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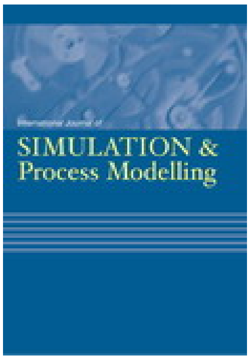

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Research on cooperative game model for distributed photovoltaic microgrid based on blockchain

Liang-jiang Wei, Wei Jian, Shun-kai Lu, Bao-chuan Fu*, Bao-ping Jiang and Xin Zhang

School of Electronics and Information Engineering,
Suzhou University of Science and Technology,
Suzhou 215009, China
Email: wei08222022@163.com
Email: jianwei0895@163.com
Email: lushunk2020@163.com
Email: fubc@163.com
Email: bpjiang@usts.edu.cn
Email: zxin1128@126.com
*Corresponding author

Abstract: In recent years, as the dual-carbon target has been proposed, the installed capacity of distributed photovoltaic (PV) systems has been increasing annually. As a novel networking approach, a microgrid can integrate distributed energy resources and enable the effective grid connection and utilisation of distributed PV energy. Based on this, a distributed PV microgrid group power trading model is proposed, which is based on blockchain technology and game theory. This provides a new approach to optimise the electricity market of microgrids. The cooperative game model of microgrid groups can effectively solve the interest issues of microgrid users. The simulation results demonstrate that due to the transparent and open nature of blockchain, microgrids can effectively engage in dynamic games, achieve the nearby consumption of distributed PV energy, and verify the feasibility and effectiveness of the model.

Keywords: blockchain; cooperative game; microgrid; distributed photovoltaic system.

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Biographical notes: Liang-jiang Wei received his Bachelor's degree in Electrical Engineering and Automation from Huaiyin Institute of Technology, Huaiyin, China. He is now a postgraduate student for Master's degree majoring in Building Intelligence at the Suzhou University of Science and Technology (SUST), Suzhou, China and is currently researching on blockchain applications in microgrids.

Wei Jian received his Bachelor's degree in Electrical Engineering and Automation from Changshu Institute of Technology, Changshu, China. He is now a postgraduate student for Master's degree majoring in Building Intelligence at the SUST, Suzhou, China and is currently researching on blockchain applications in microgrids.

Shun-kai Lu received his Bachelor's degree in Electrical Engineering and Automation from Nanjing Institute of Technology, Nanjing, China. He is now a postgraduate student for Master's degree majoring in building intelligence at the SUST, Suzhou, China and is currently researching on application of edge computing in smart community.

Bao-chuan Fu received his MS in Electronic Measurement and Instrumentation from Harbin University of Science and Technology, Harbin, China in 1988 and PhD in Control Theory and Control Engineering from Tongji University, Shanghai, China in 2008. He is a Professor in Computer Science at the SUST. His research interests include network control, intelligent building, system optimisation, mathematical modelling in complex systems, etc.

Bao-ping Jiang graduated from the School of Mathematical Sciences and the School of Oceanography and Atmosphere of Ocean University of China in June 2019. From October 2017 to April 2019, he jointly trained as a doctoral student in the School of Mechanical Engineering of Politecnico di Milano (Politecnico di Milano), Italy. From September 2020–August 2022, he was a Postdoctoral Fellow at the School of Automation, Nanjing University of Aeronautics and Astronautics. He is an Associate Professor at the SUST and is mainly engaged in the research of intelligent control and system, etc.

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Xin Zhang received her BS and MS degrees in Mathematics from Liaocheng University, Liaocheng, China, in 2013 and 2015, respectively, and PhD in Control Science and Engineering from Donghua University, Shanghai, China in 2020. She is currently a Lecturer with SUST. Her current research interests include stability analysis and stochastic control for neural networks and hybrid systems.

1 Introduction

In recent years, distributed PV power generation has become increasingly accepted and rapidly popularised among electricity users due to its simple structure, ease of installation, and relatively low cost (Qiu et al., 2022; Jiang et al., 2021). According to publicly available data from the National Energy Administration, as of the end of 2021, China's cumulative grid-connected PV capacity was nearly 306 GW, of which distributed PV accounted for 35.1%. The newly added distributed PV grid-connected capacity in 2021 alone was 29.28 GW (Wang et al., 2022b; Zhou et al., 2021b). At present, many users of distributed PV power generation participate in grid connection through self-consumption and feeding excess electricity back to the grid. They can only sell the surplus energy to local power grids or aggregators, while electricity buyers can only purchase electricity from local power grids or aggregators (Lu et al., 2020). There is no direct electricity trading among users. Therefore, the traditional transaction model has the problem of not being able to realise nearby consumption of electricity, leading to redundant dispatching of electricity and causing wastage of resources (Jin et al., 2021). Additionally, there are issues of fairness in transactions between users and data security protection in the process of microgrid transactions. The PV power market urgently needs a new type of information interaction technology (Duda et al., 2022). By introducing blockchain technology into the electricity trading of microgrids, a new transaction model can be provided for distributed PV microgrids, which can enhance the fairness, transparency, security, real-time performance, and programmability of transactions. The implementation of dynamic adjustments in PV microgrids (He et al., 2022) can help optimise power dispatching (Hua et al., 2022), promoting the sustainable development and widespread adoption of such systems.

As microgrids continue to improve the utilisation of distributed PV equipment, many scholars have conducted research on optimising the distribution of distributed energy in microgrids. Wang et al. (2022a) proposed a power trading model based on cooperative game theory was proposed for PV microgrid clusters, which optimised the energy dispatching problem to some extent. However, due to a lack of effective means for information exchange among microgrid clusters, the system's robustness remains poor. Abdullah et al. (2022) proposed a blockchain-based energy market model for decentralised microgrids with corresponding reputation mechanisms designed to ensure the viability of transactions. Zhou et al. (2021a) studied the cooperative game between large power grid generators and micro-grid aggregators under blockchain, and ensured the sustainable development of the power supply side by promoting the cooperation of power suppliers. Chen et al. (2022) proposed a microgrid electricity market trading model based on coalition chain and game theory regarding the problems of high operation cost and low security in traditional electricity trading of microgrid, which reduces the cost of electricity purchase by users to a certain extent. Xu et al. (2022) proposed a microgrid group information interaction model based on blockchain technology and solves the model using an improved ant colony algorithm. Yang et al. (2021) proposed a distributed energy management method for virtual power plants based on blockchain technology, and develops a decentralised optimisation algorithm to optimise energy transactions and scheduling among users. Siqin et al. (2022) proposed a distributed energy optimisation and scheduling model based on cooperative game theory to ensure the normal operation of a multi-community microgrid cooperative alliance.

This paper focuses on the effective nearby consumption of electricity in distributed PV microgrids, and constructs a cooperative game model based on blockchain technology for information exchange and power transaction decision making between distributed PV microgrids. This model aims to optimise the energy dispatching strategy among microgrid groups, maximise the avoidance of wasted PV energy, and ensure the reasonable distribution of interests among multiple parties.

The main contributions of this article are as follows:

1. a blockchain-based distributed information and power trading platform for PV microgrids was established, enabling resource sharing and distribution, and reducing energy waste
2. the model combines blockchain technology and cooperative game theory to achieve the decentralisation and autonomy of electricity transactions in distributed PV microgrids, improving the efficiency and economic benefits of energy utilisation.
3. a novel power trading decision-making mechanism is proposed based on game theory that balances the interests of various microgrids while ensuring the energy security and stability of the entire system.

In summary, this model provides a new solution for information exchange and power trading decisions between distributed PV microgrids, which is expected to play an important role in the future energy market.

The remaining part of this paper is organised as follows: In Section 2, the overall system architecture of distributed PV microgrid, the relationship between PV microgrid groups and the construction of power trading framework are introduced. In Section 3, the direct trade model and cooperative game model are established, and the income distribution model is established in the cooperative alliance. In Section 4, the data are simulated and compared on MATLAB, and the simulation results are analysed and discussed. Some conclusions are drawn in Section 5.

2 Distributed PV microgrid power trading model

2.1 Overall system architecture

In conventional distributed PV microgrids, electricity transactions are limited to the local power grid or aggregate merchants, preventing direct exchange between microgrid users. As a result, conventional microgrid power trading falls short in terms of facilitating nearby energy consumption and optimising energy dispatch.

In order to enable direct electricity trading among microgrid users, it is possible to construct a distributed electricity market model for PV microgrids, with its constituent parts distributed as depicted in Figure 1.

On the supply side, aggregator merchants act as energy suppliers in the system and can purchase electricity from the local power grid and microgrid users, or obtain electricity through distributed generation and energy storage equipment. At the same time, aggregator merchants can sell electricity to local power grid or microgrid users to generate revenue (Leeuwen et al., 2020).

On the demand side, microgrid users can both purchase electricity from aggregator merchants and other users, and obtain electricity through their own distributed PV generation and energy storage equipment. Meanwhile, if microgrid users generate more electricity than they consume, they can sell the excess electricity to other consumers or aggregators and earn corresponding income. (Zhou et al., 2022; Wang et al., 2020).

Thus, the distributed PV microgrid electricity market set φ can be expressed as:

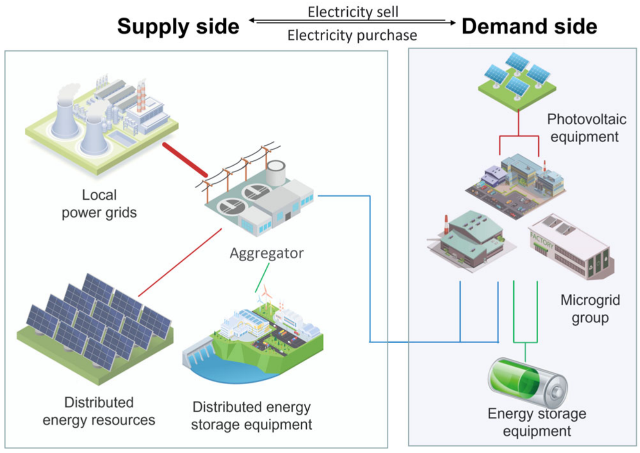
$$\varphi = (G_s, A_\alpha, U_t) \quad (1)$$

$$A_\alpha = (A_t^G, A_t^U) \quad (2)$$

where G_s represents the sale of electricity from the local grid, through which electricity is sold to aggregators; A_α is the aggregator trading set. As a key transaction subject, the aggregator conducts two-way transactions with the local power grid and users at the same time, including two-way power transaction A_t^G between the aggregator and the local power grid and two-way power transaction A_t^U between the aggregator and the user; U_t is the microgrid user trading electricity, through which the customer completes electricity sales and purchase transactions with the aggregator and other users.

In summary, the distributed PV microgrid each purchase and sale of electricity can be in the system, to achieve the overall effective operation.

Figure 1 Schematic diagram of distributed PV microgrid group (see online version for colours)



2.2 Relationships between distributed PV microgrid clusters

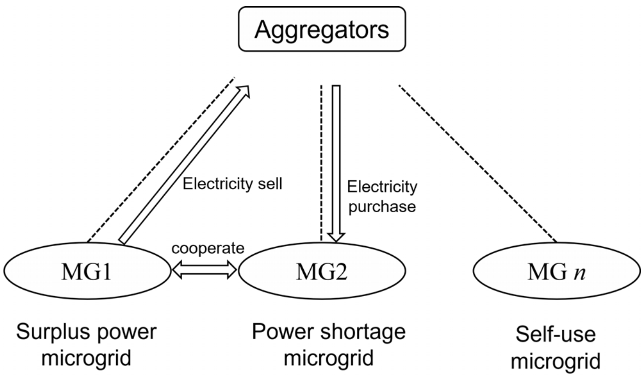
Distributed PV microgrids have certain peculiarities in their load plans and PV output due to their respective different characteristics.

- Surplus microgrid: in some PV microgrids, favorable conditions for PV equipment installation can result in electricity generation that exceeds consumption, leading to a phenomenon known as 'surplus electricity'. For instance, in industrial areas like highway port, PV equipment can be distributed and installed on the rooftops of large factory buildings. However, as the logistics industry typically requires less electricity, this type of microgrid is often referred to as a 'surplus microgrid'.
- Power shortage microgrid: in some PV microgrids, the demand for electricity often exceeds the amount generated, resulting in a phenomenon known as 'power shortage'. As an example, distributed PV equipment installed on the rooftop of a manufacturing enterprise that operates around the clock may not generate enough electricity to achieve self-sufficiency, resulting in what is known as a 'power shortage microgrid'.
- 'Self-use' microgrid: in certain PV microgrids, power generation is approximately equal to power consumption, enabling them to achieve 'self-sufficiency'. This is a type of microgrid known as a 'pure self-use microgrid', where there is no purchasing or selling of electricity to the grid. For example, in some rural residential communities, the distributed photovoltaic equipment installed on the roof of each household can basically achieve self-sufficiency, resulting in a predominantly 'self-use' microgrid.

In summary, the transaction status between distributed PV microgrids is shown in Figure 2. The ‘self-generating’ microgrids are less likely to transact with aggregators. In general, the shortage microgrid purchases electricity directly from the surplus microgrid, which reduces the cost of purchasing electricity from the shortage microgrid and increases the revenue of the surplus microgrid. Therefore, a cooperative alliance between the residual microgrid and the shortage microgrid can reduce the cost of energy dispatch by ‘selling electricity through a wall’, and greatly enhance the overall efficiency of the microgrid group.

Based on the above analysis, this paper proposes a blockchain-based cooperative game model among distributed PV microgrid clusters, through a cooperative alliance formed among microgrid clusters, in order to achieve the purpose of reducing the cost of electricity consumption of all parties and realising energy consumption in close proximity.

Figure 2 Power transaction status of distributed PV microgrid



2.3 Blockchain-based network architecture

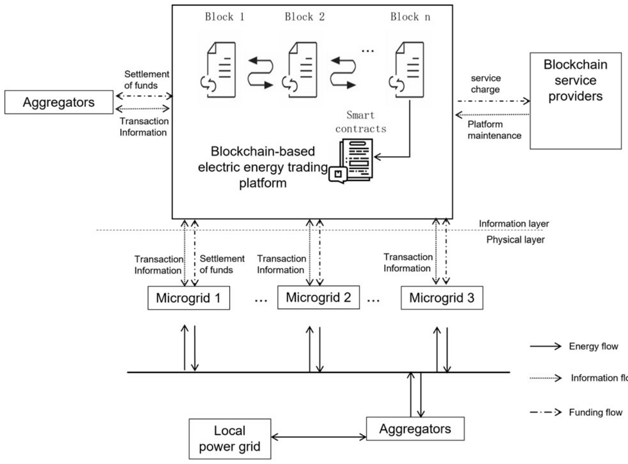
Aggregators play a key role as market players in the above-mentioned PV microgrid electricity market model.

Aggregators not only provide services to customers and local grids in terms of energy, but also provide trading data and trading platform services related to electricity trading for microgrid customers. As a result, if aggregators are not supervised, there is a low level of transparency and credibility in trading. At the same time, the aggregator’s centralised management of transaction data is prone to data security issues, such as vulnerability to malicious attacks and risk of data loss.

Blockchain technology has the characteristics of decentralisation, transparency, and immutability. Therefore, introducing the blockchain ledger structure into the electricity market model can effectively solve the above-mentioned problems (Huang et al., 2021). The blockchain-based distributed PV microgrid power trading framework is shown in Figure 3.

On the physical layer, electricity can be dispatched between the aggregator and the various microgrid users. The local grid can be dispatched to and from the aggregator.

Figure 3 Power transaction architecture of distributed PV microgrid based on blockchain



On the information layer, aggregators and microgrid users register their electricity purchase and sale information and settle the corresponding funds through the blockchain electricity trading platform, and finally complete the peer-to-peer transactions. At the same time, a service provider for the blockchain electricity trading platform is set up, which is operated by a third party and is responsible for the maintenance and management of the platform information, and charges a certain service fee from aggregators and users, the service fee charging rules can be expressed as follows.

$$p_s = \eta p_t \tag{3}$$

where p_s is the blockchain service provider service fee revenue; η is the blockchain service fee weight; p_t is the total transaction amount recorded on the blockchain ledger.

At the same time, blockchain service providers and other trusted nodes act as ‘miners’ to verify all transaction information and add legitimate transaction information to the blockchain by generating new blocks (Yang et al., 2022).

Thus, the blockchain-based distributed PV microgrid transaction form can be expressed as a quintet. As shown in equation (4).

$$\gamma = \left(M_\alpha, Q_\alpha, D_c, C_u, S_\alpha\right) \tag{4}$$

where M_α is the user information update, the update information includes user personal identification number, user wallet balance, user credit score and other information; Q_α is the user quotation information, the information includes user quotation, user quotation, user declaration time stamp and other information; D_c is the smart trading matching contract, the contract includes bilateral auction contract and peer-to-peer trading contract; C_u is the user credit evaluation; S_α is the trading settlement information, the information includes credit settlement and energy final delivery settlement.

In summary, blockchain technology can be introduced in distributed PV microgrid trading to provide an open, transparent, fair and just trading environment for microgrid users. At the same time, under the supervision of smart contracts and reputation system, it circumvents the problem of market disruption caused by too much centralised power of aggregators.

3 Distributed PV microgrid blockchain model

3.1 PV microgrid direct trading model

In the traditional model, each PV microgrid trades directly with an aggregator based on its own power profile.

First, the day can be divided into 24 time periods, defined Δt as a trading cycle, so that $\Delta t = 1$ h, and the whole trading cycle T can be expressed as:

$$T = \{[0, \Delta t], \ldots, [(k-1)\Delta t, k\Delta t], \ldots, [23 \cdot \Delta t, 24 \cdot \Delta t]\} \tag{5}$$

Assume that there are n microgrids in the microgrid cluster. Let the load power of the i microgrid in the k time period be L_i^k; the power of i PV generation equipment is P_i^k. If the load power of the microgrid is greater than the PV power, then the microgrid is a shortage microgrid and vice versa. Assume that the price of electricity sold to the aggregator by the surplus microgrid is p_s^k in time k hours; and the price of electricity purchased from the aggregator by the shortage microgrid is p_b^k. Based on the fundamental laws of the market, in general, the purchase price of electricity during the same period is higher than the selling price of electricity, that is $p_b^k \geq p_s^k$.

Therefore, if microgrid i is a residual microgrid, its revenue E_i^k consists of self-generation revenue and residual feed-in revenue at time k, which can be expressed as:

$$E_i^k = \Delta t\left[p_b^k \cdot L_i^k + p_s^k \cdot \left(P_i^k - L_i^k\right)\right] \tag{6}$$

If microgrid i is a power-deficient microgrid, then its E_i^k revenue in time period k is the self-consumption revenue, which can be expressed as:

$$E_i^k = \Delta\left(p_b^k \cdot P_i^k\right) \tag{7}$$

Since microgrid i is short of electricity at this time, microgrid i needs to purchase electricity from the aggregator and therefore microgrid i has an expense, the cost of S_i^k which can be expressed as:

$$S_i^k = \Delta t\left[p_b^k \cdot \left(L_i^k - P_i^k\right)\right] \tag{8}$$

δ is a Boolean variable indicating the state of microgrid i. A value of 1 indicates that microgrid i is a surplus microgrid and vice versa, so the following equation can be obtained.

$$\delta = \begin{cases} 1 & P_i^k - L_i^k \geq 0 \\ 0 & P_i^k - L_i^k < 0 \end{cases} \tag{9}$$

In summary, the revenue E_i of microgrid i over the entire trading cycle T can be expressed as:

$$\begin{aligned} E_i = &\sum_{k=1}^{24} \Delta t\left[p_b^k \cdot L_i^k + p_s^k \cdot \left(P_i^k - L_i^k\right)\right]\delta \\ &+\sum_{k=1}^{24} \Delta t\left(p_b^k \cdot P_i^k\right)(1-\delta) \end{aligned} \tag{10}$$

And the expenditure S_i of microgrid i over the entire transaction cycle T can be expressed as:

$$S_i = \sum_{k=1}^{24} \Delta t\left[p_b^k \cdot \left(L_i^k - P_i^k\right)\right](1-\delta) \tag{11}$$

Therefore, in this distributed PV microgrid group, the total benefit E can be expressed as:

$$E = \sum_{i=1}^{n} E_i \tag{12}$$

And the overall microgrid expenditure S can be expressed as:

$$S = \sum_{i=1}^{n} S_i \tag{13}$$

In this model, each distributed PV microgrid accounts independently for its own revenues and expenses. The expenses of the microgrids in the event of a power shortage are the electricity bills they themselves have to pay, independent of the benefits of installing PV generation equipment, and therefore need to be accounted for independently.

3.2 PV microgrid blockchain ledger

Blockchain technology has been developed in recent years and has been widely used in research areas related to microgrids.

Through the microgrid power trading mechanism built by blockchain technology, aggregators and microgrids can effectively interact with each other on information such as trading tariffs, electricity consumption periods and electricity consumption. Due to the open and transparent nature of blockchain, the blockchain ledger can provide effective information for all parties to adjust their power purchase and sales strategies. At the same time, the blockchain's tamper-evident nature not only makes electricity transactions fairer and more reliable, but also ensures the authenticity of transaction information. Therefore, each PV microgrid user can realise real-time transactions and strategy adjustments through the blockchain ledger according to their own needs and interests, without the need for direct intervention by aggregators.

Ethernet-based smart contracts provide a Turing-complete programming environment. Therefore, in the actual power trading of distributed photovoltaic microgrids, the blockchain ledger can achieve decentralised management and intelligent distribution of energy. Through smart contracts, energy can be automatically traded and distributed on the blockchain ledger, thereby achieving more efficient and reliable energy management to ensure the feasibility of transactions. The specific contracts are listed below:

1 Contract for updating user information: the blockchain service provider can update users' basic and power consumption information through this contract to ensure the smooth progress of subsequent transactions. At the same time, the contract can also examine the credit of customers and suspend transactions for customers with poor credit, so as to ensure a healthy order in the electricity market.

2 User offer contract: in this contract, the customer can declare the desired transaction price and electricity and record the above data on the blockchain.

3 User matching contracts: in this stage, the smart contract matches user transactions through a two-way auction mechanism with peer-to-peer trading to conclude the deal.

4 User reputation contract: due to the tamper-evident nature of the blockchain, a user's malicious actions will be recorded on the blockchain ledger. Therefore, in this contract, the user's reputation can be assessed based on his or her behaviour. Penalties can be imposed on users with malicious intent by deducting their reputation points or banning them from participating in the next transaction.

5 Settle the contract: through this contract, the final transaction behaviour of each party in the system is settled, and the transfer of electricity rights and related fees is completed. At the same time, the settlement of reputation points can be carried out in this contract to ensure the implementation of the penalty mechanism.

In summary, by designing a blockchain ledger and transaction method for distributed PV microgrids, it can make the electricity market more open, transparent and fair. Compared to traditional means of information interaction, the introduction of blockchain technology solves the problem of excessive power and lack of supervision of aggregators. At the same time, it ensures the rights and interests of microgrid users and is more conducive for the trading parties to adjust their trading behaviour to the actual situation.

3.3 *PV microgrid game model*

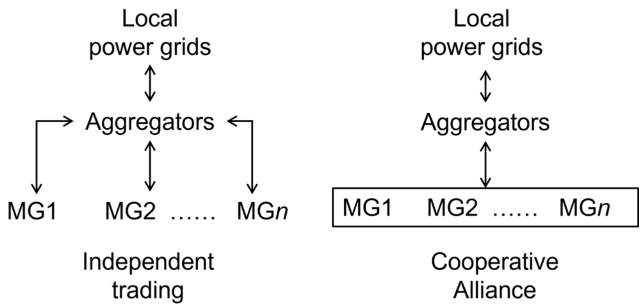
The cooperative game differs from the non-cooperative game in that it places more emphasis on the concept of collective cooperation and win-win situation. Cooperative alliances need to meet the following requirements:

1 for cooperative alliances, the collective total revenue is greater than the sum of the revenue obtained from their respective direct transactions

2 for the distribution of the collective total revenue, the revenue allocated to each participant shall not be lower than the revenue from their direct transactions, immediate the revenue distribution shall be reasonably distributed according to the contribution of each participant.

For a distributed PV microgrid cluster, the benefits of a cooperative alliance of microgrids must be greater than the benefits of direct trading for each microgrid due to the difference in purchase and sale prices. Therefore, the distributed PV microgrid group prefers to form a cooperative alliance to trade with aggregators, and the form of the alliance is shown in Figure 4.

Figure 4 Independent transaction form and alliance transaction form



For a cluster of distributed PV microgrids, the participating cooperative alliances are each surplus and deficit microgrid. Assuming that the cooperative alliance u consists of n microgrids, define the total alliance revenue as $E(u)$. Then, according to equation (10), the total benefit of the alliance can be calculated as:

$$\begin{aligned} E(u) = & \sum_{k=1}^{24}\sum_{i\in u}\Delta t\left[p_b^k \cdot L_i^k + p_s^k \cdot \left(P_i^k - L_i^k\right)\right]\lambda \\ & + \sum_{k=1}^{24}\sum_{i\in u}\Delta t\left(p_b^k \cdot P_i^k\right)(1-\lambda) \end{aligned} \tag{14}$$

where λ is

$$\lambda = \begin{cases} 1 & \sum_{i\in u}\left(P_i^k - L_i^k\right) \geq 0 \\ 0 & \sum_{i\in u}\left(P_i^k - L_i^k\right) < 0 \end{cases} \tag{15}$$

The additional benefit ΔE generated compared to the direct transaction model is the difference between the total benefit generated by the cooperative alliance and the sum of all benefits under the direct transaction model.

$$\Delta E = E(u) - E \tag{16}$$

In this model, each distributed PV microgrid forms a cooperative alliance for greater benefits, and trades with aggregators in the form of an alliance. This not only avoids the loss of profit from the low price of electricity sold by the surplus microgrids and the high price of electricity purchased by the shortage microgrids, but also enables internal dispatching through blockchain smart contracts within the alliance, realising the ‘sale of electricity through a wall’ and greatly reducing the energy loss caused by repeated dispatching of electricity.

3.4 PV microgrid revenue distribution model

After the distributed PV microgrid cluster cooperative alliance has achieved revenue, the revenue earned by the alliance needs to be distributed.

The profits of each microgrid should be reasonably allocated according to its contribution to the alliance. Therefore, the Shapley value method can be used to allocate the total profits, obtaining results that satisfy all microgrids. The Shapley value method was proposed by Shapley in 1953 (Liat et al., 2023). Based on the degree of contribution, this method allocates the profits of cooperative alliances, avoiding egalitarianism in allocation. The rules for applying the Shapley value method to allocate the total profits of the cooperative alliance of distributed PV microgrids are as follows.

Firstly, the application of the Shapley value method requires the following conditions to be met:

1 if no one participates in the alliance, the gain is zero

2 when an alliance is formed, the alliance gain should be greater than the sum of the independent trading gains of each participant.

The above can be expressed as follows:

$$v(\varnothing) = 0 \tag{17}$$

$$v(s_1 \cup s_2) \geq v(s_1) + v(s_2) \qquad s_1 \cap s_2 = \varnothing \tag{18}$$

where $v(\varnothing)$denotes the benefit of an uninvolved alliance; $v(s_1 \cup s_2)$ denotes the benefit of an alliance formed by a participant s_1 and a participant s_2; $v(s_1)$ and $v(s_2)$, denotes the respective benefit of a participant s_1 and a participant s_2, respectively.

For a cluster of distributed PV microgrids, it is clear that the requirements of equations (17) and (18) are satisfied based on the previous analysis. Therefore, the Shapley value method can be applied to calculate the benefits due to each microgrid participating in the cooperation. For any microgrid i, the benefits $v(i)$ can be expressed as:

$$v(i) = \sum_{s \in U_i} \omega(|s|)[v(s) - v(s \setminus i)] \quad i = 1, 2, \ldots, n \tag{19}$$

$$\omega(|s|) = \frac{(n - |s|)!(|s| - 1)!}{n!} \tag{20}$$

where U_i is all subsets of the cooperative alliance containing microgrid i; $|s|$ is the number of elements in subset s; $\omega(|s|)$ denotes the weight; $v(s)$ is the total gain of alliance s; $v(s\setminus i)$ is the total gain of the new alliance formed by removing microgrid i from alliance s.

4 Simulation study

4.1 Simulation data

Taking into account the realistic installation of distributed PV equipment, this paper intends to select three groups of PV microgrids MG1, MG2 and MG3 in an industrial park in Suzhou City to form a microgrid cluster for simulation. MG1 and MG2 are manufacturing companies and MG3 is a logistics park. The basic parameters of the PV microgrid are shown in Table 1.

Table 1 Basic parameters of distributed PV microgrid

Microgrid	*PV installed capacity (MWp)*	*PV absorption ratio*
MG1	0.66	90%
MG2	2.24	90%
MG3	15	25%

Based on the actual power consumption of each microgrid and the light conditions in Suzhou, the average PV power curve and load power curve for each time period of the microgrid were calculated as shown in Figures 5 and 6.

Figure 5 Microgrid PV power generation

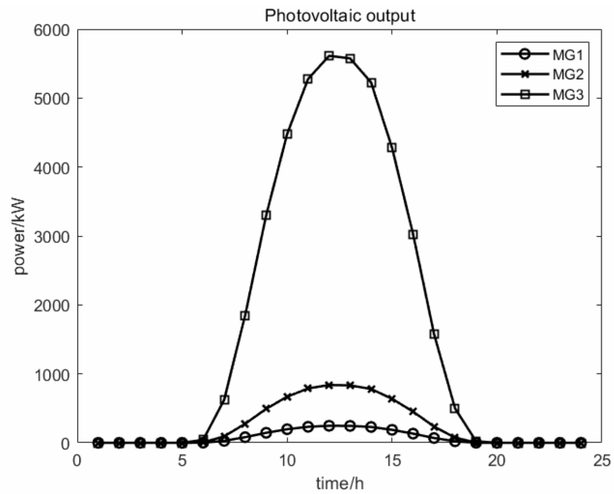
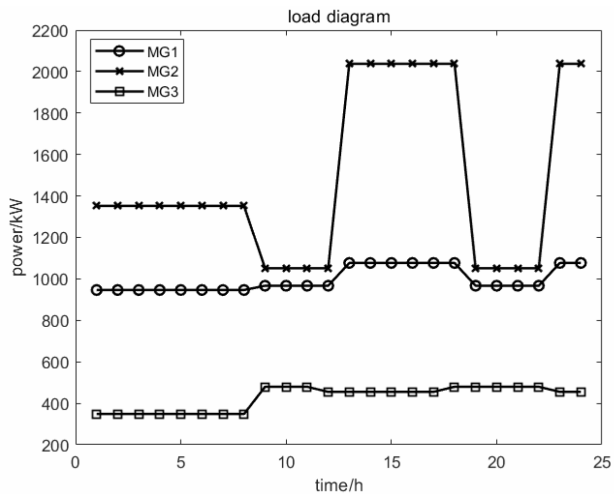
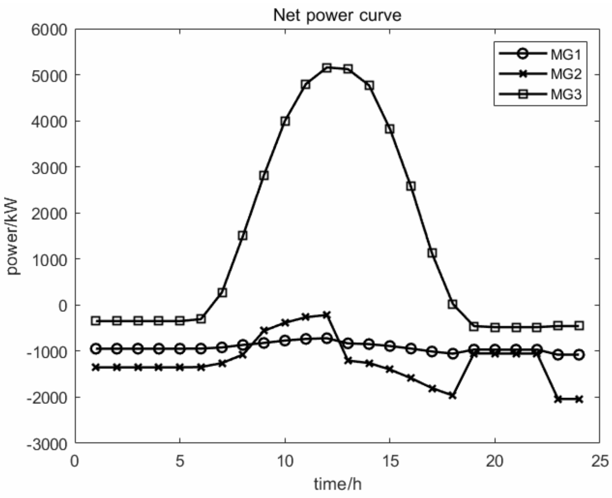


Figure 6 Microgrid load power



According to the PV output and load situation of each microgrid, the net power curve of distributed PV microgrid can be derived, as shown in Figure 7. From the net power curve, it can be seen that MG1 and MG2 are always in the state of power shortage; MG3 is a surplus power microgrid during the period of 6:00~18:00. Therefore, during the period of 6:00~18:00, the three microgrids can know the power consumption status of other microgrids through the blockchain power trading platform, thus forming a cooperative alliance.

Figure 7 Microgrid net power



Based on the FGD benchmark tariff and PV policy subsidy data released by Suzhou City, the PV residual feed-in tariff is 0.38 yuan/(kW·h).

Based on the benchmark desulfurisation electricity price and PV policy subsidies released by the Suzhou municipal government, the price for surplus PV electricity sold back to the grid is 0.38yuan/(kW·h). The price for electricity consumption during peak and off-peak hours is calculated on the basis of peak and valley tariffs by time, as shown in Table 2.

Table 2 Time-of-use electricity price

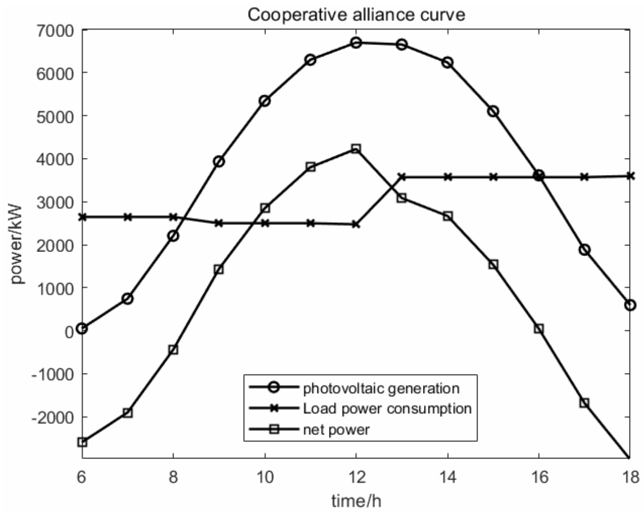
Time frame		*Electrovalence [yuan/(kW·h)]*
Peak section	8:00~12:00 18:00~22:00	1.08
Flat section	12:00~18:00 22:00~00:00	0.70
Valley section	0:00~8:00	0.36

4.2 *Analysis of simulation results*

Assuming that the total simulation time is 24 hours, the distributed PV microgrid and aggregator direct transaction model and game transaction model under the block chain are simulated.

First of all, if microgrid MG1, MG2 and MG3 form a cooperative alliance, they can share each other's electricity consumption through blockchain ledger, and realise surplus electricity mutual use through smart contract. As can be seen from the above, the three groups of microgrids can form a cooperative alliance during 6:00~18:00. Therefore, the PV power, load power and net power of the cooperative alliance can be obtained through calculation, as shown in Figure 8.

Figure 8 Each parameter curve of cooperative alliance



Secondly, after forming a cooperative alliance for power-lacking microgrid MG1, MG2 and residual microgrid MG3, the distribution of income generated by the alliance can be carried out by the cooperative game income distribution method based on Shapley value. The specific distribution calculation is shown in Table 3, Table 4 and Table 5, in which 1, 2 and 3 respectively represent MG1, MG2 and MG3.

Table 3 Alliance revenue distribution of MG1

Cooperation alliance	*{123}*	*{12}*	*{23}*	*{2}*
Residual microgrid		{3}	{1}	{13}
$v(s)$	31,067.8	6,809.1	26,270.3	5,259.5
$v(s\backslash 2)$	23,048.4	1,549.6	17,936.5	0
$v(s) - v(s\backslash 2)$	8,019.4	5,259.5	8,333.8	5,259.5
$\|s\|$	3	2	2	1
$\omega(\|s\|)$	1/3	1/6	1/6	1/3
v_{MG2}	6,691.9			

Table 4 Alliance revenue distribution of MG2

Cooperation alliance	*{123}*	*{12}*	*{13}*	*{1}*
Residual microgrid		{3}	{2}	{23}
$v(s)$	31,067.8	6,809.1	23,048.4	1,549.6
$v(s\backslash 1)$	26,270.3	5,259.5	17,936.5	0
$v(s) - v(s\backslash 1)$	4,797.5	1,549.6	5,111.9	1,549.6
$\|s\|$	3	2	2	1
$\omega(\|s\|)$	1/3	1/6	1/6	1/3
v_{MG1}	3,226.0			

Table 5 Alliance revenue distribution of MG3

Cooperative alliance	*{123}*	*{13}*	*{23}*	*{3}*
Residual microgrid		{2}	{1}	{12}
$v(s)$	31,067.8	23,048.4	26,270.3	17,936.5
$v(s\backslash 3)$	6,809.1	1,549.6	5,259.5	0
$v(s) - v(s\backslash 3)$	24,258.7	21,498.8	21,010.8	17,936.5
$\|s\|$	3	2	2	1
$\omega(\|s\|)$	1/3	1/6	1/6	1/3
v_{MG3}		21,149.9		

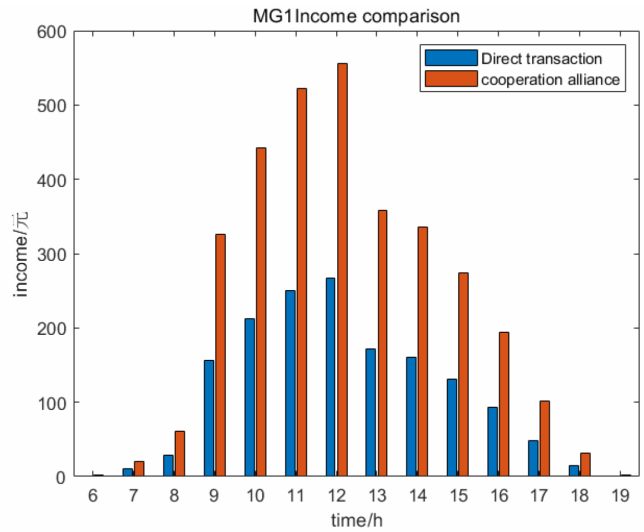
Finally, the revenue of each microgrid under the two models can be obtained based on the calculated data, as shown in Table 6.

Table 6 Microgrid revenue under two models

Microgrid	*Direct transaction income (yuan)*	*Revenue from cooperative alliances (yuan)*
MG1	1,549.6	3,226.0
MG2	5,259.5	6,691.9
MG3	17,936.5	21,149.9
Total microgrid	24,745.6	31,067.8

As shown in Table 6, the overall gain from using cooperative alliances with aggregator transactions is 25.5% higher compared to direct transactions. Under the Shapley-based cooperative gaming revenue distribution, the revenue of MG1, MG2 and MG3 increased by 108.2%, 27.2% and 17.9% respectively. This is due to the effective interaction of information between microgrids in real time under the blockchain ledger and the support of smart contracts for the interoperability of surplus power from each microgrid, which leads to the formation of cooperative alliances.

Figure 9 Comparison of profit in MG1 (see online version for colours)



In summary, the benefits of MG1, MG2 and MG3 can be obtained for the direct transaction model versus the cooperative alliance model as shown in Figures 9, 10 and 11, respectively.

Figure 10 Comparison of profit in MG2 (see online version for colours)

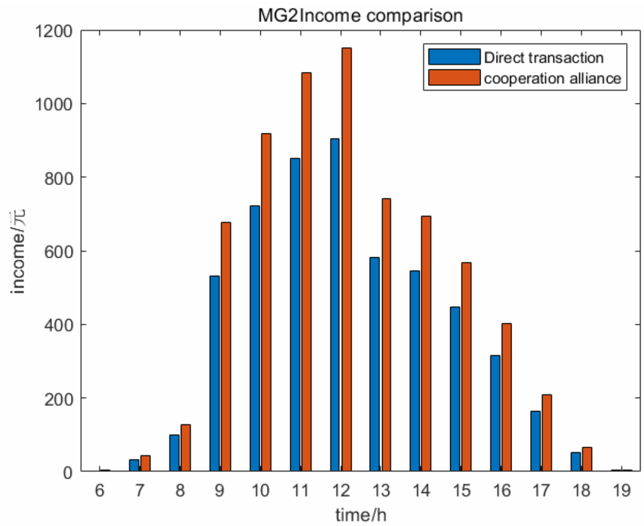
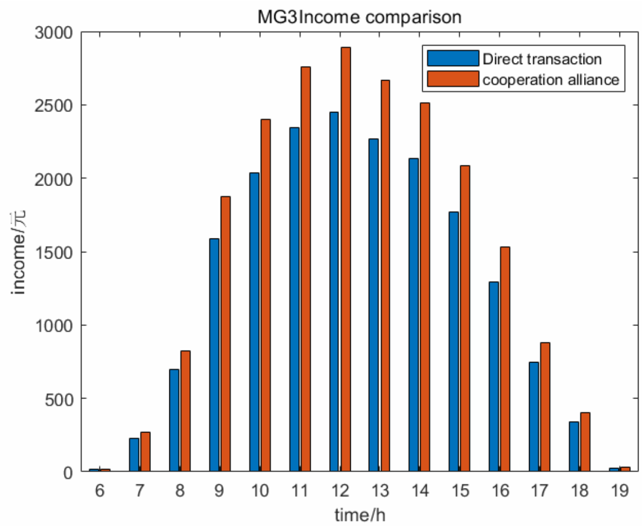


Figure 11 Comparison of profit in MG3 (see online version for colours)



It can be seen from Figures 9 to 11 that under the blockchain power trading mechanism, the cooperative alliance formed by each distributed PV microgrid has a greater increase in revenue compared to that without cooperative gaming. This also proves that the cooperative game model of multiple microgrids under blockchain proposed in this paper can effectively reduce the cost of electricity consumption and improve the benefits of microgrids. The results of comparing our model with microgrid transactions without blockchain are presented in Table 7.

Simulation experiments have demonstrated that the cooperative game solution not only effectively improves the economic benefits among multiple microgrids but also achieves energy sharing between them. The blockchain-based microgrid market gives transaction parties the power of choice and increases the flexibility of the electricity market. By utilising transaction information on the blockchain, it can effectively guide and predict the user group selection of microgrids, achieving more balanced demand response, reducing electricity costs, and improving the efficiency of microgrids.

Table 7 Comparison of microgrid transactions with and without blockchain

Comparative content	*Without blockchain*	*With blockchain*
Means of information interaction	Agency-centred	Blockchain ledger
Information reliability	Agent credit guarantee	Open and credible
Average electricity cost [yuan/(kw·h)]	0.68	0.59
Aggregate income (yuan)	24,745.6	31,067.8
Degree of new energy utilisation	Low	High

5 Conclusions

This paper proposes a blockchain-based model for distributed PV microgrids, tailored to their actual situation. The model employs a cooperative game to analyse the optimal trading strategy of the microgrid cluster. The paper draws several conclusions based on theoretical and arithmetic analysis.

1. This paper constructs a blockchain-based cooperative game model for distributed PV microgrids. Through the blockchain ledger, each microgrid is prompted to make decisions based on real-time power generation and consumption, in order to form a cooperative alliance to trade with aggregators, which reduces the cost of electricity used by microgrids and realises the full utilisation of energy.
2. Compared with the direct transaction mode of distribution network, the cooperation model can not only improve the overall revenue of the alliance, but also improve the revenue of each microgrid user by introducing Shapley value method to distribute the revenue of the alliance.The method reasonably distributes the revenue according to the contribution of each participant to the alliance as a whole, which not only allows the power shortage microgrid to reduce its power purchase cost, but also allows the surplus power microgrid to enhance its own revenue, achieving a win-win situation for all parties.
3. The simulation example verifies the feasibility and validity of the model. The calculation results show that the PV revenue of each microgrid is increased accordingly. At the same time, the cooperative alliance's 'walled sale of electricity' through smart contracts enables energy to be consumed in close proximity and greatly reduces the losses in repeated energy dispatch.

The above research focuses on user matching and profit distribution based on cooperative game under the blockchain framework, without considering specific blocking management and physical constraints of the system, which can be further studied in the following part.

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