_{k,t}^{\mathrm{C}} - P_{k,t}^{\mathrm{D}} - \sum_{i=1}^{m} \pi_i P_{k,i,t}^{\mathrm{PV}} \tag{4}$$

If $\Delta P_{k,t}^{l}$ is more than zero, it represents a load power shortage after the load is charged by the prosumer k; otherwise, it represents residual electric power after other prosumers discharge from its ES.

The energy reciprocity among prosumers needs to satisfy the following principles: the prosumers can transfer the residual electricity power to other prosumers, but the total power exchange cannot exceed their remaining electric power. Meanwhile, the prosumers with power shortages can receive electrical power from other prosumers, but the overall power received cannot exceed their shortage power. The constraint conditions of energy reciprocity are represented in Equation (5).

$$\begin{cases} \sum\limits_{j=1,2,\ldots,n,j\neq k} D_{kj} P_{k,j,t} \leq -\Delta P_{k,t}^{l} & \Delta P_{k,t}^{l} < 0 \\ \sum\limits_{j=1,2,\ldots,n,j\neq k} D_{jk} P_{j,k,t} \leq \Delta P_{k,t}^{l} & \Delta P_{k,t}^{l} > 0 \end{cases} \tag{5}$$

In (5), D_{kj} represents a binary state variable, which means the power will be transferred from the prosumer k to the prosumer j while the subscript number of D_{kj} indicates the direction of power transmission from the prosumer k to the prosumer j.

Power reciprocity among the multi-prosumers involves cooperation. In general, energy reciprocity among prosumers is obtained by trading according to the internal electricity price. However, the joint operation of prosumers is proposed to minimize the overall operating cost of the PRCO in this study: since the mutual power is only transferred within the PRCO without an external cost, the internal electricity price of energy sharing in the PRCO can be ignored.

The ordered energy dispatching of the prosumers is obtained by the relationship of internal energy balance and power reciprocity, as shown in Figure 3. In Figure 3, it mainly contains three cases, which are as follows:

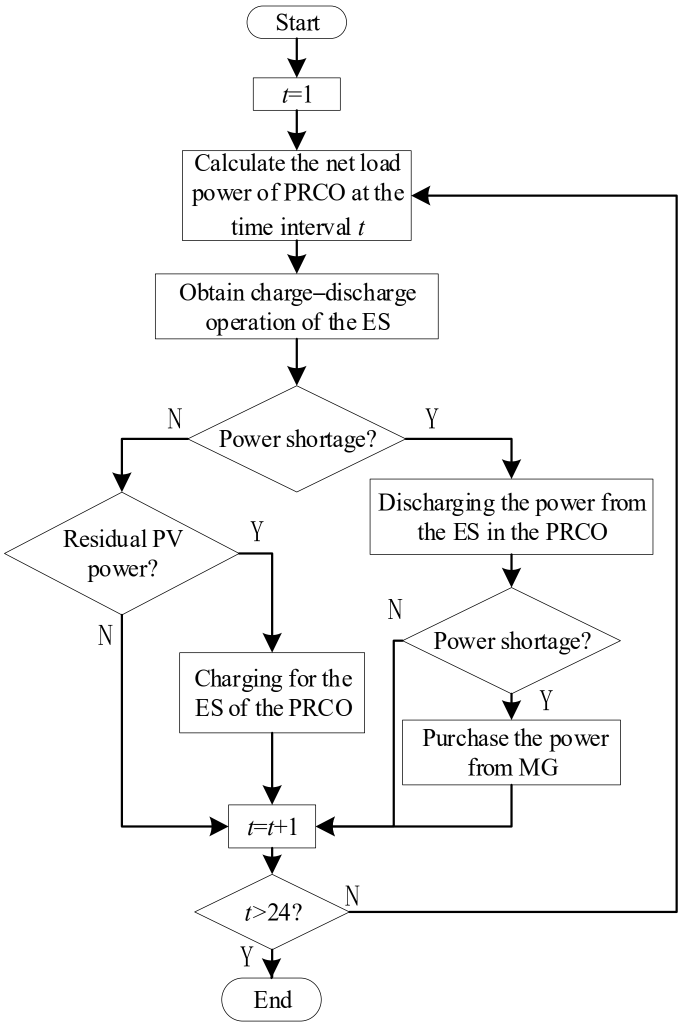

Figure 3. Ordered charge–discharge operation strategies in PRCO.

Case 1: there is no power shortage and no residual power in the PRCO in the current period then the solution enters into the next optimization period.

Case 2: there is no power shortage in the PRCO in the current period, but with residual PV power. The PRCO stores the residual power in the ES and enters into the next optimization period.

Case 3: a power shortage exists in the PRCO in the current period; the power shortage will be balanced by discharging from the ES. If the capacity of the ES is insufficient, the PRCO will purchase the power from the MG, then enter the next period of optimization.

3.4. The Energy Storage Sharing Mechanism of the PRCO

The prosumers in the MG possess different load characteristics, energy storage usage, and PV dispatching. To develop ES sharing, a cooperative PRCO is formed to realize the inter-utilization of residual electricity instead of trading with the MG.

The prosumers first utilize their own energy storage to satisfy the power shortage while the output of new energy is insufficient. A greater inadequacy of stored energy will generate a demand for energy sharing. Conversely, the supply of sharing ES is formed as the output of new energy is surplus. Consequently, a cooperation agreement between the prosumers occurs to improve the mutual utilization and the overall benefit of the system.

Each prosumer can increase their benefits by allocating the net profits reasonably after the alliance. Thereby, there is a driving force to form a cooperative association.

4. The Game Optimal Scheduling Model of the MG with a PRCO

4.1. The Optimization Model of PRCO

As a follower, the PRCO optimizes the electricity consumption arrangement to minimize the cost of electricity consumption.

4.1.1. Objective Function

The optimization objective is the sum of each prosumer's utility function and contains the comprehensive cost and the consumption utility. The comprehensive cost includes the cost of purchasing electricity and the charging–discharging loss of ES in the PRCO, which are as follows:

$$\min J_2 = \begin{pmatrix} \sum\limits_{t=1}^{24} \lambda_t \left(\Delta P_{k,t}^{l}\right)^{+} + \theta_t \left(\Delta P_{k,t}^{l}\right)^{-} + \\ \sum\limits_{t=1}^{24} c_{ess,k}\left(P_{k,t}^{C} + P_{k,t}^{D}\right)^{\smile} \sum\limits_{t=1}^{24} k_{lk} \ln\left(1 + l_{k,t}\right) \end{pmatrix} k = 1, 2, \ldots, n \tag{6}$$

In (6), $k_{lk} \ln(1 + l_{k,t})$ represents the power utility [24] obtained by consuming power $l_{k,t}$ for the prosumer k, $k \in [1, 2, \ldots, n]$; the operators $(.)^{+}$ and $(.)^{-}$ denote the positive part and the negative part in the brackets, respectively:

$$(x)^{+} = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases}, (x)^{-} = \begin{cases} x, & x \leq 0 \\ 0, & x > 0 \end{cases} \tag{7}$$

4.1.2. Constraints

The SOC (state-of-charge) constraints of each prosumer needs to consider the influence of exchange power with other members of the PRCO at each scheduling interval. Until the end of the optimization process, it is required to summarize the total equivalent net power and feed it back to the model of the leader's optimization. The constraints of the follower (PRCO) are as follows:

(1) Load constraints

$$\max\left(l_{k,t}^{\min}, P_{k,t}^{D} - P_{k,t}^{C}\right) \leq l_{k,t} \leq l_{k,t}^{\max} \tag{8}$$

In (8), the load parameters $(l_{k,t}^{\min}, l_{k,t}^{\max})$ are affected by the shift load and the interruptable load value at each time interval.

(2) SOC constraints of ES in the PRCO

The ES behaviors of prosumers are limited by the constraints of the remaining SOC capacity and charging–discharging power capacity, as shown in (9):

$$\begin{cases} 0 \leq P_{k,t}^{\mathrm{C}}, P_{k,t}^{D} \leq P_{k}^{\mathrm{Cap}} \\ \mathrm{SOC}_{k}^{\min} \cdot E_{k}^{\mathrm{Cap}} \leq E_{k,t} \leq E_{k}^{\mathrm{Cap}} \\ E_{k,t} = E_{k,t-1} + \Delta t \left(\eta^{\mathrm{C}} P_{k,t}^{\mathrm{C}} - \frac{P_{k,t}^{\mathrm{D}}}{\eta^{\mathrm{D}}} + P_{ex,k,t} \right) \\ \sum\limits_{k=1}^{n} P_{ex,k,t} = 0 \\ P_{ex,t}^{k} = \sum\limits_{j=1,2,\ldots,n, j \neq k} D_{kj} P_{k,j,t} \end{cases} \tag{9}$$

The sharing of ES can be achieved by exchanging power between the prosumers in the PRCO to balance the members' power shortage or surplus. While energy storage sharing is considered in the above equations, the cooperation model involving coalition is formed; otherwise, it is called the direct model.

4.2. The Optimization Model of the MG

4.2.1. Objective Function

The objective function is to minimize the operation costs, as shown in (10).

$$\begin{cases} \min J_1 = \sum\limits_{t=1}^{24} c_t g_t + \sum\limits_{t=1}^{24} p_{x,t} P_{tie,t} \\ \sum\limits_{t=1}^{24} c_t g_t = C_{\mathrm{DE}} + C_{\mathrm{MT}} \end{cases} \tag{10}$$

In (10), the cost models of a diesel generator and gas turbine are as follows [25]:

(1) The model of generation cost for a diesel generator is shown in Equation (11):

$$C_{\mathrm{DE}} = \sum_{t=1}^{T} \alpha (P_{\mathrm{DE},t})^2 + \beta P_{\mathrm{DE},t} + \gamma + \sum_{t=1}^{T} (k_{\mathrm{DE}} P_{\mathrm{DE},t}) \tag{11}$$

(2) The model of generation cost for a gas turbine is shown in (12):

$$C_{\mathrm{MT}} = C_{fuel} \sum_{t=1}^{T} \frac{P_{\mathrm{MT},t}}{LHV \times \eta_t} + \sum_{t=1}^{T} (k_{\mathrm{MT}} P_{\mathrm{MT},t}) \tag{12}$$

4.2.2. Constraints

(1) The constraints of the output and ramp rate for gas turbines and diesel generators

$$\begin{cases} P_{\mathrm{MT}}^{\min} \le P_{\mathrm{MT},t} \le P_{\mathrm{MT}}^{\max} \\ P_{\mathrm{DE}}^{\min} \le P_{\mathrm{DE},t} \le P_{\mathrm{DE}}^{\max} \\ \left| P_{\mathrm{MT},t} - P_{\mathrm{MT},t-1} \right| \le \Delta P_{\mathrm{MT}}^{\max} \\ \left| P_{\mathrm{DE},t} - P_{\mathrm{DE},t-1} \right| \le \Delta P_{\mathrm{DE}}^{\max} \end{cases} \tag{13}$$

(2) The constraints of active power balance

$$\begin{cases} P_{\mathrm{DE},t} + P_{\mathrm{MT},t} + P_{tie,t} = \Delta P_{l,t} \\ \Delta P_{l,t} = \sum\limits_{k=1}^{n} \Delta P_{k,t}^{l} \end{cases} \tag{14}$$

(3) The constraint of electricity sales revenue

$$\sum_{t=1}^{24} \lambda_t (\Delta P_{l,t})^+ + \theta_t (\Delta P_{l,t})^- = C_{\mathrm{ope}} \tag{15}$$

(4) The constraint of tie-line active power

$$P_{tie,t} \le |P_{tie}^{\max}| \tag{16}$$

In (16), when the MG purchases the power from the upper power grid, the power value $P_{tie,t}$ is positive; otherwise, it is negative.

(5) The constraint of electricity price

To ensure the gain of the MG, the electricity price should be greater than the marginal cost of power generation shown in Formula (17).

$$c_t \le \lambda_t \le \lambda_t^{\max} \tag{17}$$

In (17), the value of $\lambda_t^{\max}$ is equal to the selling price of the upper grid.

4.3. Coalition's Income Distribution Based on Shapley Value Method

The Shapley value method is employed for the distribution data to establish a fair distribution of income following a coalition. The Shapley value method distributes income according to the marginal contribution of the members. Moreover, the income obtained by the participant is equal to the average value of its marginal contribution to the alliance [26]. The precondition of adopting the Shapley value method is to distribute the overall interests needed to meet the stability of the alliance structure, called the overall rationality. The overall rationality means the benefits after the cooperation are greater than the sum of the benefits based on the direct transaction model. In addition to the overall rationality, the precondition also needs to satisfy the individual rationality. The individual rationality signifies that the benefits to each prosumer based on the cooperation model are more than the results obtained by the direct transaction model.

The income v_i related to the prosumer i is shown in Equation (18) for the proposed cooperative model:

$$v_i = \sum_{s(i \in s_i)} \frac{(n - |s|)!(|s| - 1)!}{n!}[v(s) - v(s/i)] \tag{18}$$

In (18), s_i is all subsets of the coalition containing the prosumer i; $|s|$ is the number of users in the subset s; $v(s)$ is the income generated by set s; and $v(s/i)$ denotes the total revenue from the formation of a cooperative alliance by the remaining prosumers after the member i is removed from the set s.

The prosumers joined in the coalition can effectively avoid purchasing electricity from the MG at a higher price and selling surplus electricity to the MG at a lower price. Thus, the prosumers with surplus electricity obtain the additional benefits and the prosumers with deficient electricity share the lower electricity costs through the coalition's income distributed by Shapley value method.

5. The Solution of the Proposed Game Model

The solution of the game model is mainly divided into two steps:

(1) In the first step, the PRCO as a follower considers the scheduling resources (PV power, ES capacity, price mechanism, and load) and optimizes the charging–discharging strategies of the ES and electricity arrangement.
(2) In the second step, the MG as leader optimizes the price to reduce the operational costs and ensure the electricity sales revenue.

In the game optimization, the participants take each other's optimal strategy in the last round as input conditions. As the leader, the MG sets the ToU price according to the electricity consumption strategies of the PRCO. As the follower, the PRCO determines the strategies of electricity consumption according to the ToU price and the load demands. It will further affect the electricity price formulated by the MG. By adjusting the respective strategies continuously between the leader and the follower, Stackelberg equilibrium of the game model is achieved if the deviation of the solution in two adjacent iterations is less than a specific error range.

5.1. Existence Proof of the Stackelberg Equilibrium

The solutions $\{\lambda_t^*, l_t^*\}$ are supposed as Stackelberg equilibrium strategies for the proposed game model. In other words, the leader (MG) formulates the price λ_t^* for the follower (PRCO) and the PRCO respond to the price. Furthermore, the PRCO adjusts the energy arrangement strategy l_t^*. In this way, the interests of both sides in the game process can be balanced. According to the definition of SE (Stackelberg Equilibrium) [27], Stackelberg equilibrium for the game exists if the following conditions are fulfilled:

(1) The leader and the follower are continuous functions of their decision variables, and the optimal sets of both sides in the game model are non-empty, closed, and bounded convex in the Euclidean space.
(2) Given the leader's strategy, the objective function of the follower has a unique optimal strategy solution.

5.1.1. The Proof of Condition (1)

From the above models, the leader's strategy sets need to satisfy Formula (17) and the follower's strategy sets need to conform to Equation (8). Therefore, the strategy sets of the MG and PRCO are non-empty, closed, and bounded convex in the Euclidean space. Furthermore, the objective functions of the MG and the prosumers cluster are a continuous function of each variable. Thus, the condition (1) is satisfied.

5.1.2. The Proof of Condition (2)

There is a unique optimal load consumption strategy for the PRCO according to the optimal electricity price strategy given by the MG. In other words, the utility function J_2 of the PRCO is a continuous and quasi-concave function under the corresponding strategy set in the optimization process.

The optimal strategies of the PRCO are obtained in the follower's game optimization by taking the partial derivative of the objective function J_2 based on the leader's strategy. The first-order partial derivative of J_2 is equal to zero, and the optimal strategies of the PRCO can be described as follows:

$$\begin{cases} \frac{\partial J_2}{\partial l_t} = \lambda_t - \frac{k_l}{1+l_t} \\ l_t^* = \frac{k_l}{\lambda_t^*} - 1 \end{cases} \tag{19}$$

The objective function of the PRCO carries out the second-order partial derivative of l_t and l_i and it can be expressed as follows:

$$\frac{\partial^2 J_2}{\partial l_t \partial l_i} = \frac{-k_l}{(1+l_t)^2} \tag{20}$$

It is evident from Equation (20) that the Hessian matrix of the objective function J_2 is a negative definite matrix, which means the objective function J_2 is a concave function, and the solution $l_t(\lambda_t^*)$ is the unique optimal strategy of the PRCO if the electricity price is given.

From the above proofs, the scheduling model based on the Stackelberg game proposed in this paper can reach Stackelberg equilibrium.

Meanwhile, the optimal load strategy based on game theory can be obtained under the incentives of electricity price according to Formula (19). When Equation (19) is substituted into Equation (8), the variation range of electricity price can be obtained as follows:

$$\frac{k_l}{l_t^{\max}+1} \le \lambda_t \le \frac{k_l}{max\left(l_t^{\min}, \sum\limits_{i=1}^{m} \pi_i P_{i,t}^{\mathrm{PV}} + P_t^{\mathrm{D}} - P_t^{\mathrm{C}}\right)+1} \tag{21}$$

From the Formula (21), the electricity price depends on the variation range of load. Therefore, the optimal range of load demand corresponds to a specific range of electricity price.

According to the above analysis, the cost function {minJ_1} is a convex function in the domain range of the MG's electricity price $\{R \mid c_t \le \lambda_t \le \lambda_t^{\max}\}$.

Therefore, for any $r \in R$, the cost function of the MG {minJ_1} has a local optimal price $[\lambda_{t,r}^*]$, that the cost function {minJ_1} reaches at a local optimal value. By solving the local optimal cost of all sub-domain intervals r and comparing the cost values, the global optimal cost and its corresponding global optimal price can be obtained:

$$\begin{cases} (\gamma_1^*) = \min_{\gamma_1 \in R} \max_{\gamma_2 \in R_2(\gamma_1)} J_1(\lambda_{t,r}^*, \gamma_2) \\ \gamma_1^* = [\lambda_t^*] \end{cases} \quad (22)$$

where γ_1^* represents the optimal decision variables of the leader; γ_2 represents the decision variables of the follower; and $R_2(\gamma_1)$ represents response set of the energy consumption plan of the follower. Substituting $[\lambda_t^*]$ into Equation (21), the optimal load strategy of the MG can be obtained. The master–slave game equilibrium solution is obtained, and the equilibrium of the MG with a PRCO is realized.

5.2. The Solution of the Master–Slave Game Model

The proposed optimization scheduling model belongs to the category of a bi-level optimization game. Therefore, the model is solved by considering bi-level optimization theory [28].

To avoid falling into the local optimal solution in the traditional PSO algorithm, AWPSO (Adaptive Weight Particle Swarm Optimization) is introduced to enhance global search ability [29]: the inertial weight linear differential decrease strategy is developed to ensure better inertial weight in different search stages. The AWPSO solves the model of the upper-level leader. However, the lower-level followers are solved using the YALMIP/CPLEX toolbox in MATLAB, and the strategy is subsequently fed back to the upper model. The model of master–slave game scheduling in the MG system with a PRCO is solved by using AWPSO and CPLEX, shown in Figure 4. The main solution steps are elaborated on below:

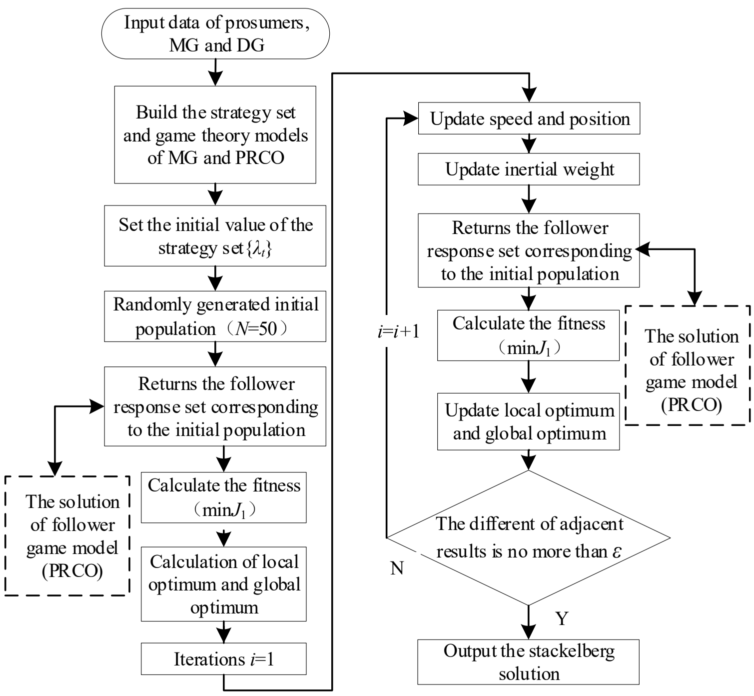

Figure 4. Solving process of the proposed game model.

(1) The original data and parameters needed for the proposed game model are input. It includes various parameters such as the predicted power of the wind and light in the MG and the load demand in each period.

(2) The AWPSO algorithm randomly generates the leader's sample with a certain number of populations, and the fitness calculation considers the influence of the follower strategy.

(3) Under the incentives of the ToU price, the PRCO optimizes the charging–discharging strategy and the power consumption arrangement for maximizing its own benefits, and feeds the strategies back to the MG; the MG continue to optimize the ToU price for ensuring its revenue, and sends the price to the PRCO.
(4) The individuals with the highest fitness are selected as the optimal solution of the current round, and the next generation of the population is generated to continue the optimization.
(5) The optimal solutions are continuously updated with the increase in the iterations until the convergence is achieved. That means, after several rounds of alternating cycle solutions, it will be stopped until neither side of the game entities can change its own strategies to obtain greater benefits.
(6) The Stackelberg equilibrium solution is output, including the MG's optimal ToU price and the optimal energy consumption strategies of the PRCO.

6. Simulations and Discussions

6.1. Simulation Settings

The simulations are based on a real community MG with five kinds of prosumers, including office buildings, residential buildings, hotels, commercial buildings, and restaurants [30]; those prosumers are combined into a coalition, as shown in Figure 1. The initial value of the ToU price is shown in Table 1. The basic data of each member in the PRCO is shown in Table 2. The parameters of the DGs (distributed generations) in the MG are shown in Table 3. The predicted value of load power and PV outputs for all prosumers are provided in Ref. [8], as shown in Figures 5 and 6. The charging–discharging loss coefficient of ES in the prosumers is set as 0.2, and the initial SOC is set to be 0.2. It is given that the minimum value of SOC equals 0.1, and the maximum value of SOC equals 1. Meanwhile, η^C and η^D are both equal 0.96. The other coefficients of the DGs are as follows: α = 0.0071, β = 0.2333, γ = 0.4333, C_{fuel} = 0.573, and LHV = 9.7. The rate of the interruptible load is 80%. The limit of tie-line power with the upper distribution network is 100 kW.

Table 1. Initial price of the system (CNY/kWh).

Time Interval	Initial Selling Price of MG	Feed-in Tariff for PV	Selling Price of the Upper Grid
02:00–10:00	0.598	0.4	0.631
24:00–02:00 10:00–15:00	0.795	0.4	0.924
15:00–24:00	1.011	0.4	1.405

Table 2. Capacity data of all prosumers.

Users	PV Capacity/kW	Power Capacity/kW	Energy Capacity/kWh
Prosumer 1	10	8	40
Prosumer 2	15	8	40
Prosumer 3	20	8	45
Prosumer 4	20	11	65
Prosumer 5	25	15	80

Table 3. The parameters of the DGs.

DG Type	Number	Capacity (kW)	Cost Coefficient (CNY/kWh)	Subsidized Price (CNY/kWh)	Ramp Rate (kW/h)
Diesel generator	1	100	0.0764	0	20
Gas turbine	1	65	0.051	0	10
PV	5	30	0.015	0.1	—

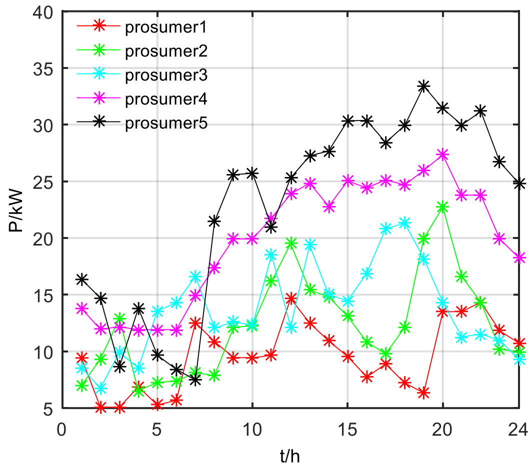

Figure 5. Original load of each prosumer.

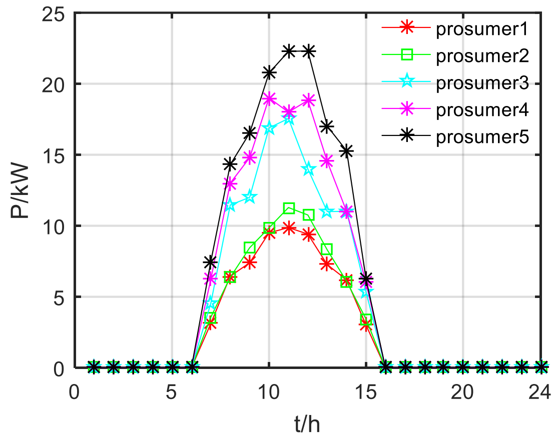

Figure 6. Expectation value of PV outputs in each prosumer.

The parameters of the AWPSO algorithm are as follows: the population size equals 50, the maximum iterations equal 100, the maximum speed is 0.5, the minimum speed equals −0.5, the acceleration factor is 1.5, the maximum inertia weight is 0.8, and the minimum inertia weight is 0.1. The computer is configured as an intel Core i7 processor with a 1.8 GHz main frequency and 16 GB memory capacity.

The parameters of the Yalmip/Cplex solver are shown in Table 4. Taking prosumer 1 and prosumer 5 as the examples, the scenarios of photovoltaic predicted output are drawn, as shown in Figure 7, and the probability distribution of each scenario is shown in Figure 8. The scheduling cycle is set to 24 h, and the time interval is 1 h.

Table 4. Simulation parameters of Yalmip/Cplex solver.

Solver Options	Default Value
Algorithm	'interior-point'
MaxIter	1000
Tolfun	1.00×10^{-6}
TolX	1.00×10^{-15}
InitBarrierParam	0.1
InitTrustRegionRadius	quadratic root of number of variables
ObjectiveLimit	-1.0×10^{20}
TolCon	1.00×10^{-6}

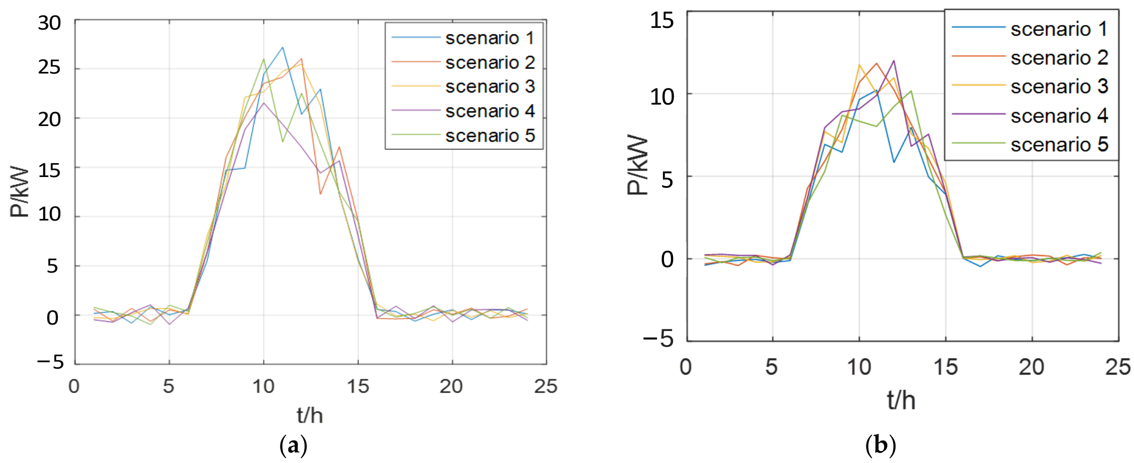

Figure 7. Five typical scenarios of PV outputs of prosumers. (**a**) The scenarios of prosumer 1; (**b**) the scenarios of prosumer 5.

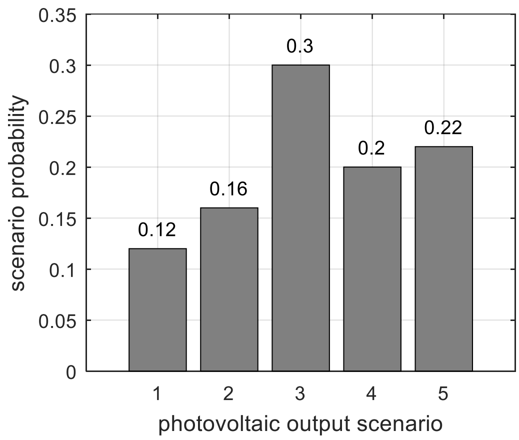

Figure 8. Probability of photovoltaic output scenarios.

6.2. Comparative Analysis of Game Optimization

6.2.1. Comparative Analysis of Economic Benefits

The first simulation case is based on the game model proposed in this study. Figure 9 shows the convergence of objective functions of both participants. The economic benefits of the two models are shown in Table 5.

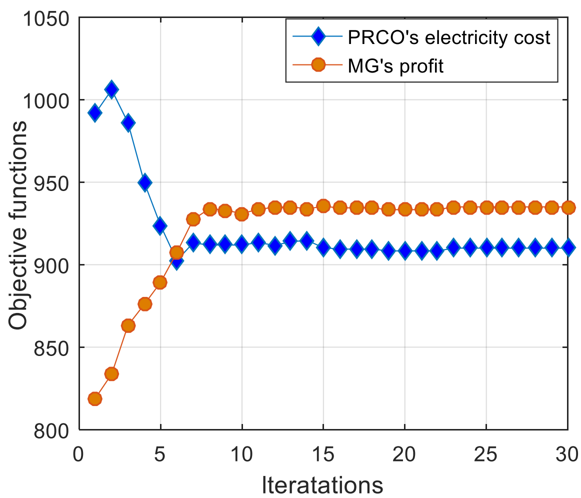

Figure 9. Convergence of objective functions of both participants.

Table 5. Economic benefits of MG with multi-prosumers.

Optimizing Indexes	Without Game Optimization	With Game Optimization
MG's profit (CNY)	771	935
PRCO's electricity cost (CNY)	912	910
Marginal cost of DG (CNY/kWh)	2.2287	1.485
Peak–valley difference (kW)	97.81	67.4
Mean variance of load fluctuation	32.33	17.763

In Figure 9, with the increases in iteration rounds, the objective function value of game participants gradually tends to be stable, and the iteration is terminated in the 30th round. The economic benefits of the MG without game optimization and with game optimization are presented in Table 5. The game optimization improves all indexes with lower electricity costs for prosumers compared with those of the prosumers without the game optimization. The superior results with game optimization are attributed to the incentives of the game scheduling strategy.

6.2.2. Simulations of Energy Scheduling of the MG with a PRCO

The scheduling results of the MG with game optimization are shown in Figure 10. To compare with the proposed game model, Figure 11 shows the scheduling results without game optimization.

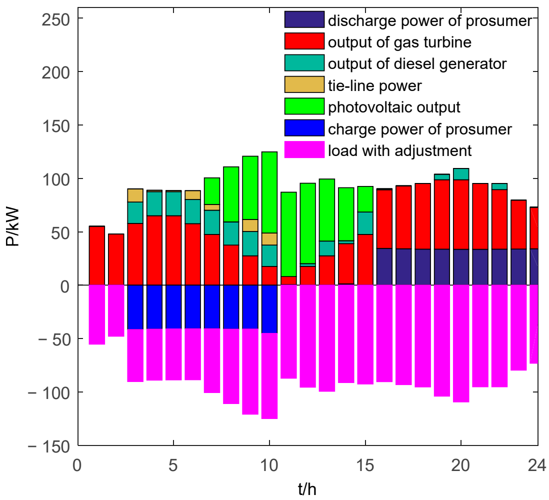

Figure 10. Scheduling curves of the MG with game optimization.

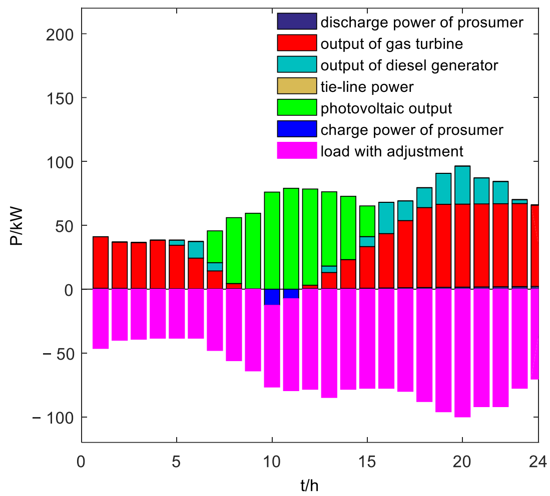

Figure 11. Scheduling curves of the MG without game optimization.

It is illustrated in Figure 10 that the MG encourages the load electricity consumption of the PRCO during 02:00–10:00 (valley price periods), and the demand for charging the ES increases. The MG will compensate for the remaining power shortage after utilizing all PV resources power. Meanwhile, the start up of controllable generation units, in turn, depends on their cost to satisfy the load demand of the PRCO. The generating cost will increase with the increase in the output according to the above Equations (11) and (12); however, the purchase price with the upper grid is constant.

During 10:00–15:00 (flat price periods), the PV power of the PRCO is sufficient with less power shortage, which can alleviate the generation pressure of the controllable generation units in the MG. The start sequence of these units is consistent with that of the valley section.

While the electricity demand of the coalition increases during 15:00–24:00 (peak price periods), the MG stimulates the prosumers' orderly discharging of the ES and adjusts the load strategy to reduce the power demand of MG. The remaining power shortage will be balanced mainly by the output of gas turbine generation.

In Figure 11, charge-discharge operation of the ES in PRCO is almost not working. The scheduling behaviors of the MG are similar, with the flat section shown in Figure 10.

6.2.3. ToU Price with and without Game Optimization

The comparison of the ToU price with and without game scheduling is enumerated in Table 6.

Table 6. Comparison of ToU price (CNY/kWh).

Time Interval	Initial Value without Game Optimization	The Value with Game Optimization
02:00–10:00	0.598	0.492
24:00–02:00, 10:00–15:00	0.795	0.801
15:00–24:00	1.011	1.11

In Table 6, except the periods of 02:00~10:00, the electricity price in other periods increases with game optimization, which is caused by the adjustment of the PRCO. The scheduling resources of prosumers without game optimization are not utilized exhaustively in the process of game optimization. Additional benefits are obtained in the MG by increasing the electricity price. Meanwhile, the prosumers also control the cost of electricity consumption through demand-side response as much as possible. Finally, the electricity price is stabilized at one equilibrium point.

6.3. Comparisons of the PRCO's Cooperation Model

The second simulation case is based on the direct transaction model and the cooperation model for numerical experiments of the PRCO with energy storage sharing.

6.3.1. Comparison of Electricity Consumption Costs

Table 7 shows the total cost calculated by the Shapley value method under different alliance forms. {p1}{p2}{p3}{p4}{p5} means all prosumers are operating individually; {p1,p2,p3,p4,p5} means all prosumers combined into a coalition. The total cost of each coalition is changed with the different form. Through comparative analysis, it can be seen that the total cost under the {p1,p2,p3,p4,p5} coalition form is no more than the cost of any other alliance.

Table 7. Total cost comparison with different coalition forms.

No.	Prosumer Coalition Type	Total Cost/CNY
1	{p1}{p2}{p3}{p4}{p5}	1120.5
2	{p1,p2}{p3}{p4}{p5}	1086.8
3	{p1,p2,p3}{p4}{p5}	1016.3
4	{p1,p2,p3,p4}{p5}	961.7
5	{p1,p2,p3,p5}{p4}	951
6	{p1,p2,p4,p5}{p3}	946.9
7	{p1,p3,p4,p5}{p2}	940.4
8	{p1} {p2,p3,p4,p5}	954.6
9	{p1,p2,p3,p4,p5}	910

The basic economic indicators of the prosumers are shown in Table 8. Meanwhile, the actual cost of each prosumer is calculated in Table 9 according to the Shapley value method for distributing the cooperative residual profits.

Table 8. Comparison of economic indicators of prosumers whether forming into a coalition.

Style	Index	Total
Without Coalition	Cost/CNY	1120.5
	Peak-to-valley difference/kW	87.18
With Coalition	Cost/CNY	910
	Peak-to-valley difference/kW	67.4
Comparison (%)	Cost (%)	18.79%

Table 9. Economic comparison among all kinds of prosumers.

Style	Prosumer 1	Prosumer 2	Prosumer 3	Prosumer 4	Prosumer 5
Without Coalition/CNY	134.9749	178.5697	181.643	285.955	339.357
With Coalition/CNY	110.39	151.53	153.53	236.28	258.27
Comparison/%	18.21%	15.14%	15.48%	17.37%	23.89%

In Table 8, the overall cost of the PRCO is reduced by 18.79% compared with the direct transaction model. It means the overall rationality is achieved and the peak-to-valley difference is reduced from 87.18 kW to 67.4 kW, which is attributed to the energy reciprocity of the PRCO. Specifically, the electricity cost of all prosumers distributed by the SVM is reduced by 18.21%, 15.14%, 15.48%, 17.37% and 23.89%, respectively, and the individual rationality is also achieved, shown in Table 9. Moreover, the resources of the PRCO are utilized to the greatest extent through the complementary sharing of ES among prosumers, and the performance of complementation is reflected obviously.

6.3.2. Discussion of Charging–Discharging Scheduling Obtained by the Cooperation Model

The scheduling results of all prosumers without coalition are shown in Figure 12. After combining into the PRCO, the scheduling results of all prosumers are shown in Figure 13; the sharing power among prosumers in the coalition is shown in Figure 14.

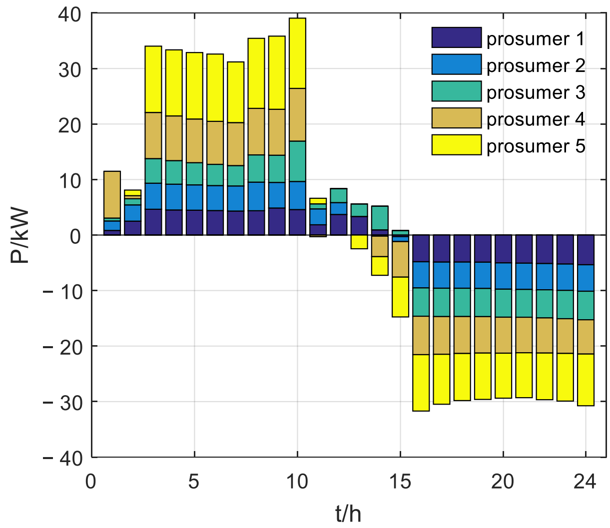

Figure 12. Charging–discharging scheduling of the prosumers without coalition.

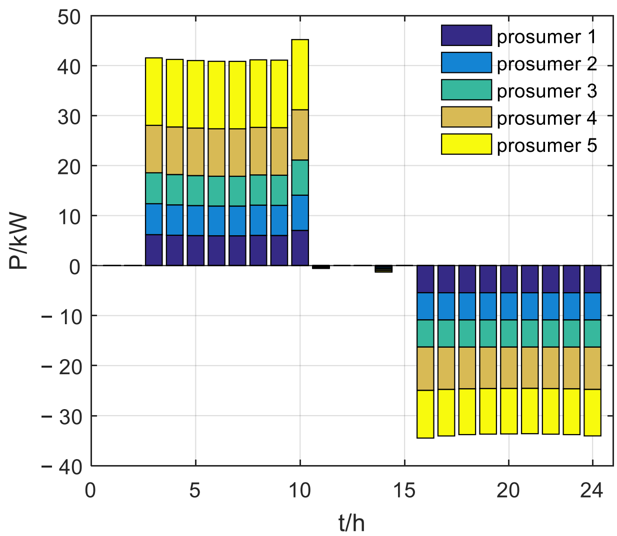

Figure 13. Charging–discharging scheduling of the prosumers with coalition.

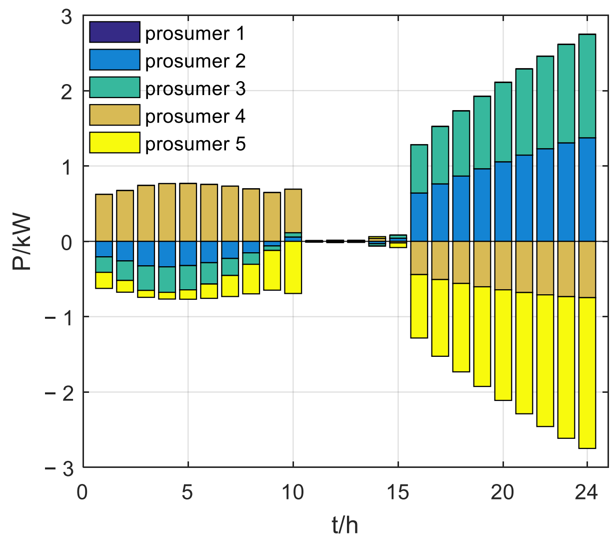

Figure 14. The sharing power between each prosumer and other members.

Although each prosumer has achieved the lowest energy cost through demand-side response, they only coordinate their own scheduling resources without coalition. The performance of scheduling resources in each prosumer is different in each time sequence; thus, the charging–discharging scheduling behaviors for ES are fully disordered, as shown in Figure 12. The charging and discharging behaviors coexist at 10:00–15:00 without energy sharing of prosumers, which may cause the waste of ES resources.

After the prosumers are combined into the PRCO, the ES of each prosumer not only balances their own energy demand, but also participates in the coordination of energy scheduling with other members. The difference in energy scheduling for each member is balanced by sharing electricity from ES in the coalition; charging and discharging cannot coexist at the same time interval, as shown in Figure 13. Moreover, the charging–discharging behaviors for ES in each prosumer are consistent in the whole through energy storage sharing among those prosumers. It can realize the ordered charging–discharging scheduling and promote the overall efficiency of the PRCO.

In Figure 14, the prosumers' sharing power is balanced in each time interval, and the energy reciprocity and mutual compensation is obtained by sharing energy storage resources, and the cost of the PRCO is reduced, as shown in Table 8. The whole balance the PRCO is achieved to obtain the ordered charge and discharge operation of ES.

7. Conclusions

To obtain energy reciprocity and reduce waste of resources due to the chaotic charge–discharge operation in prosumers, an optimal scheduling strategy of microgrids with a development of prosumers' energy sharing based on game theory is proposed in this paper. The conclusions are as follows:

(1) The sharing strategy of ES can be developed by forming a prosumer coalition to obtain the ordered charge–discharge operation and improve the utilization efficiency of ES.
(2) By optimizing the ToU electricity price of the MG, it can effectively guide the PRCO to adjust their energy consumption strategies to be consistent with the load demand trend of the MG, and can ensure the operating income of the MG.
(3) The Shapley method is introduced to distribute the cooperative residual profits by forming a PRCO, and the energy reciprocity of the multi-prosumers is achieved to reduce the cost of electricity consumption for the prosumers.
(4) The higher profits with the lower peak–valley difference can be obtained in the MG by mutual game behaviors between the MG's price and the electricity consumption strategies of the PRCO, and the master–slave game interaction is utilized between the MG and PRCO which can balance the interests of both players.

In the future, the joint operation between multi-microgrids will be further considered, and the impact of multi-microgrid optimization strategies on the revenue of prosumers in the electricity market will be analyzed.

Author Contributions: Conceptualization, X.L. and K.S.; methodology, F.L. and X.L.; software, B.Z.; writing—original draft, F.L.; writing—review and editing, K.S. and F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China under Grant 52077120, the Visiting Research Fund of State Key Laboratory of Water Resources Engineering and Management under Grant 2023SDG02.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

Abbreviations

ES	energy storage.
MG	Microgrid.
PRCO	prosumer coalition.
ToU	time-of-use price.
PV	Photovoltaic.
SVM	Shapley value method.
P_t^{PV}	the actual value of PV output at the time interval t.
$P_t^{\mathrm{PV},f}$	the predicted value of PV output at the time interval t.
δ_t^{PV}	the deviation of PV prediction at the time interval t.
$P_{\mathrm{total}}^{\mathrm{PV}}$	the total installed capacity of the PV.
$\Delta P_{k,t}^{l}$	the residual electricity load of the prosumer k at the time interval t.
$l_{k,t}$	the original load of the prosumer k at the time interval t.
$P_{k,t}^{\mathrm{C}}$	the battery charging power of the prosumer k at the time interval t.
$P_{k,t}^{\mathrm{D}}$	the discharging power of the prosumer k at the time interval t.
m	the number of PV output scenarios.
$P_{k,i,t}^{\mathrm{PV}}$	the PV power of the prosumer k at the time interval t in scenario i.
π_i	the probability of scenario i.
$P_{k,j,t}$	the exchange power transferred from the prosumer k to the prosumer j.
λ_t, θ_t	the selling and buy-back price of the MG at the time interval t.
n	the number of prosumers in the PRCO.
$c_{ess,k}$	the cost coefficient of charging–discharging in prosumer k.
k_{lk}	the preference coefficient of prosumer k.
$l_{k,t}^{\min}, l_{k,t}^{\max}$	the minimum and maximum load value of the prosumer k.
$P_k^{\mathrm{Cap}}, E_k^{\mathrm{Cap}}$	the power capacity and energy capacity of the prosumer k.
$E_{k,t}$	the remaining energy capacity of the prosumer k.
$\mathrm{SOC}_k^{\min}$	the minimal SOC of ES in the prosumer k.
$P_{ex,k,t}$	the exchange power between the prosumer k and other members in the PRCO at the time interval t.
$\eta^{\mathrm{C}}, \eta^{\mathrm{D}}$	the charging and discharging efficiency of the prosumers.
c_t, g_t	the marginal cost and the total output of DGs in the MG at the time interval t.
$p_{x,t}, P_{tie,t}$	the trading price and the trading power between the MG and the upper grid at the time interval t.
$C_{\mathrm{DE}}, C_{\mathrm{MT}}$	the cost models of a diesel generator and gas turbine.
$P_{\mathrm{DE},t}$	the output of the diesel generator at the time interval t.
k_{DE}	the operation cost coefficient of the diesel generator at the time interval t.
α, β and γ	the cost coefficients of diesel generators.
C_{fuel}, LHV	the price and the low calorific value of natural gas.
$P_{\mathrm{MT},t}, \eta_t$	the net output power and the unit efficiency of the gas turbine.
k_{MT}	the cost coefficient related to the operation and maintenance of the gas turbine.
$P_{\mathrm{MT}}^{\min}, P_{\mathrm{MT}}^{\max}$	the minimum and maximum power of the gas turbine.
$\Delta P_{\mathrm{MT}}^{\max}$	the maximum climbing power of the gas turbine.
$P_{\mathrm{DE}}^{\min}, P_{\mathrm{DE}}^{\max}$	the minimum and maximum power of the diesel generator.
$\Delta P_{\mathrm{DE}}^{\max}$	the maximum climbing power of the diesel generator.
$\Delta P_{l,t}$	the residual electricity load of the prosumer coalition at the time interval t.
C_{ope}	the electricity selling profits of the MG.
$P_{tie}^{\max}$	the maximum power that can be transmitted from the distribution network.
$\lambda_t^{\max}$	the upper limit of the price for selling electricity in the MG.
l_t	the load power of the PRCO at the time interval t.
l_i	the load power of the PRCO at the time interval i.
l_t^*	the optimal load power of the PRCO at the time interval t.
λ_t^*	the optimal price of the MG at the time interval t.
k_l	the preference coefficient of the PRCO.
$l_t^{\min}, l_t^{\max}$	the minimum and maximum load value of the PRCO.
$P_{i,t}^{\mathrm{PV}}$	the PV power of the PRCO at the time interval t in scenario i.
P_t^{D}	the battery charging power of the PRCO at the time interval t.
P_t^{C}	the battery discharging power of the PRCO at the time interval t.

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