energies

Article

Optimization Dispatch of Distribution Network–Prosumer Group–Prosumer Considering Flexible Reserve Resources of Prosumer

Hao Zhong [1,2], Lanfang Li [1,2,*], Qiujie Wang [1,2], Xueting Wang [2] and Xinghuo Wang [2]

[1] Hubei Provincial Key Laboratory for Operation and Control of Cascaded Hydropower Station, China Three Gorges University, Yichang 443002, China; zhonghao022@163.com (H.Z.); 2025cdc@ctgu.edu.cn (Q.W.)
[2] College of Electrical Engineering & New Energy, China Three Gorges University, Yichang 443002, China; chief1999@163.com (X.W.); lilanfang0012@163.com (X.W.)
* Correspondence: xxfang@ctgu.edu.cn

Abstract: The bidirectional uncertainty of source and load creates scarcity in the reserve resources of the distribution network. Therefore, it is highly significant for the safe and economic operation of the system to harness spare energy storage capacity from prosumers to provide reserves. This paper proposes a bi-layer optimal scheduling model of "distribution network–prosumer group–prosumer" that considers the flexible reserve resources of a prosumer. The upper layer is the "distribution network–prosumer group" optimization model, in which the distribution network sets the electricity price and reserve price according to its own economic benefit and sends it to the prosumer group and guides it to participate in the scheduling of the resources of the prosumer. The lower layer is the "prosumer group–prosumer" optimization model, where the prosumer group incentivizes the prosumer to adjust its energy storage charging and discharging plans through prices and mobilize its own resources to provide flexible reserve resources. The results show that the optimal method proposed in this paper can fully utilize flexible reserve resources from prosumers, improve the economy of distribution network operations, and reduce the pressure of providing reserves using the upper grid.

Keywords: prosumer; energy storage; flexible reserve; bi-level optimization; price

check for updates

Citation: Zhong, H.; Li, L.; Wang, Q.; Wang, X.; Wang, X. Optimization Dispatch of Distribution Network–Prosumer Group–Prosumer Considering Flexible Reserve Resources of Prosumer. *Energies* **2024**, *17*, 5731. https://doi.org/10.3390/en17225731

Academic Editor: Ahmed Abu-Siada

Received: 28 October 2024
Revised: 11 November 2024
Accepted: 12 November 2024
Published: 15 November 2024

1. Introduction

In the context of "carbon peak" and "carbon neutrality", large-scale new energy installations are being connected to the grid and are gradually transitioning from supplementary power to main power [1,2]. Due to the new energy output being susceptible to the environment, weather, and other natural factors, the load in the distribution network also has the same uncertainty [3,4]. The uncertainty on the source–load side of the distribution network is significantly enhanced, and system power balance regulation faces more severe challenges [5]. In the actual operation of the system, the reasonable reservation and scheduling of rotating reserves is the main measure used to effectively cope with the two-way source–load side uncertainty. However, in the past, the reserve demand was usually met only by thermal power units in the upper grid, which has limited regulation capabilities, lacks environmental protection and has difficulty meeting the current flexibility demand of the system [6]; therefore, fully exploiting the flexibility of the reserve resources to participate in system regulation and improve the security and economy of distribution network operations is an urgent problem to be solved.

The widespread use of distributed photovoltaics (PVs) and energy storage systems (ESSs) on the load side has transformed the traditional grid end-user into a prosumer with two-way energy interaction characteristics [7], enabling the user to satisfy their own electricity demand while selling the surplus electricity to the distribution network [8]. In the process of system operations, the problem of uncertainty in the output of wind turbines (WTs) and PVs should be considered first. To address this problem, many scholars have already conducted research. The stochastic programming method of convex models proposed in [9] can generate multiple typical scenarios by considering the uncertainty of PV and WT output and establish the corresponding optimization model. The authors of [10] describe the uncertainty of PV, WT, and load prediction errors based on a Gaussian stochastic distribution probability model. The authors of [11] propose a method for constructing wind power probability distribution based on principal component analysis and kernel density estimation that effectively characterizes the uncertainty of wind power output.

Energy storage, as an important device supporting the flexible operation of the distribution network, has better responsiveness and operates more flexibly than a thermal power unit, which is a flexible reserve resource [12,13]. At present, the use of energy storage to provide reserves has become a hot research topic, and many scholars have studied it. The authors of [14] studied the multi-operation mode of energy storage in the consumption of wind power while participating in the market of electric energy and backup auxiliary services. The authors of [15] considered the economic benefits under two application scenarios, energy storage arbitrage and providing reserves, and optimally allocated the capacity and power of energy storage. The authors of [16] proposed a bidding decision method for wind storage plants in the electric energy and reserve market based on the modeling of the residual demand curve to achieve the maximum return of wind storage plants. The above studies mainly consider centralized energy storage on the source side in order to provide reserve resources, and there are fewer studies on tapping the reserve potential of decentralized energy storage on the user side.

The Notice on the Pilot of Market-based Trading of Distributed Generation issued by the National Energy Administration (NEA) provides policy support for the development of user-side market-based trading [17]. However, due to the stochastic and fluctuating nature of production and prosumer production, individual resources are limited and more dispersed, making it difficult to directly participate in market scheduling [18,19]. In this context, the prosumer group is introduced as an intermediate coordination layer to aggregate the resources of prosumers in a certain area to participate in the electric energy and reserve market, and the prosumers can carry out power mutualization with the distribution network through the prosumer group so as to realize the resource allocation of the system in a more reasonable way.

In [20], the load aggregator quantifies the integration of prosumer resources, and the distribution system operator (DSO) guides the aggregator to make power adjustments through the price so as to realize the optimal dispatch of prosumer resources; however, the integrated resources only include the purchased and sold power of prosumers. The authors of [21] constructed a power pricing mechanism using blockchain for the transactions between prosumers and operators, incentivizing the power transactions between prosumers and operators via the internal electricity price to maximize the interests of both prosumers and operators; however, the impact of the energy storage of prosumers on the optimization of system reserve resources is not considered. The authors of [22] constructed a two-layer optimization model of the DSO and aggregator by exploiting the resource regulation potential of the demand side through a load aggregator, ignoring the interests of the customers managed by the aggregator, and the aggregator does not effectively integrate the customer-side flexibility reserve resources. The above literature only studies the participation of prosumers in the electric energy market, and less research has been conducted on the consideration of the coupling relationship between electric energy and reserves and the simultaneous participation of consumers in the electric energy and reserve markets.

Based on the above analysis, this paper establishes a "distribution network–prosumer group–prosumer" optimal scheduling model for electric energy and reserves based on distribution network–prosumer group–prosumer-distributed ESSs to provide flexible reserves. Among them, the upper layer is the "distribution network–prosumer group" optimization model, where each prosumer group adjusts the transaction strategy with the distribution network according to the electricity price set by the DSO; the lower layer is the "prosumer group–prosumer" optimization model, where the prosumer group guides the prosumers to adjust the charging and discharging plan of the ESS through the price. Finally, the effectiveness of the proposed method is verified by case analysis.

2. Bi-Level Optimized Scheduling Framework

2.1. Framework of the "Distribution Network–Prosumer Group–Prosumer" Model

The structure of the distribution network system containing multiple prosumers is shown in Figure 1.

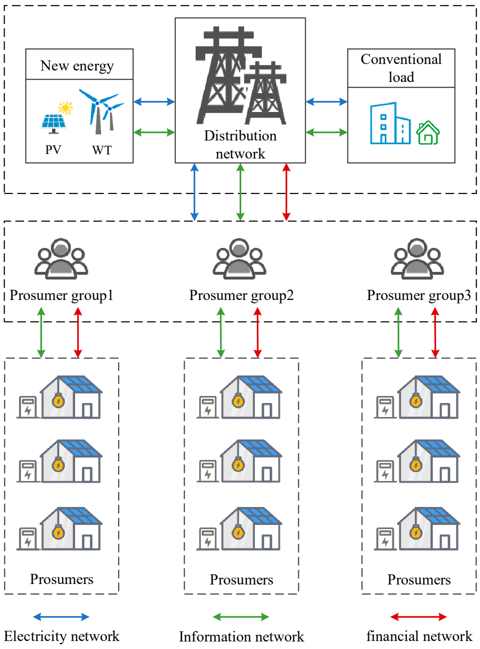


Figure 1. Schematic of "distribution network–prosumer group–prosumer".

The distribution network contains new energy generation systems such as WT and PV, as well as conventional loads. The prosumers are connected to the distribution network at different locations, and the prosumers in the same area are aggregated by the corresponding prosumer groups and interact with the distribution network. Due to the deviation between the actual power of new energy sources and loads and the predicted value, rotating reserves need to be introduced to balance this uncertain power deviation. Both the distribution network and prosumers have reserve requirements. Under the guidance of the prosumer group, the prosumers utilize energy storage to provide reserves for themselves and also provide reserves to the distribution network, and the rest of the reserve requirements of the distribution network are satisfied by purchasing from the upper grid.

2.2. Bi-Layer Optimization Model of Distribution Network with Prosumers

This paper proposes a bi-layer optimal scheduling model containing distribution network–prosumer group–prosumer group, as shown in Figure 2. Firstly, the DSO sets the power purchase price and reserve price, and sends them to the prosumer group. The prosumer group aggregates prosumer resources based on the price information from the DSO, and determines the amount of electricity, reserve capacity and price for the prosumer group when trading with prosumers within the group. Then, the prosumer group transmits the aggregated prosumer information to the DSO, which then updates the issued electricity price and reserve price according to the received information. Finally, the two layers form a closed-loop iteration to realize the optimal distribution network–prosumer group–prosumer of the electricity and reserve.

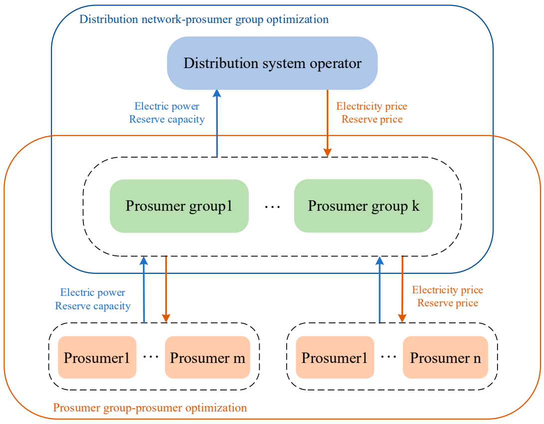


Figure 2. Bi-level optimization model of distribution network with prosumers.

3. Models

3.1. "Distribution Network–Prosumer Group" Optimization Model

3.1.1. Objective Function of Distribution Network

The goal of the DSO is the minimization of its own comprehensive operating cost, and the development of the electricity price and the reserve price issued to prosumer groups. The objective function is shown in Equation (1) (the following equations are omitted at scheduling intervals Δt):

$$U^{\mathrm{D}} = C^{\mathrm{N}} + C^{\mathrm{buy}} - C^{\mathrm{sell}} \tag{1}$$

where U^{D} is the comprehensive operation cost of the DSO. In this paper, 24 h before, the day is divided into T time periods, and T is taken as 24. C^{N}, C^{buy} and C^{sell} are the operation and maintenance costs of WTs and PVs in the distribution network, the energy purchase cost of the DSO, and the sales revenue, respectively, as shown in Equations (2)–(4).

$$C^{\mathrm{N}} = \sum_{t=1}^{T} \left(\sum_{i=1}^{I} P_{i,t}^{\mathrm{PV}} \gamma^{\mathrm{PV}} + \sum_{j=1}^{J} P_{j,t}^{\mathrm{WT}} \gamma^{\mathrm{WT}} \right) \tag{2}$$

where I and J are the number of PVs and WTs; $P_{i,t}^{\mathrm{PV}}$ and $P_{j,t}^{\mathrm{WT}}$ are the predicted outputs of PV i and WT j in the distribution network in time period t; and γ^{PV} and γ^{WT} are the operation and maintenance cost coefficients of PVs and WTs.

$$C^{\mathrm{buy}} = \sum_{t=1}^{T} \left[P_t^{\mathrm{grid}} c_t^{\mathrm{p}} + R_t^{\mathrm{grid,up}} c_t^{\mathrm{r,up}} + R_t^{\mathrm{grid,dn}} c_t^{\mathrm{r,dn}} + \sum_{k=1}^{K} \left(P_{k,t}^{\mathrm{d}} s_t^{\mathrm{dp}} + R_{k,t}^{\mathrm{d,up}} s_t^{\mathrm{dr,up}} + R_{k,t}^{\mathrm{d,dn}} s_t^{\mathrm{dr,dn}} \right) \right] \tag{3}$$

where P_t^{grid} is the power purchased from the upper grid by the DSO in time period t; $R_t^{\mathrm{grid,up}}$ and $R_t^{\mathrm{grid,dn}}$ are the upper and lower reserve capacities purchased from the upper grid by the DSO in time period t; c_t^{p}, $c_t^{\mathrm{r,up}}$ and $c_t^{\mathrm{r,dn}}$ are the electricity prices sold by the upper grid and the upper and lower reserve price in time period t, respectively; $P_{k,t}^{\mathrm{d}}$ is the power sold by the prosumer group k in time period t; $R_{k,t}^{\mathrm{d,up}}$, $R_{k,t}^{\mathrm{d,dn}}$ are the upper and lower reserve capacities provided by the prosumer group k in time period t; and s_t^{dp}, $s_t^{\mathrm{dr,up}}$ and $s_t^{\mathrm{dr,dn}}$ are the electricity price and the upper and lower reserve prices set by the DSO during time period t.

$$C^{\mathrm{sell}} = \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{n=1}^{N} \left(P_{k,n,t}^{\mathrm{s}} s_t^{\mathrm{p}} + R_{k,n,t}^{\mathrm{s,up}} s_t^{\mathrm{r,up}} + R_{k,n,t}^{\mathrm{s,dn}} s_t^{\mathrm{r,dn}} \right) \tag{4}$$

where K and N are the number of prosumer groups and prosumers; $P_{k,n,t}^{\mathrm{s}}$ is the purchased power of the prosumer n in the prosumer group k in time period t; $R_{k,n,t}^{\mathrm{s,up}}$ and $R_{k,n,t}^{\mathrm{s,dn}}$ are the upper and lower reserve capacities purchased by the prosumer n in time period t; and s_t^{p},

$s_t^{\mathrm{r,up}}$ and $s_t^{\mathrm{r,dn}}$ are the electricity price and the upper and lower reserve price of the DSO in time period t.

3.1.2. Constraints

(1) Power balance constraint

The output power of the new energy source and the power supplied to the DSO by the upper grid and the prosumer groups shall be equal to the sum of the power used by the conventional loads in the distribution network and the power sold by the DSO to the prosumer groups.

$$P_t^{\mathrm{grid}} + \sum_{j=1}^{J} P_{j,t}^{\mathrm{WT}} + \sum_{k=1}^{K} P_{k,t}^{d} = P_t^{\mathrm{L}} + P_t^{s} \tag{5}$$

where P_t^{L} is the total power consumption of conventional loads in the distribution network, and P_t^{s} is the total power sold by the DSO to prosumers.

(2) Distribution network reserve requirement constraints

$$R_t^{\mathrm{grid,up}} + \sum_{k=1}^{K} R_{k,t}^{\mathrm{d,up}} - \sum_{k=1}^{K}\sum_{n=1}^{N} R_{k,n,t}^{\mathrm{s,up}} \geq F_t^{\mathrm{d,up}} \tag{6}$$

$$R_t^{\mathrm{grid,dn}} + \sum_{k=1}^{K} R_{k,t}^{\mathrm{d,dn}} - \sum_{k=1}^{K}\sum_{n=1}^{N} R_{k,n,t}^{\mathrm{s,dn}} \geq F_t^{\mathrm{d,dn}} \tag{7}$$

where $F_t^{\mathrm{d,up}}$ and $F_t^{\mathrm{d,dn}}$ are the upper and lower reserve capacities required by the net load in the distribution network in time period t. The reserve requirement of the distribution network is determined based on the Monte Carlo method after describing the probability density curves of the new energy and load forecast errors [23].

(3) Contact line constraints

The interaction of the DSO with the upper grid and the prosumer group is realized through the contact line. Therefore, it is necessary to limit the amount of power interacting between the DSO and the upper grid and prosumer groups to the upper limit of the transmission capacity of the contact line.

$$P_t^{\mathrm{grid}} + R_t^{\mathrm{grid,up}} - R_t^{\mathrm{grid,dn}} \leq \overline{P}^{\mathrm{d}} \tag{8}$$

$$P_{k,t}^{\mathrm{d}} + R_{k,t}^{\mathrm{d,up}} - R_{k,t}^{\mathrm{d,dn}} \leq \overline{P}^{\mathrm{k}} \tag{9}$$

where $\overline{P}^{\mathrm{d}}$ is the upper limit of transmission capacity in the contact line between the DSO and the upper grid, and $\overline{P}^{\mathrm{k}}$ is the upper limit of transmission capacity between the prosumer group k and the DSO.

(4) Electricity price constraints

The price set by the DSO for transactions with the prosumer groups should be more attractive than the price at which it trades with the upper grid.

$$\begin{cases} s_t^{\mathrm{dp}} < c_t^{\mathrm{p}} \\ s_t^{\mathrm{dr,up}} < c_t^{\mathrm{r,up}} \\ s_t^{\mathrm{dr,dn}} < c_t^{\mathrm{r,dn}} \end{cases} \tag{10}$$

3.2. "Prosumer Group–Prosumer" Optimization Model

3.2.1. Objective Function of Prosumer Group

The prosumer group, as an intermediate link connecting the DSO and the prosumers, seeks to gain revenue from the tariff difference in the electric energy and reserve markets.

The objective function of the prosumer group is to maximize its own comprehensive revenue, as shown in Equations (11)–(13):

$$U_k^{\mathrm{Q}} = C_k^{\mathrm{sell}} - C_k^{\mathrm{buy}} \tag{11}$$

$$C_k^{\mathrm{sell}} = \sum_{t=1}^{T} \left(P_{k,t}^{\mathrm{d}} s_t^{\mathrm{dp}} + R_{k,t}^{\mathrm{d,up}} s_t^{\mathrm{dr,up}} + R_{k,t}^{\mathrm{d,dn}} s_t^{\mathrm{dr,dn}} \right) \tag{12}$$

$$C_k^{\mathrm{buy}} = \sum_{n=1}^{N} \sum_{t=1}^{T} \left(P_{k,n,t}^{\mathrm{b}} s_{k,t}^{\mathrm{bp}} + R_{k,n,t}^{\mathrm{b,up}} s_{k,t}^{\mathrm{br,up}} + R_{k,n,t}^{\mathrm{b,dn}} s_{k,t}^{\mathrm{br,dn}} \right) \tag{13}$$

where U_k^{Q} is the consolidated revenue of the prosumer group k; C_k^{sell} is the revenue of the prosumer group k for supplying electricity and reserve to the DSO; C_k^{buy} is the total cost of the prosumer group k for purchasing electricity and reserve capacity from prosumers; $P_{k,n,t}^{\mathrm{b}}$ is the power purchased by the prosumer group k from the prosumer n during time period t; $R_{k,n,t}^{\mathrm{b,up}}$ and $R_{k,n,t}^{\mathrm{b,dn}}$ are the reserve capacity provided by the prosumer n to the prosumer group k in time period t; $s_{k,t}^{\mathrm{bp}}$ is the price of electricity set by the prosumer group k in time period t; and $s_{k,t}^{\mathrm{br,up}}$ and $s_{k,t}^{\mathrm{br,dn}}$ are the upper and lower reserve prices set by the prosumer group k in time period t.

3.2.2. Objective Function of Prosumer

The prosumer develops the charging and discharging strategy for ESSs with the objective of minimizing the combined cost of electricity after participation in the electric energy and reserve markets. The objective function is shown in Equations (14)–(16):

$$U_{k,n}^{\mathrm{H}} = C_{k,n}^{\mathrm{zc}} - C_{k,n}^{\mathrm{hb}} + \sum_{t=1}^{T} [P_{k,n,t}^{\mathrm{RPV}} \gamma^{\mathrm{p}} + (P_{k,n,t}^{\mathrm{ess,c}} + P_{k,n,t}^{\mathrm{ess,d}} + R_{k,n,t}^{\mathrm{ess,\ dn}} + R_{k,n,t}^{\mathrm{ess,\ up}}) \gamma^{\mathrm{ess}}] \tag{14}$$

$$C_{k,n}^{\mathrm{zc}} = \sum_{t=1}^{T} \left(P_{k,n,t}^{\mathrm{s}} s_t^{\mathrm{p}} + R_{k,n,t}^{\mathrm{s,up}} s_t^{\mathrm{r,up}} + R_{k,n,t}^{\mathrm{s,dn}} s_t^{\mathrm{r,dn}} \right) \tag{15}$$

$$C_{k,n}^{\mathrm{hb}} = \sum_{t=1}^{T} \left(P_{k,n,t}^{b} s_{k,t}^{\mathrm{bp}} + R_{k,n,t}^{\mathrm{b,up}} s_{k,t}^{\mathrm{br,up}} + R_{k,n,t}^{\mathrm{b,dn}} s_{k,t}^{\mathrm{br,dn}} \right) \tag{16}$$

where $U_{k,n}^{\mathrm{H}}$ is the combined cost of electricity consumption of the prosumer; $C_{k,n}^{\mathrm{hb}}$ is the return obtained by prosumer n from selling excess electricity and reserve; $C_{k,n}^{\mathrm{zc}}$ is the cost of purchasing electricity and reserve for prosumer n; $P_{k,n,t}^{\mathrm{RPV}}$ is the predicted output of the rooftop PV of prosumer n in time period t and γ^{p} is the cost of rooftop PV per unit of active output; $P_{k,n,t}^{\mathrm{ess,\ c}}$ and $P_{k,n,t}^{\mathrm{ess,\ d}}$ are the day-ahead charging and discharging power of the ESSs; $R_{k,n,t}^{\mathrm{ess,\ up}}$ and $R_{k,n,t}^{\mathrm{ess,\ dn}}$ are the upper and lower reserve capacities provided by the ESSs; and γ^{ess} is the unit charging and discharging cost of the ESSs.

3.2.3. Constraints

(1) Constraints on the purchase and sale of electricity and reserve by the prosumer

$$P_{k,n,t}^{\mathrm{b}} \cdot P_{k,n,t}^{\mathrm{s}} = 0 \tag{17}$$

$$R_{k,n,t}^{\mathrm{b,up}} \cdot R_{k,n,t}^{\mathrm{s,up}} = R_{k,n,t}^{\mathrm{b,up}} \cdot R_{k,n,t}^{\mathrm{s,dn}} = 0 \tag{18}$$

Equation (17) indicates that the prosumer will not purchase and sell electricity at the same time during the same period of time. Equation (18) indicates that the prosumer will not purchase and sell reserves at the same time during the same period of time.

(2) Power balance constraints for prosumer

$$P_{k,n,t}^{\mathrm{s}} + P_{k,n,t}^{\mathrm{RPV}} + P_{k,n,t}^{\mathrm{ess,d}} - P_{k,n,t}^{\mathrm{ess,c}} = P_{k,n,t}^{\mathrm{L}} + P_{k,n,t}^{\mathrm{b}} \tag{19}$$

where $P_{k,n,t}^{\mathrm{L}}$ is the predicted power consumption of the loads of prosumer n in prosumer group k during the time period t.

(3) Prosumer reserve requirement constraints

$$R_{k,n,t}^{\mathrm{s,up}} + R_{k,n,t}^{\mathrm{ess,\ up}} \geq F_{k,n,t}^{\mathrm{up}} + R_{k,n,t}^{\mathrm{b,up}} \tag{20}$$

$$R_{k,n,t}^{\mathrm{s,dn}} + R_{k,n,t}^{\mathrm{ess,\ dn}} \geq F_{k,n,t}^{\mathrm{dn}} + R_{k,n,t}^{\mathrm{b,dn}} \tag{21}$$

where $F_{k,n,t}^{\mathrm{up}}$ and $F_{k,n,t}^{\mathrm{dn}}$ are the upper and lower reserve demands of the prosumer n.

(4) Operation constraints of ESS

The charging and discharging power constraints for the ESSs are shown below:

$$0 \leqslant P_{k,n,t}^{\mathrm{ess,\ d}} \leqslant u_{k,n,t}^{\mathrm{p}} P_{k,n,\max}^{\mathrm{ess,d}} \tag{22}$$

$$0 \leqslant P_{k,n,t}^{\mathrm{ess,\ c}} \leqslant \left(1 - u_{k,n,t}^{\mathrm{p}}\right) P_{k,n,\max}^{\mathrm{ess,c}} \tag{23}$$

$$E_{k,n,t} = E_{k,n,t-1} + \eta^{\mathrm{c}} P_{k,n,t}^{\mathrm{ess,c}} - \frac{1}{\eta^{\mathrm{d}}} P_{k,n,t}^{\mathrm{ess,d}} \tag{24}$$

$$E_{k,n,\min} \leq E_{k,n,t} \leq E_{k,n,\max} \tag{25}$$

$$E_{k,n,0} = E_{k,n,T} \tag{26}$$

where $P_{k,n,\max}^{\mathrm{ess,c}}$ and $P_{k,n,\max}^{\mathrm{ess,d}}$ are the maximum permissible charging and discharging power of the ESSs; η^{c} and η^{d} are the charging and discharging efficiencies of the ESSs; $u_{k,n,t}^{\mathrm{p}}$ is the charging and discharging state of the ESSs in time period t, which is discharging when it is 1 and charging when it is 0; $E_{k,n,t}$ is the residual energy of the ESSs in time period t; and $E_{k,n,\min}$ and $E_{k,n,\max}$ are the minimum and maximum values of the residual energy of the ESSs.

The power constraints needed for the ESSs to provide reserves are shown below:

$$0 \leqslant R_{k,n,t}^{\mathrm{ess,\ up}} \leqslant u_{k,n,t}^{\mathrm{r}} P_{k,n,\max}^{\mathrm{ess,d}} \tag{27}$$

$$0 \leqslant R_{k,n,t}^{\mathrm{ess,\ dn}} \leqslant \left(1 - u_{k,n,t}^{\mathrm{r}}\right) P_{k,n,\max}^{\mathrm{ess,c}} \tag{28}$$

$$E_{k,n,t}^{\mathrm{R}} = E_{k,n,t-1}^{\mathrm{R}} + \eta^{\mathrm{c}} \left(P_{k,n,t}^{\mathrm{ess,c}} + R_{k,n,t}^{\mathrm{ess,\ dn}}\right) - \frac{1}{\eta^{\mathrm{d}}} \left(P_{k,n,t}^{\mathrm{ess,d}} + R_{k,n,t}^{\mathrm{ess,\ up}}\right) \tag{29}$$

$$E_{k,n,\min} \leq E_{k,n,t}^{\mathrm{R}} \leq E_{k,n,\max} \tag{30}$$

$$E_{k,n,0}^{\mathrm{R}} = E_{k,n,T}^{\mathrm{R}} \tag{31}$$

$$0 \leq P_{k,n,t}^{\mathrm{ess,d}} + R_{k,n,t}^{\mathrm{ess,\ up}} \leq P_{k,n,\max}^{\mathrm{ess,d}} \tag{32}$$

$$0 \leq P_{k,n,t}^{\mathrm{ess,c}} + R_{k,n,t}^{\mathrm{ess,\ dn}} \leq P_{k,n,\max}^{\mathrm{ess,c}} \tag{33}$$

where $u_{k,n,t}^{\mathrm{r}}$ is the reserve state of the ESSs in time period t, where 1 refers to the provision of upper reserves and 0 refers to the provision of lower reserves; and $E_{k,n,t}^{\mathrm{R}}$ is the residual energy in time period t after taking into account the charging and discharging plan and the reserve capacity.

Equations (22), (23), (27) and (28) represent the ESS charging and discharging power constraints; Equations (24), (25), (29) and (30) represent the residual energy constraints;

Equations (26) and (31) denote that the residual energy is equal at the beginning and end moments; and Equations (32) and (33) represent the joint operation constraints of the charging and discharging plan and the reserve arrangement.

4. Solution Methodology

The distribution network–prosumer group optimization model and the prosumer group–prosumer optimization model constructed in this paper are coupled and contain nonlinear constraints, which are difficult to solve directly. In this paper, the model is transformed by the Karush–Kuhn–Tucker (KKT) method [24,25], which turns the prosumer model into the constraints of the prosumer group model. Then, the transformed nonlinear terms are linearized by the big-M method to form a two-layer mixed-integer linear programming problem. The upper and lower layers of the transformed model have the prices set by the DSO and the interacting electric power and reserve capacity are set as coupling variables. The lower layer is solved by the solver Gurobi, and the upper layer is solved iteratively by the improved particle swarm algorithm. The solution process is shown in Figure 3, and the specific steps are as follows:

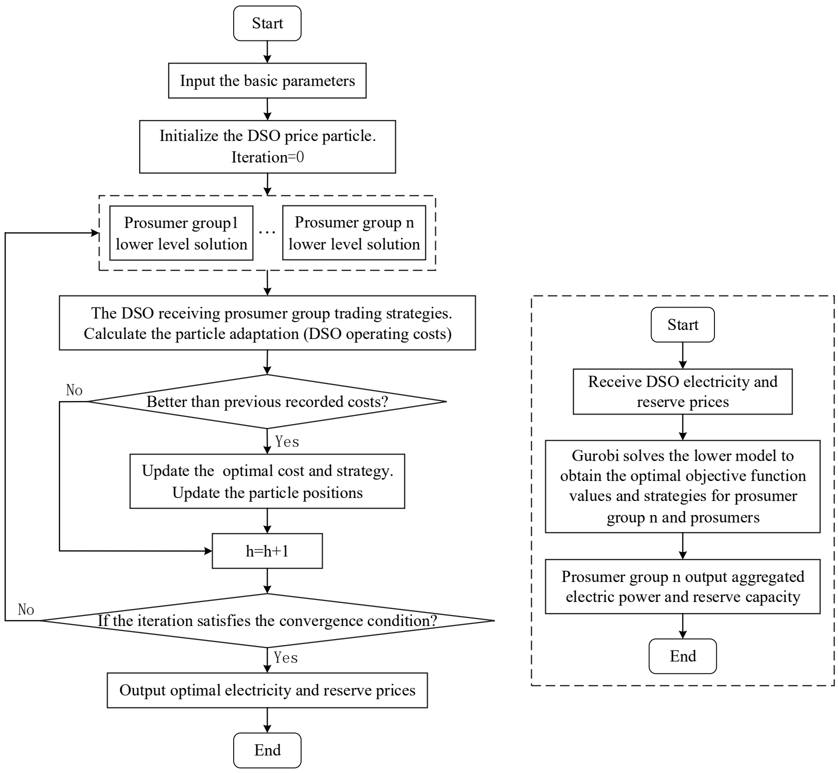


Figure 3. Flowchart of solving process.

Step 1: Input various basic parameters of the upper grid, distribution network and prosumers.

Step 2: Generate the initial electricity price particle according to the constraints of the distribution network layer.

Step 3: Use the Gurobi solver to determine the electric power and reserve capacity of the prosumers aggregated in the prosumer group under the DSO electricity price and reserve price at this time.

Step 4: After the DSO receives the trading strategy of the prosumer groups, calculate the updated particle adaptation, which is the updated DSO operating cost.

Step 5: Determine whether the DSO operating cost at this time is better than the previous calculation. If no, increase the number of iterations by one. If yes, update the optimal cost and optimal strategy, and update the optimal particle location.

Step 6: Judge whether the number of iterations satisfies the convergence condition. If no, return to step 3. If yes, output the optimal result.

5. Case Study

5.1. Case Introduction

Based on the predicted power of WT and PV and the load of a regional power grid, the arithmetic system constructed by combining the characteristics of the model is as follows:

The installed capacities of PV and WT accessed in the distribution network are 800 kW and 1500 kW, respectively, and the WT and PV operation and maintenance cost coefficient is 0.255 yuan/(kWh) [21]. The new energy and load data of the distribution network are shown in Figure 4 [26].

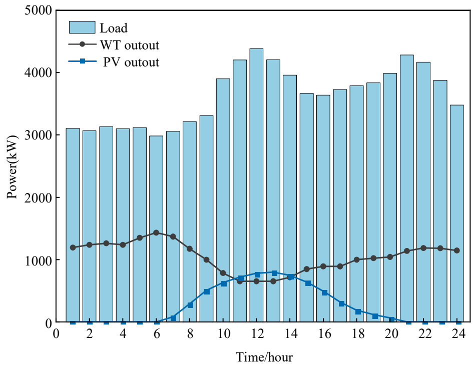


Figure 4. New energy and load data for distribution network.

In this paper, the optimal scheduling period is taken as 1 day and divided into 24 time periods. The electricity price of the DSO is the peak and valley levelized price [27], as shown in Table 1. The prices of the upper reserve and lower reserve are 0.9 yuan/(kWh) and 0.6 yuan/(kWh), respectively.

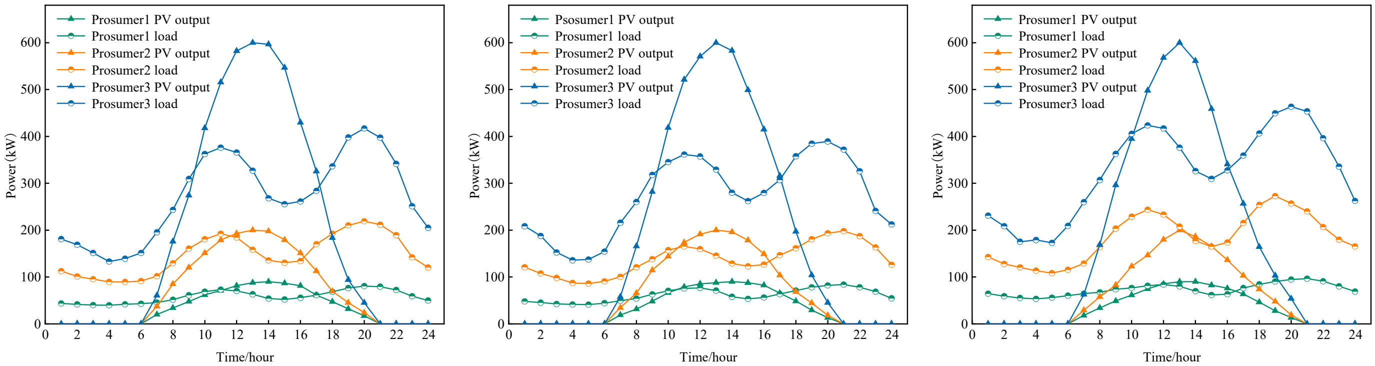
Table 1. Time-of-use price of DSO.

Period	Time Period	Electricity Price/(yuan/(kWh))
Peak period	08:00–12:00; 18:00–22:00	0.83
Off-peak period	07:00–08:00; 12:00–18:00	0.49
Valley period	00:00–07:00; 22:00–24:00	0.17

Three prosumer groups are connected to the distribution network through contact lines at different nodes, and each prosumer group contains three prosumers with installed rooftop PV capacities of 90 kW, 200 kW, and 600 kW, respectively. The power generation cost of rooftop PV is 0.2 yuan/(kWh). The parameters of the ESS within each prosumer are shown in Table 2 [28–30]. The PV output and load data of the prosumers in each prosumer group are shown in Figure 5.

Table 2. Parameters of ESS within each prosumer.

	ESS1	ESS2	ESS3
Capacity (kWh)	50	200	500
$\eta^{\mathrm{c}}/\eta^{\mathrm{d}}$	0.95	0.95	0.95
$P^{\mathrm{ess,c}}_{k,n,\max}$ (kW)	20	80	200
$P^{\mathrm{ess,d}}_{k,n,\max}$ (kW)	20	80	200
$E_{k,n,\min}$ (kWh)	2.5	10	25
$E_{k,n,\max}$ (kWh)	47.5	190	475
$E^{\mathrm{R}}_{k,n,0}$ (kWh)	15	50	125
γ^{ess} (yuan/(kWh))	0.018	0.018	0.018



(a) PV and load data for prosumer group1 (b) PV and load data for prosumer group2 (c) PV and load data for prosumer group3

Figure 5. PV and load data for prosumer groups.

5.2. Optimization Results for DSO Price and Reserve

The DSO sets electricity prices and reserve prices to be sent down to the prosumer group, as shown in Figure 6. During 01:00~09:00, 14:00~18:00 and 23:00~24:00, the lower reserve demand is slightly higher than the upper reserve demand. Therefore, the DSO guides the prosumer group to aggregate the lower reserve resources of the prosumers with a higher lower reserve price. The consumption of load electricity is relatively small at this time, so the electricity price is low. The upper reserve price increases significantly during the afternoon peak hours from 10:00 to 13:00 and the evening peak hours from 19:00 to 22:00. Due to the large PV output during the midday peak hour and the large WT output during the evening peak hour, the upper reserve demand of the distribution network increases significantly. Therefore, the DSO sets higher reserve prices for prosumer groups and aggregates the reserve resources of prosumers. At the same time, due to the high load power consumption and the higher reserve price on the main network than on the electricity price, the DSO sets a higher electricity price that is lower than the upper reserve price. In this case, the DSO chooses to prioritize reserve trading with the prosumer group in order to improve the economy of its own operation.

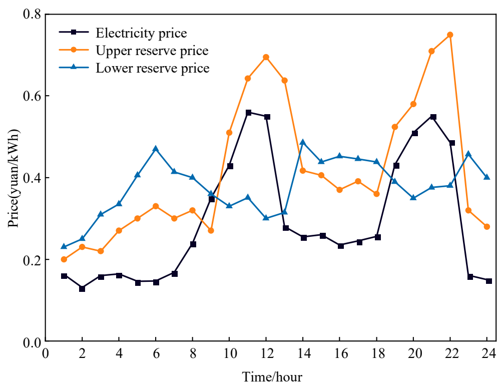


Figure 6. DSO electricity prices and reserve prices.

Figure 7 shows the optimal decision regarding the reserve for each time period of the distribution network, where Figure 7a,b show the optimization results of the upper and lower reserve, respectively. Combining the analysis of Figures 6 and 7, it can be seen that part of the distribution network's reserve demand is met by the prosumer groups and the other part is provided by the upper grid. During the time periods 11:00~13:00 and 19:00~22:00, the price of the upper reserve issued by the DSO is high, and the prosumer groups provide the upper reserve accordingly. Especially in the time period 21:00~22:00, the upper reserve price set by the DSO is close to the price of the upper grid, which incentivizes each prosumer group to aggregate more upper reserve resources. During the time periods 05:00~07:00, 14:00~16:00 and 23:00~24:00, the lower reserve price set by the DSO is high, and the prosumer groups bear part of the lower reserve demand of the distribution network. Under the effect of price incentives, at 06:00 and 14:00, when the lower reserve price is higher, the prosumer group trades more lower reserves with the DSO to achieve the optimal operational efficiency of the prosumer group and the distribution network.

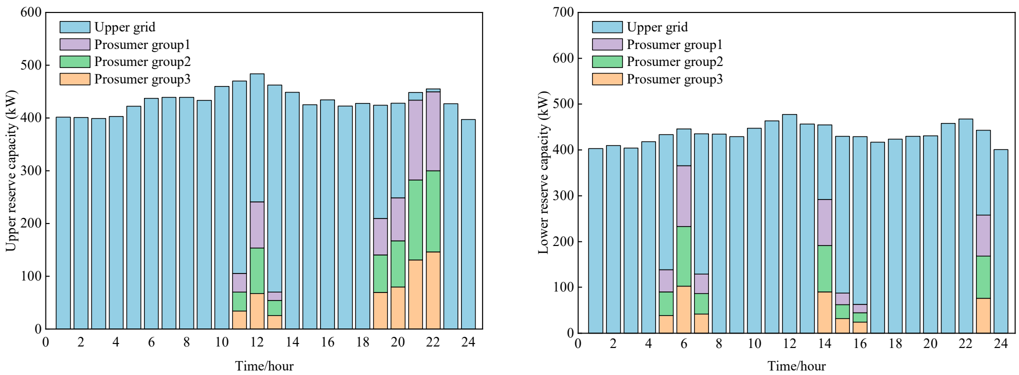


Figure 7. Optimal reserve decision of DSO.

5.3. Optimization Results for Prosumers

5.3.1. Analysis of ESS Charging and Discharging Strategy

Taking prosumer group 1 as an example, we analyze the results of the ESSs of three prosumers participating in optimal scheduling at each time period, as shown in Figure 8. Among them, Figure 8a–c show the ESS charging and discharging strategies of prosumers 1~3, respectively.

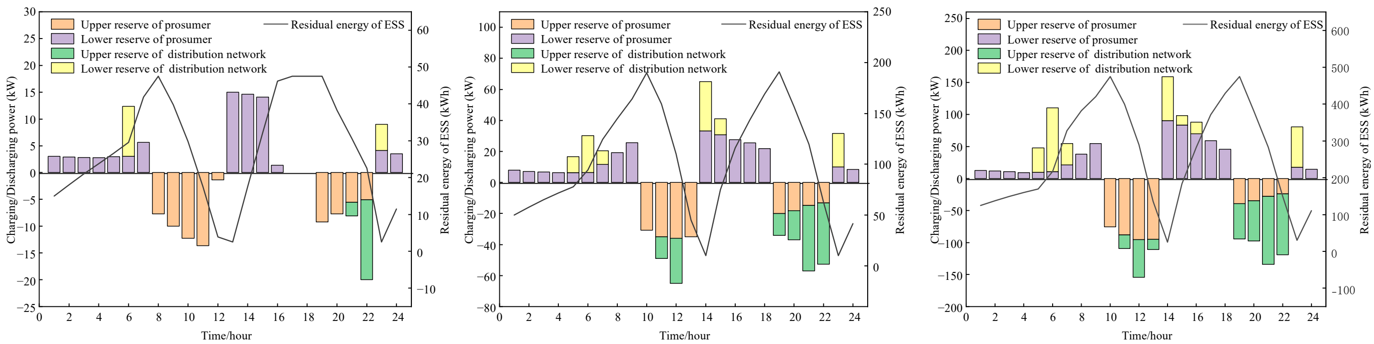


Figure 8. Charging and discharging strategies of ESS.

At the load lunchtime peak hours of 10:00~13:00 and evening peak hours of 19:00~22:00, prosumers have a higher reserve demand due to the uncertainty of load electricity consumption and rooftop PV output; thus, the price of purchasing upper reserve from the DSO is higher. At this time, the ESS has a lot of remaining energy, so it is in the discharging state to provide the upper reserve and thus meet its own reserve demand and sell the excess energy to the DSO to obtain more revenue. During 01:00~07:00, 23:00~24:00 and 14:00~18:00 in the afternoon when the load drops, the ESS turns to the charging state to satisfy its own demand for a lower reserve while selling a lower reserve to the DSO. At this time, the ESS stores energy in the form of providing lower reserve, in preparation for the large amount of reserve demand during the peak load hours.

By comparing the charging and discharging strategies of the three prosumers' ESSs in Figure 8a–c, it can be seen that prosumer 3 provides more flexible reserves to the DSO because of the larger capacity of the storage configured to satisfy its own reserve demand, and that it still has a larger margin. On the other hand, prosumer 1 has a smaller energy storage capacity and most of the capacity is used to meet its own reserve demand. During peak and trough load hours, the upper grid units usually run on a high or low output curve, resulting in there being few upper or lower reserve resources available to them. At this time, the flexible reserves provided by the prosumers' ESSs can, to a certain extent, reduce the reserve pressure on the upper grid.

5.3.2. Electricity Energy and Reserve Market Trading Results

As an example, production and consumption prosumer 3 in production and consumption prosumer group 1 is analyzed for its participation in electric energy and reserve market transactions in each time period. This is shown in Figure 9, where positive values indicate the prosumer's purchase of external electricity and purchase of reserves.

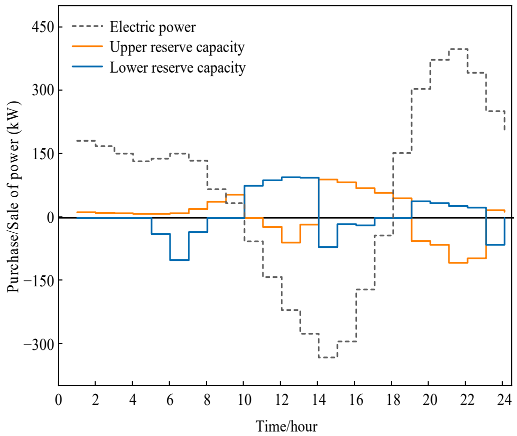


Figure 9. Trading results of prosumer 3 in the electricity and reserve market.

During the time period 10:00~17:00, the prosumer rooftop PV output is large, and there is excess power after load dissipation. Therefore, it sells electricity to the DSO, and in the rest of the time period, prosumers have a shortage of power and thus purchase power from the DSO. Combined with Figures 8c and 9, it can be seen that during the time periods 01:00~09:00, 14:00~18:00 and 23:00~24:00, the ESS discharges to provide the lower reserve. At this time, the prosumer purchases the upper reserves without purchasing the lower reserves. At 05:00~07:00, 14:00~16:00 and 23:00, prosumers sell their lower reserves to the DSO because there is unused capacity after the ESS meets its own lower reserve demand. During the time periods 10:00~13:00 and 19:00~22:00, the ESS remains charged to provide upper reserves, at which time the prosumer only purchases the lower reserves, and sells the upper reserves to the DSO because there is still idle capacity after the ESS meets its own upper reserve demand.

5.4. Comparative Analysis of Different Cases

In order to compare and analyze the optimal scheduling of distribution networks and prosumers, this paper sets up two comparison cases. Case 1 is that the prosumers only participate in the day-ahead energy market and do not participate in the reserve market. Case 2 is that the prosumers participate in both the day-ahead energy and reserve markets, which is the method proposed in this paper.

As an example of the comparative analysis of prosumer 3 in prosumer group 1, Figure 10 shows the optimization result for ESS in Case 1. Figure 8c is the optimization result of ESS in Case 2. As can be seen from Figure 9, in the time periods 01:00~09:00, 14:00~18:00 and 23:00~24:00 in Case 1, the ESS provides a lower reserve to itself. At this time, the ESS is not full and the DSO electricity price is low, so it continues to keep charging to store electricity. Then it releases energy at the peak load time to profit from the electricity price difference. During the peak load hours 10:00~13:00 and 19:00~22:00, the ESS provides upper reserve to itself. Since the price of electricity is high at this time, the ESS will continue to release the remaining energy in the form of electricity, realizing the arbitrage of a peak and valley price difference and reducing the cost for users. Comparing Figures 8c and 10, it can be seen that when the prosumer does not participate in the reserve market, after the ESS meets its own reserve demand, it will store electricity to realize the electricity price arbitrage and enhance the prosumer's revenue. However, since the reserve price is higher than the electricity price, the combined cost of participating in the reserve market is smaller for the prosumer in a comprehensive way.

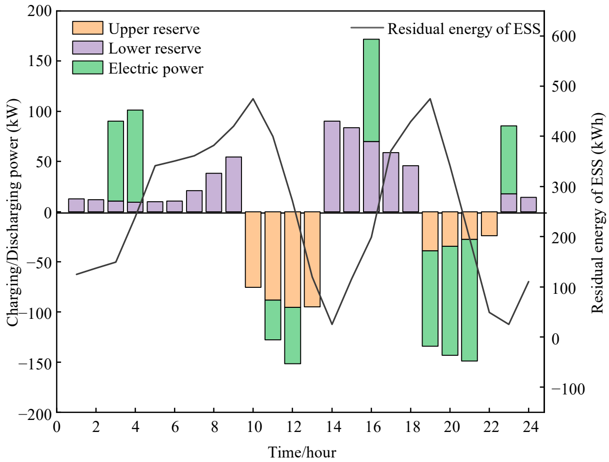


Figure 10. Charging and discharging strategies of ESS in Case 1.

Table 3 shows the integrated operating costs and reserve transactions of the DSO in both cases. From Table 3, it can be seen that compared with Case 1, the integrated operating cost of the DSO in Case 2 decreased from CNY 30,372.87 to CNY 29,007.76, which is a reduction of 4.49%. In Case 2, the prosumer group aggregates the prosumer resources to provide the DSO with cumulative upper reserve and lower reserve capacities of 1758.40 kW and 1332.40 kW during the dispatch cycle, accounting for 16.93% and 12.76% of the total upper reserve and lower reserve demand of the distribution network, respectively. In Case 1, the upper grid is the only reserve supplier. All the reserve demand of the distribution network is borne by it, resulting in high reserve pressure on the upper grid, especially during the peak load period when the units are supplied with large amounts of electricity, which leads to a reduction in the reserve supply capacity. In Case 2, the prosumers ensure the balance of day-ahead energy in the energy market and also participate in the reserve market to provide flexible reserves, which not only relieves the reserve pressure on the upper grid, but also improves the flexibility and economy of distribution network operation.

Table 3. Comparison of DSO operating costs and reserve results.

Case	Comprehensive Operating Costs (¥)	Percentage Decline	Upper/Lower Reserve (kW)	
			The Upper Grid	Prosumer Group
1	30,372.87	/	10,389.32/10,438.57	0/0
2	29,007.76	4.49%	8630.91/9106.17	1758.40/1332.40

Table 4 shows the combined cost of electricity for each prosumer in both cases. From the table, it can be seen that the costs for the prosumers in Case 2 are all lower than those in Case 1. In Case 1, due to participation in the energy market only, the prosumers' revenue is only the revenue gained from the corresponding sale of energy. In Case 2, the revenue obtained by the prosumer after participating in the reserve market consists of the revenue obtained from the sale of electric energy and the reserves, and the final combined total cost is lower than that in Case 1. This shows that the method proposed in this paper improves the economics of the operation of the prosumers.

Table 4. Comparison of integrated electricity costs for prosumers.

Prosumer Group	Prosumer	Cost (¥)		
		Case 1	Case 2	Percentage Decline
1	1	630.74	613.55	2.73%
	2	1545.11	1511.61	2.17%
	3	2695.63	2644.37	1.90%
2	1	670.36	666.43	0.59%
	2	1401.19	1356.40	3.20%
	3	2633.69	2573.53	2.28%
3	1	806.11	804.47	0.20%
	2	2108.73	2104.85	0.18%
	3	3259.25	3188.05	2.18%

6. Conclusions

In this paper, a prosumer group is introduced as an intermediate coordination layer to aggregate the resources of prosumers with rooftop PV and ESS. Based on the ability of prosumers to provide flexible reserves, this paper proposes a distribution network–prosumer group–prosumer optimal scheduling strategy under the "distribution network–prosumer group–prosumer" architecture, and obtains the following conclusions through the analysis of cases:

(1) The prosumer group acts as an intermediate coordination layer to aggregate the reserve resources of prosumers, and then trades with the DSO, so that the DSO reduces the reserve capacity purchased from the upper grid, and reduces the reserve pressure on the upper grid;
(2) Under the incentive effect of price, prosumers adjust the charging and discharging plan of ESS, thus utilizing their own flexible reserve resources to participate in reserve market transactions, which enriches the reserve resources in the system and enhances the flexibility of system operation;
(3) After participating in the electric energy and reserve market, the prosumer reduces the total cost of its own operation. The comprehensive operating cost of the DSO is also reduced, effectively improving the economy of system operation.

Moreover, while the dispatch strategy proposed in this paper can better stimulate the reserve potential of prosumers, it does not take into account the fact that the reserve capacities of different prosumer groups are different, and there may be complementary synergistic relationships. Future research should focus on the complementary synergistic relationship between different prosumer groups to better adapt to different scenarios and further enhance the economics of power system operation.

Author Contributions: Conceptualization, L.L. and H.Z.; methodology, L.L.; software, L.L. and X.W. (Xinghuo Wang); validation, Q.W. and X.W. (Xueting Wang); formal analysis, L.L.; investigation, X.W. (Xinghuo Wang); resources, Q.W.; data curation, X.W. (Xueting Wang); writing—original draft preparation, L.L.; writing—review and editing, H.Z. 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 and the Natural Science Foundation of Hubei Province, grant number: 52307109 and 2022CFD167.

Data Availability Statement: The original contributions presented in this study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: This research was supported by Hao Zhong's group of China Three Gorges University. We deeply appreciate their diligent work and contribution.

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

References

1. Long, J.; Chen, W.; Zhang, Z. Opportunities and challenges from energy transition: Based on carbon neutrality strategy case study in China. *Environ. Resour. Ecol. J.* **2023**, *7*, 1–8.
2. Wang, K.; Niu, D.; Yu, M.; Liang, Y.; Yang, X.; Wu, J.; Xu, X. Analysis and countermeasures of China's green electric power development. *Sustainability* **2021**, *13*, 708. [CrossRef]
3. Meng, L.; Yang, X.; Zhao, Z. An economic optimal dispatch strategy for active distribution networks considering photovoltaic-load uncertainty and rotating reserve constraints. *Electr. Power Constr.* **2022**, *43*, 63–72.
4. Mohandes, B.; Moursi, M.S.E.; Hatziargyriou, N.; Khatib, S.E. A Review of power system flexibility with high penetration of renewables. *IEEE Trans. Power Syst.* **2019**, *34*, 3140–3155. [CrossRef]
5. Liu, L.; Hu, Z. Data-driven regulation reserve capacity determination based on bayes theorem. *IEEE Trans. Power Syst.* **2020**, *35*, 1646–1649. [CrossRef]
6. Li, Y.; Zhao, T.; Wang, P.; Gooi, H.B.; Wu, L.; Liu, Y.; Ye, J. Optimal operation of multimicrogrids via cooperative energy and reserve scheduling. *IEEE Trans. Ind. Inf.* **2018**, *14*, 3459–3468. [CrossRef]
7. Parag, Y.; Sovacool, B.K. Electricity market design for the prosumer era. *Nat. Energy* **2016**, *1*, 16032. [CrossRef]
8. Ossenbrink, J. How Feed-in Remuneration Design shapes residential PV prosumer paradigms. *Energy Policy* **2017**, *108*, 239–255. [CrossRef]
9. Liang, Z.; Chung, C.; Zhang, W.; Wang, Q.; Lin, W.; Wang, C. Enabling high-efficiency economic dispatch of hybrid AC/DC networked microgrids: Steady-state convex bi-directional converter models. *IEEE Trans. Smart Grid* **2024**, accept. [CrossRef]
10. Huang, H.; Zhou, M.; Zhang, L.; Li, G.; Sun, Y. Joint Generation and Reserve Scheduling of Wind-solar-pumped Storage Power Systems under Multiple Uncertainties. *Int. Trans. Electr. Energy Syst.* **2019**, *29*, 12003. [CrossRef]
11. Xu, C.; Xu, X.; Yan, Z.; Li, H. Distributionally robust optimal dispatch method considering mining of wind power statistical characteristics. *Autom. Electr. Power Syst.* **2022**, *46*, 33–42.
12. Mahesh, M.; Vijaya Bhaskar, D.; Narsa Reddy, T.; Sanjeevikumar, P.; Holm-Nielsen, J.B. Evaluation of ancillary services in distribution grid using large-scale battery energy storage systems. *IET Renew. Power Gener.* **2020**, *14*, 4216–4222. [CrossRef]
13. Pan, L.; Chen, J. Optimal Energy Storage Configuration of Prosumers with Uncertain Photovoltaic in the Presence of Customized Pricing-Based Demand Response. *Sustainability* **2024**, *16*, 2230. [CrossRef]
14. Song, T.; Li, K.; Han, X. Coordinated Operation strategy of energy storage system participating in multiple application scenarios. *Autom. Electr. Power Syst.* **2021**, *45*, 43–51.
15. Tang, Z.; Liu, Y.; Wu, L.; Liu, J.; Gao, H. Reserve model of energy storage in day-ahead joint energy and reserve markets: A stochastic UC solution. *IEEE Trans. Smart Grid* **2021**, *12*, 372–382. [CrossRef]
16. Zhao, Z.; Liu, Y.; Guo, L. Bidding decision making method of wind power-energy storage integrated station based on residual demand curve. *Autom. Electr. Power Syst.* **2023**, *47*, 99–108.
17. Wang, S.; Sun, G.; Wu, C. Two-stage robust optimization model of multiple prosumers based on centralized-decentralized trading mechanism. *Electr. Power Autom. Equip.* **2022**, *42*, 175–182.
18. Patrizi, N.; LaTouf, S.K.; Tsiropoulou, E.E.; Papavassiliou, S. Prosumer-centric self-sustained smart grid systems. *IEEE Syst. J.* **2022**, *16*, 6042–6053. [CrossRef]
19. Ma, L.; Liu, W.; Sun, H.; Liu, N.; Shi, J. Contract theory based transaction strategy for prosumers to participate in the frequency modulation ancillary service market. *Power Syst. Technol.* **2021**, *45*, 1347–1356.
20. Hu, J.; Li, Y.; Wu, J.; Ai, X. A Day-ahead optimization scheduling method for prosumer based on iterative distribution locational marginal price. *Power Syst. Technol.* **2019**, *43*, 2770–2780.
21. Boiarkin, V.; Rajarajan, M.; Al-Zaili, J.; Asif, W. A novel dynamic pricing model for a microgrid of prosumers with photovoltaic systems. *Appl. Energy* **2023**, *342*, 121148. [CrossRef]
22. Banaei, M.; Oloomi-Buygi, M.; Zabetian-Hosseini, S.-M. Strategic gaming of wind power producers joined with thermal units in electricity markets. *Renew. Energy* **2018**, *115*, 1067–1074. [CrossRef]
23. Liu, S.; Yang, Y.; Yang, Z.; Chen, Q. Reserve Capacity determination and its cost allocation considering stochastic characteristics of renewable energy. *Autom. Electr. Power Syst.* **2023**, *47*, 10–18.
24. Sinha, A.; Soun, T.; Deb, K. Using Karush-Kuhn-Tucker proximity measure for solving bilevel optimization problems. *Swarm Evol. Comput.* **2019**, *44*, 496–510. [CrossRef]
25. Kleinert, T.; Labbé, M.; Ljubić, I.; Schmidt, M. A survey on mixed-integer programming techniques in bilevel optimization. *EURO J. Comput. Optim.* **2021**, *9*, 100007. [CrossRef]
26. Li, X.; Fang, Z.; Li, F.; Xie, S.; Cheng, S. Game-based optimal dispatching strategy for distribution network with multiple microgrids leasing shared energy storage. *Proc. CSEE* **2022**, *12*, 6611–6625.
27. Zhong, H.; Chen, Z.; Xiong, W.; Li, S.; Li, X. Optimal dispatch of distribution network considering reactive power auxiliary services of photovoltaic prosumers. *Power Syst. Technol.* **2022**, *46*, 4863–4875.
28. Ma, Y.; Hu, Z.; Song, Y. Hour-ahead optimization strategy for shared energy storage of renewable energy power stations to provide frequency regulation service. *IEEE Trans. Sustain. Energy* **2022**, *13*, 2331–2342. [CrossRef]

29. Zang, T.; Wang, S.; Wang, Z.; Li, C.; Liu, Y.; Xiao, Y.; Zhou, B. Integrated planning and operation dispatching of source–grid–load–storage in a new power system: A coupled socio–cyber–physical perspective. *Energies* **2024**, *17*, 3013. [CrossRef]
30. Zhang, B.; Huang, J. Shared energy storage capacity configuration of a distribution network system with multiple microgrids based on a stackelberg game. *Energies* **2024**, *17*, 3104. [CrossRef]