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ORIGINAL PAPER

Decentralized peer-to-peer energy trading: A blockchain-enabled pricing paradigm

Jingya Dong[1] · Peiming Ning[1] · Han Zhao[1] · Chunhe Song[2]

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Abstract
To fully utilize the energy on the user side and establish a new integrated energy trading system to realize energy transactions among users, it is imperative to conduct research on the architecture and pricing models of energy trading systems. Based on the study of the application of blockchain technology in energy trading, this paper constructs a peer-to-peer (P2P) energy trading system using blockchain technology, enabling users to conduct energy transactions without the involvement of a third party. A dynamic energy pricing method based on game theory according to the supply–demand ratio (SDR) is proposed in this paper. The pricing model considers user satisfaction and energy supply–demand comprehensively, introduces the concept of game theory, and constructs an optimized microgrid trading model under the P2P information interaction state. This paper also discusses the application scenarios and operation processes of the P2P energy system, and carries out relevant tests. The test results show that the system has high performance and efficiency, and can meet the needs of energy trading. Finally, through simulation examples, it is proved that the pricing model proposed in this paper provides users with significant benefits and technical support, and can serve as a reference for the application of blockchain in P2P energy trading.

Keywords Energy trading · Blockchain · Pricing model · Smart contract · Game theory

1 Introduction

Under the "dual carbon" targets, distributed energy systems have garnered tremendous attention worldwide due to their high energy efficiency, flexibility, and environmental sustainability (Lei et al. 2024). Accelerating the development of distributed energy is one of the significant measures to advance the energy revolution and construct a clean, low-carbon, safe, and efficient energy system (Abdel-mawgoud et al. 2022). It is also an inevitable choice for ensuring energy security. Supporting the development of renewable energy refers to promoting the healthy, efficient, and sustainable development of distributed energy through technological innovation, the improvement of market mechanisms, and policy support (Mohapatra 2022; Abdel-Basset et al. 2022). Therefore, it is necessary to establish local energy markets, enabling distributed energy to be traded locally without the intervention of intermediaries, allowing direct transactions between users (Gorbatcheva et al. 2024).

In recent years, peer-to-peer (P2P) energy trading has become the primary solution for prosumers to actively participate in the energy market, with the aim of extending the advantages of traditional power grids by sharing distributed energy among multiple users (Zhang et al. 2024a; Gad et al. 2022). On one hand, P2P energy trading allows prosumers to conduct surplus energy transactions with local energy users, thereby generating corresponding benefits (Zhang et al. 2024b). On the other hand, P2P energy trading provides end-users with greater flexibility and more opportunities to consume clean energy (Aminlou et al. 2024). Moreover, P2P energy trading plays a positive role in the healthy development of regional energy grids, such as reducing peak demand (Yu et al. 2024), lowering maintenance and operational costs (Zhai et al. 2024), and enhancing system reliability. Concurrently, as the underlying technology for digital currencies like Bitcoin, blockchain, compared to traditional technologies, possesses characteristics of security, transparency, immutability, and decentralization. It offers an effective technical means and a friendly framework for

✉ Chunhe Song
songchunhe@sia.cn

1 School of Computer and Artificial Intelligence, Zhengzhou University, Zhengzhou 450001, China

2 Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China

achieving open, efficient, and decentralized resource allocation (Wu et al. 2024).

The application of blockchain in energy trading has gradually come into the focus of researchers (Agung and Handayani 2022), encompassing aspects such as the network framework of integrated energy service blockchain (Wang et al. 2022; Ma et al. 2022; Otoum et al. 2022), interaction models (Dong et al. 2022a), credit assessment (Woo et al. 2021), security protection technologies (Iftikhar et al. 2023; Li et al. 2023), and data access control methods (Ren et al. 2024). Most of these studies concentrate on traditional trading markets, without considering the reality that users may simultaneously act as both energy suppliers and consumers. The design and implementation of direct trading markets among consumers, prosumers, and the power grid still require improvement (Lang et al. 2021). On the other hand, energy prices are typically determined by the state, which does not necessarily reflect the local situation of energy surplus or shortage (Dong et al. 2022a). In distributed energy trading, the energy conditions of different regions should be reflected to promote the development of distributed energy systems, a point that has not been addressed in previous research. Existing approaches, such as employing a two-layer stochastic model (where the upper layer maximizes the profit of wind power producers and the lower layer minimizes the cost of demand response aggregators) (He et al. 2024), can develop cost-optimal strategies for P2P energy trading. However, achieving a balance in dynamic electricity trading and the convergence of internal selling/buying prices under such circumstances is challenging. In summary, although there have been some applications of blockchain in energy trading, there are still areas of knowledge and gaps that need to be addressed:

(1) The existing pricing methods for energy transactions often overlook the actual status of energy, resulting in the failure to accurately convey energy demand signals.
(2) The performance and scalability of existing blockchain-based energy trading are insufficient, and the regulatory framework is still incomplete, with no unified standards yet established.
(3) In terms of converging towards dynamic pricing equilibrium, collaboration and operation are necessary for the common economic interests, yet the current literature on this topic is very limited.
(4) The costs, fair distribution, collaboration, and operation related to distributed energy have not been adequately studied.

Considering the aforementioned circumstances, and taking into account the intermittent power generation of users as well as the sustainable development of energy systems, this paper proposes a blockchain-based P2P energy trading system and its pricing model. The system, based on blockchain technology, implements a P2P trading method and provides efficient and trustworthy services for participating users. The transaction information, payment process, and market platform of integrated energy trading will be executed on the blockchain through smart contracts, thereby eliminating third parties. Unlike previous models, the pricing model adopted by this system utilizes game theory to dynamically price energy based on the supply-to-demand ratio (SDR) (Long et al. 2018). This pricing model, according to the current supply and demand status of energy, simulates non-cooperative games among sellers and uses Stackelberg game for negotiation between buyers and sellers. The model conveys energy transfer signals to customers through pricing at different time points, incentivizes users to increase investment in renewable energy by increasing profits, and ensures that all participants can achieve better economic benefits. The contributions of this paper are as follows:

(1) A blockchain-based P2P energy trading framework is proposed, which constructs efficient and stable large-scale localized energy transactions through decentralized trading and supervision.
(2) A dynamic energy pricing model based on SDR is proposed to provide accurate energy demand signals, ensuring that participants achieve better economic benefits.
(3) The proposed pricing model simulates non-cooperative games among sellers based on the current supply and demand status of energy, and uses Stackelberg game for negotiation between buyers and sellers.
(4) An algorithm for accelerating the convergence of price equilibrium is proposed, which accelerates the convergence of price equilibrium through different initializations.
(5) Experiments show that the proposed system and pricing method can motivate users to participate in energy buying and selling, and have practicality and cost-effectiveness in practical applications.

The remainder of this paper is organized as follows: Sect. 2 introduces the research background. In Sect. 3, we propose a blockchain-based integrated energy trading framework. In Sect. 4, we introduce the implementation of smart contracts and their pricing models. In Sect. 5, we present the system implementation and test its performance. Finally, conclusions are drawn in Sect. 6.

2 Research background

Our work focuses on the application of blockchain technology in distributed energy trading. In the following, we will briefly review the relevant literature and explain the relationship between our work and the existing studies.

2.1 The current status and future trends of distributed energy

Distributed markets integrate both centralized and decentralized elements, offering a comprehensive approach that has the potential to maximize social welfare and significantly reduce overall costs, including computational and communication expenses (Alshahrani et al. 2024; Muhtadi et al. 2021). However, the integration of distributed energy resources (DERs), especially those with intermittent generation such as solar and wind power, can lead to voltage fluctuations and frequency deviations, affecting the overall stability and reliability of the power grid (Nishanthy et al. 2023). Specifically, the following issues may arise: (1) management issues; (2) policy issues; (3) market issues; (4) security issues.

Regarding management issues, the integration of DERs, particularly in areas with high penetration of photovoltaic systems, introduces variability into the grid load due to the variability and unpredictability of renewable energy. This makes it challenging to achieve load balancing requirements (Abdel-Basset et al. 2022). Advanced forecasting and control strategies are needed to ensure the stability of the power grid (Hussain et al. 2022). Fu et al. (Fu et al. 2024) proposed a facility-based agricultural load control model rooted in crop physiological ecology to achieve agricultural load control. Gilvanejad (Gilvanejad 2024) introduced a DER control method using solid-state transformers to balance loads between feeders. At the same time, some papers related to computational efficiency, such as (Karmouni et al. 2020, 2021), may provide some references for energy-efficient management.

In terms of policy, the electricity pricing mechanism is still imperfect, lacking fair, transparent, and effective market rules (Jain K, Dhabu M, Kakde O, Funde N 2022). Xiao et al. (Xiao et al. 2022) proposed a market mechanism that substitutes energy value with objective market value. Zhu et al. (Zhu and He 2023) introduced a hybrid demand response based on distributed energy pricing. Patonia (Patonia 2025) studies the three principles of energy justice from a socio-political perspective: distributive justice, procedural justice, and recognition justice.

Regarding market issues, the current market system and pricing mechanisms are inadequate. There is a need to reflect the market supply and demand changes of various energy products and services through market-based price changes in a timely and accurate manner (Zhang et al. 2024c). Koltsaklis (Koltsaklis and Knápek 2025) proposes a day-ahead market model to achieve optimal initial energy scheduling, which aims to provide accurate price signals and optimize resource allocation.

As for security issues, the safety and stability of distributed energy systems are relatively low, making them susceptible to external factors (Rani et al. 2024). Additionally, the self-healing capabilities of distributed energy systems are weak, making it difficult to recover quickly from faults, posing certain threats to the stable operation of the power grid (Cavalcante et al. 2015). Nejad et al. (Nejad and Sun 2022) proposed a method based on the alternating direction multiplier method to enhance the resilience of distributed systems. Moreover, information security in distributed energy systems is becoming increasingly prominent, with risks of data collection, transmission, and storage being hacked and stolen, potentially leading to the leakage of operational data and affecting the normal operation of the system (Yap et al. 2023). There is an urgent need to strengthen information security guarantees for distributed energy systems. Some studies, such as (Daoui et al. 2022a, b; Yamni et al. 2020a, b), can provide some reference value for the safety performance of energy systems.

In summary, the development of distributed energy is at a critical juncture, with the potential to transform the energy landscape towards higher efficiency and sustainability. However, issues such as pricing mechanisms, security, and stability need to be addressed urgently. The integration of advanced technologies like blockchain will play a significant role in shaping the future of distributed energy trading, improving market efficiency, and achieving environmental goals.

2.2 Adoption of blockchain in decentralized energy trading

2.2.1 Introduction to blockchain technology

Blockchain technology originated from Bitcoin. A person known as Satoshi Nakamoto published the paper "Bitcoin: A Peer-to-Peer Electronic Cash System," which detailed the architectural concepts of electronic cash systems based on P2P network technology, encryption, timestamping, and blockchain technology. This laid the foundation for the development of blockchain.

From a technical standpoint, blockchain encompasses numerous scientific and technical issues, including mathematics, cryptography, the Internet, and computer programming. From an application perspective, blockchain is a distributed shared ledger and database, characterized by decentralization, immutability, full traceability, collective maintenance, and openness and transparency. These features ensure "honesty" and "transparency," providing a foundation for trust within the blockchain. The wide range of applications for blockchain is based on its ability to address information asymmetry and facilitate collaborative trust and coordinated action among multiple parties (Wang et al. 2024). Blockchain has several essential characteristics (Athanere and Thakur 2022): (1) decentralization; (2) openness; (3) independence; (4) security; (5) anonymity.

Blockchain technology can bring profound changes to the energy industry. It functions as a unique data management system that digitally identifies and tracks changes (transactions) within the system and shares this information with connected distributed computers. If most of the computers connected to the system verify the correctness, those computers check and add new entries (transactions) to the ledger. Encryption, transparency, and economic incentives prevent malicious computers from entering erroneous new entries.

2.2.2 Smart contracts

Smart contracts are proposed by the influential interdisciplinary legal scholar Nick Szabo (Szabo 1996). He defines a smart contract as "a set of promises specified in digital form, including the agreements on the execution of these promises by the contract participants" (Morris 2016). A smart contract is a self-executing contract where the terms of the agreement between buyers and sellers are directly encoded into lines of code. This code and the agreements it contains exist across a distributed, decentralized blockchain network. The code controls execution, and transactions are traceable and irreversible. Smart contracts allow trusted transactions and agreements between anonymous parties without the need for a central authority, legal system, or external enforcement mechanism. Initially, smart contracts could not be integrated into the Bitcoin blockchain network, but the emergence of Ethereum brought them to the forefront (Buterin 2014). In this system, once the buyer and seller sign the smart contract, it automatically performs operations such as energy and amount transfer.

2.2.3 Advantages of blockchain in distributed energy trading

Blockchain technology has been extensively explored for its integration into distributed energy trading due to its inherent advantages. The decentralized nature of blockchain aligns well with the demand for a flexible and efficient energy market, allowing for peer-to-peer transactions without the need for intermediaries. This reduces transaction costs and increases the speed of energy exchanges. Additionally, the immutability and transparency of blockchain ensure the security and traceability of all transactions, which is crucial for maintaining trust in the energy market.

For these reasons, the application of blockchain in distributed energy trading is becoming increasingly widespread. Galici et al. (Galici et al. 2025) compared P2P bilateral market models using economic indicators, market complexity, and congestion management, demonstrating the effectiveness of peer-to-peer energy trading for the power grid. Veerasamy et al. (Veerasamy et al. 2024) proposed a blockchain-based double auction mechanism for P2P energy trading and utilized a distributed federated learning fractional-order recurrent neural network (FL-FORNN) adaptive controller to maintain the resilience of microgrids. Boumaiza (Boumaiza 2024) developed a blockchain-based peer-to-peer platform for direct, transparent, and secure transactions between prosumers, proving that the transparency and verifiability of blockchain technology overcome the limitations of existing centralized and aggregator-based trading methods. AlSkaif et al. (AlSkaif et al. 2021) proposed two strategies to determine the transaction preferences of fully P2P local energy households and implemented a decentralized P2P trading market on a digital platform using a permissioned blockchain smart contract platform. Yang et al. (Yang et al. 2021) developed a blockchain-based energy management platform for virtual power plants, allowing users to interact with VPPs to exchange energy for mutual benefit and provide network services. Dong et al. (Dong et al. 2022b) proposed an interactive pricing and matching strategy for P2P energy trading in a blockchain environment, promoting the coordination and complementarity of energy in microgrids. Guo et al. (Guo et al. 2022) introduced a blockchain-based multiple energy trading (B-MET) system, achieving secure and efficient energy trading through the execution of their designed smart contracts.

Despite these advantages, current market and pricing mechanisms are still imperfect. There is a need to leverage the decentralized characteristics of blockchain technology to handle the large number of transactions in distributed energy and improve the performance and security of blockchain-based energy trading platforms.

3 Blockchain-based integrated energy trading system

The P2P energy trading framework studied in this paper is shown in Fig. 1. The framework proposed in this paper is centered around blockchain technology, primarily for the following reasons: (1) It enables decentralized energy trading, eliminating reliance on intermediaries and enhancing the stability and risk resistance of the energy system; (2) Energy trading involves multiple stakeholders, and information asymmetry can easily lead to trust crises. Utilizing blockchain technology helps to strengthen market trust; (3) It adapts to the distributed and intermittent characteristics of renewable energy, promoting the integration and development of distributed energy; (4) It accommodates various modes of participants, allowing for better adaptation to market changes and demands.

3.1 Research framework

As shown in Fig. 1, the proposed research framework primarily consists of four stages:

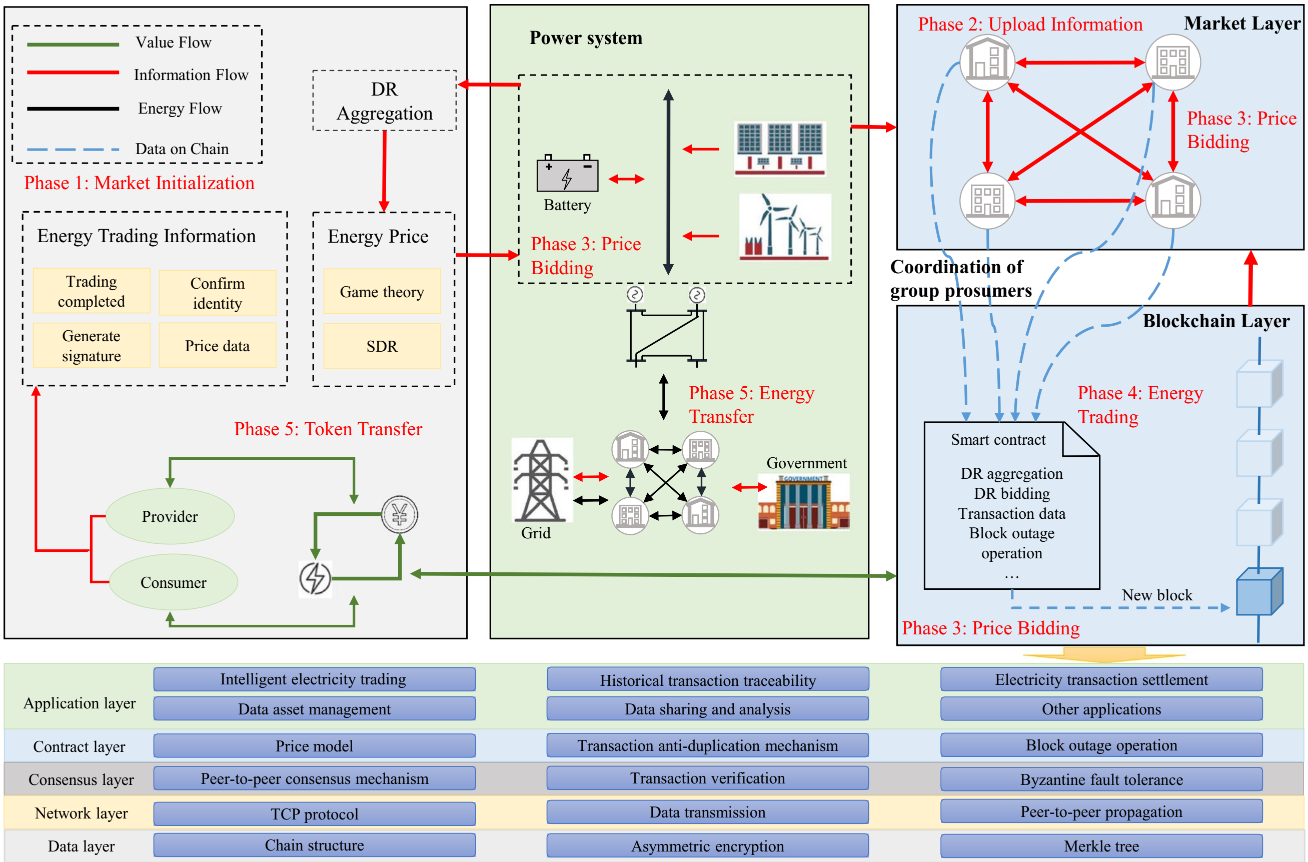

Fig. 1 System architecture model

Phase 1: Market Initialization—This stage involves initializing user information, time information, and segmented pricing data.
Phase 2: Information Update—Users submit their purchase and sale information.
Phase 3: Price Bidding—Users calculate prices based on the SDR on their client-side and submit their bids.
Phase 4: Energy Trading—Transactions are matched based on users' bid prices and bid times.
Phase 5: Value Transfer—Energy and token transfers are conducted according to the transaction information.

The blockchain system is based on a consortium chain model and includes data, network, consensus, and contract layers. The data layer encapsulates underlying blocks, relevant data, and encryption algorithms. The network layer comprises data transmission protocols and mechanisms. The consensus layer consists of consensus, validation, and security mechanisms. The contract layer mainly encapsulates technologies such as pricing models and anti-duplication mechanisms. The application layer encapsulates scenarios related to integrated energy trading. Each layer in the system performs a core task, and the collaboration between layers enables a decentralized system.

Based on these stages, the entire transaction is divided into two parts. The first part involves information exchange, including market initialization, information updates, price bidding, and the signing of energy trading contracts. The second part is the execution phase, which involves energy and value transfer, as shown in Fig. 2.

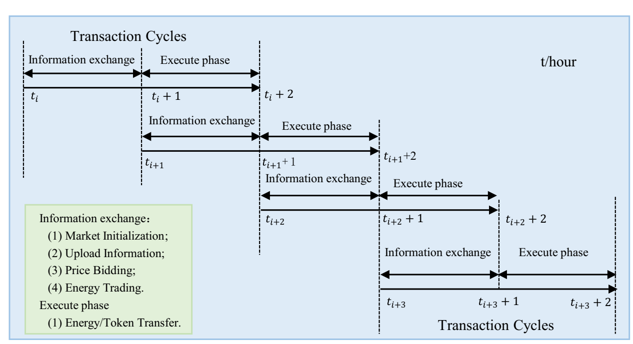

Fig. 2 Transaction cycles

3.2 Data collection and consensus protocol

3.2.1 Data on-chain

Data on-chain involves the communication between the transaction system's business node and the data acquisition module, transferring data into the system through a communication terminal (Miyachi and Mackey 2021). To facilitate this process, participants must install smart meters that communicate via the internet. These meters provide essential energy volume and price data for transactional purposes. Users who install smart meters can receive green electricity certificates, and only those who have obtained these certificates are eligible to participate in energy transactions.

3.2.2 Consensus agreement

The consensus protocol is crucial for determining how new blocks are added to the blockchain, and it forms the core layer of the blockchain architecture. Compared to Proof of Work (PoW), Proof of Stake (PoS), and Delegated Proof of Stake (DPoS) (Wahab and Mehmood 2018) the Practical Byzantine Fault Tolerance (PBFT) algorithm offers significant advantages in terms of throughput and energy consumption. Given its ability to handle high transaction throughput and maintain high efficiency (Li et al. 2020), this study selects PBFT as the consensus mechanism for P2P transactions.

3.2.3 Blockchain-based P2P energy trading system

The integrated energy trading system represents a novel value-added service that encompasses all types of electric business. It leverages existing operational expertise and incorporates innovative models and technologies to facilitate transactions. Within this system, consumers, prosumers, and power grid companies are all represented as nodes on the blockchain. Each node communicates with others and collectively maintains the public ledger.

In this system:

1. There is continuous information exchange between nodes. For instance, when a consumer purchases power resources from a nearby user, each node transmits the service request to other nodes.
2. Other nodes verify the accuracy of the information after querying and completing the P2P consensus.
3. Once a consensus is reached among the nodes, they record the consensus outcome on the blockchain.
4. Under this framework, each node possesses the capability to maintain the ledger. In the system's data area, a registry is added, which includes information such as node addresses and public keys. Nodes join the system through a registration protocol and interact after verifying each other's identities via digital signatures. The operation of the system is illustrated in Fig. 3.

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4 Smart contract and its pricing model

4.1 Smart contract

In this design proposal, smart contracts are utilized to regulate energy transactions in real-time, providing guidelines for monitoring and recording all energy transaction information. Among other functions, smart contracts execute all payment processes between prosumers, consumers, and the main grid. Due to the latency and high gas costs associated with calculations on the blockchain, this system employs off-chain computations and passes the results to smart contracts. Algorithm 1 illustrates the functioning of the smart contract. (Here, the price refers to the Nash equilibrium price, as discussed in Sect. 4.2).

Algorithm 1 Buy and sell smart contracts

Input: addr, ID, quantity, price, Time
Output: Quantity, Cost
(1) Buy:
If insufficient amount of energy required (Quantity< needed) then:
Terminate
End if
Else:
Update the quantity of the prosumer (Eq. 5)
Update the cost of the prosumer wallet with Price
End If
(2) Sell:
If Insufficient amount of energy required (Quantity< needed) then:
Terminate
If within the agreed time (Time<t) then:
Update the quantity of the prosumer (Eq. 6)
Cost of updating prosumer wallet
Else:
Update the quantity of the prosumer (Eq. 5)
Cost of updating prosumer wallet
End if

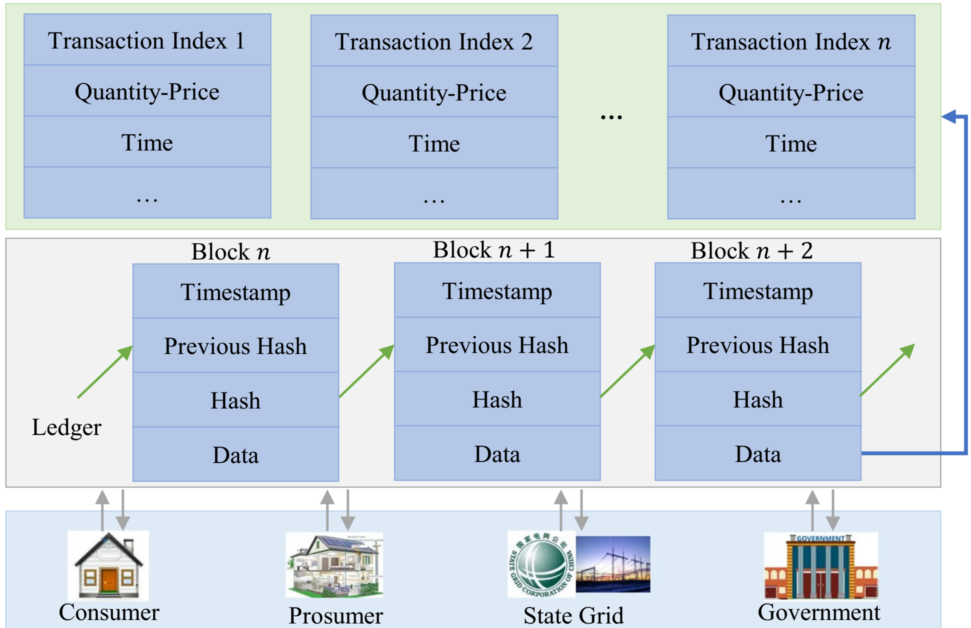


Fig. 3 System operation mode

Algorithm 1 demonstrates the feasibility of a transaction by assessing the quantities of energy being bought and sold. If the energy meets the buyer's or seller's requirements, the buyer and seller enter into a completed contract. The contract signing takes place at the time step immediately preceding the energy transition. During the energy conversion period, if the seller can provide the agreed-upon energy, the corresponding energy transfer will be executed, and the relevant wallets will be updated. However, if the seller fails to supply the agreed energy within the specified timeframe, the agreed-upon penalties will be enforced. Since the smart contract is signed and issued at the time step prior to the transaction, this paper does not account for network latency and transaction efficiency. In other words, nodes have ample time to sign contracts.

4.2 Pricing model

This section primarily discusses the energy prices and cost models that lead to pricing models.

Power generation and consumption In a given time interval t, the power generation of the i-th prosumer is defined as $G_i(t)$ (where $i = [1,2, \cdots, N]$, and N represents the number of prosumers in the network). Similarly, the consumption of the i-th prosumer in the same time interval t is defined as $C_i(t)$ (where $i = [1,2, \cdots, N]$).

Net power calculation For any user i, the net power at a given time t is expressed as (dividing a day into 24 time steps, with each time step being one hour):

$$P_i(t) = C_i(t) - G_i(t) t = [1,2, \cdots, 24] \tag{1}$$

Seller and buyer determination Since all customers have different electricity usage plans or patterns, whether a customer is a seller or a buyer depends on their net electricity at a specific time. If the energy produced exceeds the energy used, the user is considered a seller. Otherwise, they are a buyer.

Total Sales Capacity (TSC) and Total Buying Power (TBP) The definitions are as follows:

$$TSC(t) = -\sum_{i=1}^{S} P_i(t)\ P_i(t) < 0 \tag{2}$$

$$TBP(t) = \sum_{i=1}^{B} P_i(t)\ P_i(t) \geq 0 \tag{3}$$

Price and SDR relationship According to economic theory, there is an inverse relationship between price and Supply–Demand Ratio (SDR) (Ren et al. 2024). In this study, we determine the energy price after calculating the SDR. We use TBP to represent the user's energy consumption and TSC to represent the power generation. Therefore, the SDR at time t is expressed as:

$$SDR(t) = \frac{TSC(t)}{TBP(t)} \tag{4}$$

Price variation Since the selling and buying prices fluctuate at different time steps throughout the day, the prices can be expressed as:

$$X_{buy}(t) = \{X'_{buy}(1), X'_{buy}(2), \cdots, X'_{buy}(24)\} \tag{5}$$

$$X_{sell}(t) = \{X'_{sell}(1), X'_{sell}(2), \cdots, X'_{sell}(24)\} \tag{6}$$

$$X = \{X_{buy}(t), X_{sell}(t)\} \tag{7}$$

The prosumer's buying and selling prices for time t are $X_{buy}(t)$ and $X_{sell}(t)$, respectively. The grid's selling and recovery prices are expressed as $X_{high}(t)$ and $X_{low}(t)$, respectively.

Incentive mechanism To incentivize prosumers to fully participate in energy trading (especially during peak PV periods), the consumer purchase price $X_{buy}(t)$ should not exceed the price of energy purchased from the main grid $X_{high}(t)$. Additionally, the prosumer's selling price $X_{sell}(t)$ should not be lower than the selling price of the utility grid $X_{low}(t)$.

Prosumer satisfaction We quantify prosumer satisfaction using a quadratic utility function (Lang et al. 2021):

$$u_i^t = \alpha_i^t P_i^t - \frac{\beta_i^t}{2}(P_i^t)^2 \tag{8}$$

where, $\alpha_i^t > 0$ is the preference parameter of the prosumer, which varies with the prosumer, consumer, or time. $\beta_i^t > 0$ is a preset constant. P_i^t is the actual energy consumed by prosumer i.

We use the game theory method to construct the interaction model between buyers and sellers. In this pricing model, sellers compete on price through a non-cooperative game. Buyers and sellers use the Stackelberg game to negotiate between each other. We regard the seller as the leader of the Stackelberg game. The seller considers the purchase situation of the buyer, solves the problem accordingly, and obtains the best response to the buyer. Then, when prosumer ii is the buyer, its revenue function is:

$$\begin{aligned} W_i^t = u_i^t - X_j^t \sum\nolimits_{j=1}^{S} P_{j,i}^t = \alpha_i^t\left(G_i^t + \sum\nolimits_{j=1}^{S} P_{j,i}^t\right) \\ - \frac{\beta_i^t}{2}\left(G_i^t + \sum\nolimits_{j=1}^{S} P_{j,i}^t\right)^2 - \sum\nolimits_{j=1}^{S} X_j^t P_{j,i}^t \end{aligned} \tag{9}$$

where $P_{j,i}^t$ is the amount of energy that prosumer i buys from prosumer j.

When prosumer j is the seller, its income function is:

$$W_j^t = u_j^t + X_j^t \sum\nolimits_{j=1}^{B} P_{j,i}^t = \alpha_j^t\left(C_j^t\right) - \frac{\beta_j^t}{2}\left(C_i^t\right)^2 - X_j^t \sum\nolimits_{j=1}^{B} P_{j,i}^t \tag{10}$$

When buyer i selects seller j, its optimal choice is to maximize the utility function given by Eq. (9), which can be expressed as:

$$\begin{aligned} P_{j,i}^{t'} &= \underset{P_{j,i}^t}{argmax} W_i^t \\ s.t.&\begin{cases} \sum_{i=1}^{B} P_{j,i}^t \le P_j^t \\ P_{j,i}^t > 0 \\ P_{j,i}^t \le \frac{P_i^t}{\sum_{i=1}^{B} P_i^t} P_j^t \end{cases} \end{aligned} \tag{11}$$

where $P_{j,i}^t$ is the amount of energy that prosumer i buys from prosumer j, αitαit is the preference parameter of prosumer i, and β_j^t is a preset constant. The goal is to find the optimal $P_{j,i}^t$ that maximizes the utility function W_i^t.

Using Karush-Kuh-Tucker (KKT) conditions to solve Eq. (11), we can obtain the amount of electricity purchased by each buyer from the seller.

Each seller attempts to maximize its profit by selling energy. We can model the behavior between sellers using a non-cooperative game. The solution to this game is a Nash equilibrium. A Nash equilibrium exists when the following conditions are satisfied (Wang et al. 2014):

(1) The number of players is finite;
(2) The strategy set is closed, convex, and bounded;
(3) The utility function is a continuous quasi-convex function within the strategy set.

Seller j tries to maximize its revenue, which can be expressed as:

$$\begin{aligned} P_{j,i}^{t'} &= \underset{P_{j,i}^t}{argmax} W_j^t \\ s.t.&\begin{cases} X_j^t > X_{low}(t) \\ X_j^t < X_{high}(t) \end{cases} \end{aligned} \tag{12}$$

Since the seller's income increases with the increase of $P_{j,i}^t$ when X_j^t is constant, we assume that the seller can sell all the energy. In Eq. (12), $\frac{\partial^2(W_j^t)^2}{\partial(X_j^t)^2} = 0$, so W_j^t is always concave with respect to X_j^t. There are a certain number of sellers in the game, and the function given by Eq. (12) is continuous with X_j^t. Therefore, we can conclude that there is always a Nash equilibrium in the non-cooperative game between sellers.

Since it is a non-cooperative game between sellers, any seller does not know the information of other sellers before the information is published. In this case, an iterative method can only solve the Nash equilibrium between sellers. The seller's price update policy is set to:

$$X_j^t(n+1) = X_j^t(n) + \lambda(P_j^t - \sum\nolimits_{i=1}^{B} P_{j,i}^t) \tag{13}$$

The termination condition is:

$$\left|X_j^t(n+1) - X_j^t(n)\right| < \delta \tag{14}$$

Here, $X_j^t(n)$ is the price of seller j at iteration n, λ is the step size, P_j^t is the total energy available for sale by seller j, and δ is a small positive number that determines the convergence threshold.

Algorithm 2 Nash equalization algorithm

Input: The seller's initial strategy, $X_{low}(t), X_{high}(t)$
Output: Nash equilibrium state
Initialization:
  If $SDR(t) \geq 1$:
    Then $X_1^t = X_2^t = \cdots = X_S^t = X_{high}(t) - 0.01$
  Else:
    $X_1^t = X_2^t = \cdots = X_S^t = \dfrac{X_{high}(t) + X_{low}(t)}{2}$
  $n = 0$
For all $j \in S$:
  Calculate Eq. (11) to get $P_{j,i}^t$
    Calculate Eq. (12) to get seller j's income
  Calculate $\sum_{i=1}^{B} P_{j,i}^t$ and send it to other sellers
  $n = n + 1$
If Eq. (14) holds:
  Update the price according to Eq. (12)
End for

Algorithm 2 limits the rate of price increase during the iterative process, allowing the buyer to reject any price that exceeds the specified rate. This algorithm accelerates convergence by performing different initializations. Additionally, since the buyer's strategy is a response to the seller's price, controlling the update step size based on the purchase quantity can further enhance the convergence speed of Algorithm 2.

In this pricing model, the price varies according to the conditions of $SDR(t)$. When $SDR(t) > 1$, the buying price is slightly higher, and the selling price is slightly lower than the public grid's buying and selling prices. This encourages users to utilize locally produced energy during peak hours. When $SDR(t)$=1, the total selling power is equal to the total buying power ($TBP(t)$= $TSC(t)$), and no power input or output is required from the utility grid. When $SDR(t) = 0$, users are not allowed to sell; all customers must purchase energy from the main grid at a price of $X_{high}(t)$. Under this system, the selling price is not the same as the purchase price, providing more economic benefits to producers than to consumers. When $0 < SDR(t) < 1$, producers and marketers can lower prices to increase sales.

5 Results and discussion

5.1 Application scenario

This system is particularly well-suited for regions that heavily rely on external energy inputs and have significant potential for developing alternative energy sources, such as wind and solar power. It optimizes the energy structure by managing the overall energy supply and encourages users to explore new energy sources, participate in energy trading, and establish a new energy supply system cantered on clean coal, nuclear power, natural gas, and renewable energies. Within this framework, users have the flexibility to either purchase energy directly from the grid or acquire it from other users. Smart contracts facilitate the execution of energy transactions, allowing transaction parties to use various smart contracts to initiate multi-party participation records, ensuring the security and immutability of these transactions. Moreover, transaction settlements can be audited by a specialized organization, which conducts the settlements based on blockchain records and uploads the outcomes to the blockchain for verification and traceability. Unlike traditional energy distribution, which involves long-distance transmission from a single source to customers, this system's energy trading framework enables multi-directional, localized transactions. The system addresses challenges such as information security, data loss, and leakage by leveraging the ever-evolving capabilities of blockchain technology.

5.2 Implementation process

In traditional centralized data storage systems, establishing trust requires participants to submit identification documents and sign agreements, which is not only time-consuming but also resource-intensive. Given that P2P energy transactions involve many users, this conventional approach is clearly not suitable for this scenario. In contrast, our proposed blockchain—based system offers significant advantages. It leverages the transparency, immutability, and decentralization features of blockchain technology to address these issues. Our system assigns a unique electronic passport to each producer and consumer, recording their transaction plans, purchase volumes, and sales volumes on the blockchain in an immutable and irreversible manner. This is a more efficient and secure way to manage data compared to the traditional approach. Concurrently, we utilize blockchain technology to implement a decentralized trust mechanism, ensuring that every node can access and verify the data. This eliminates the complex and costly verification procedures typically required in traditional data storage, making it a more suitable solution for P2P energy transactions.

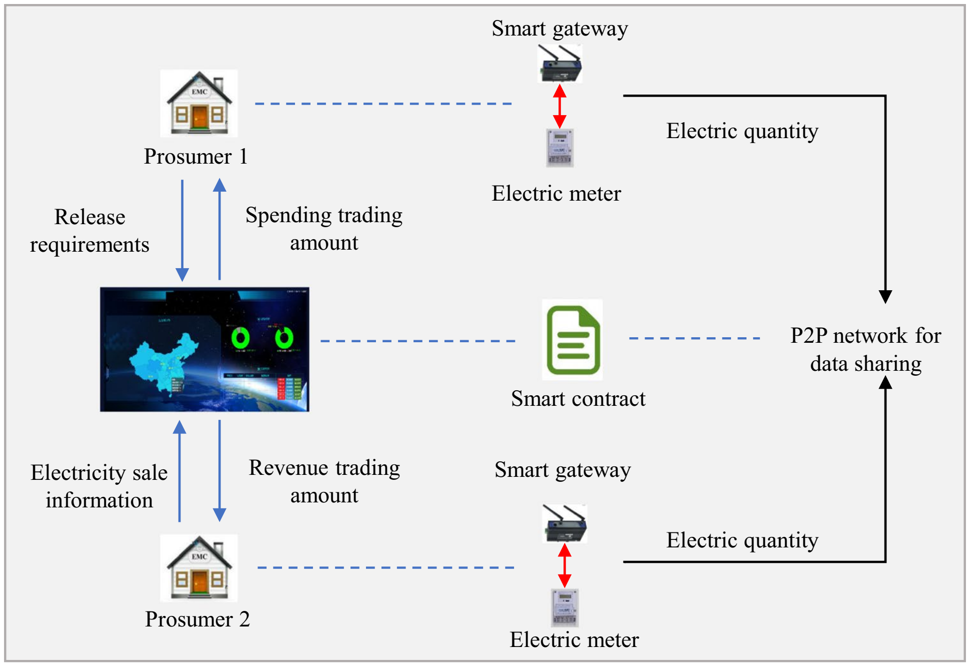


Fig. 4 System operation process

As shown in Fig. 4, the blockchain method is realized by generating blocks, with the detailed hash information included as shown in Table 1. Each hash block consists of the hash of the previous block and its own hash. It is evident that the previous hash value of the current block is the hash value of the previous block. Thus, any alteration in the data will result in changes to all subsequent data, ensuring the immutability of the data and safeguarding the security of transactions. Moreover, any changes in P2P transactions can be recorded in the blocks. The decentralized consensus mechanism is vital for detecting and repudiating attempts to tamper with data.

In the context of energy transactions, buyers initiate the process by articulating their demand for energy purchases and disseminating this information to other network participants. Sellers, in response, determine the sales price through a continuous iterative process, aligning it with the current market energy demand. Once the sellers' price is established, buyers enter into a smart contract with the sellers. This smart contract secures the transaction amount from the buyer's account and releases it to the sellers' account upon the successful completion of the transaction. Concurrently, the transaction details are recorded on the blockchain and are jointly maintained by multiple nodes, as depicted in Fig. 4.

5.3 Case study

Consider a scenario involving P2P energy transactions where prosumers have two types of loads: fixed and controllable loads, along with solar installations of varying peak power capacities (measured in kilowatts peak, kWp). The system is deployed on the Ethereum blockchain as a consortium chain. Smart contracts and API interfaces are developed using Solidity and JavaScript to facilitate communication between the smart contracts and the APIs. The system is deployed on a server equipped with 128 GB of RAM and an Intel Xeon E3 processor for testing concurrent business processing. Additionally, the cost of miners is not considered in the experiment.

This section presents the simulation results aimed at evaluating the effectiveness of the proposed pricing model for P2P energy transactions. Consider a scenario involving P2P energy transactions where prosumers have two types of loads: fixed and controllable loads, along with solar installations of varying peak power capacities (measured in kilowatts peak, kWp). The system is deployed on the Ethereum blockchain as a consortium chain. Smart contracts and API interfaces are developed using Solidity and JavaScript to facilitate communication between the smart contracts and the APIs. The system is deployed on a server equipped with 128 GB of RAM and an Intel Xeon E3 processor for testing concurrent business processing. Additionally, the cost of miners is not considered in the experiment.

5.3.1 Simulation and evaluation of P2P energy trading

This section presents the simulation results aimed at evaluating the effectiveness of the proposed pricing model for P2P energy transactions. The analysis involves a microgrid consisting of five consumers. This microgrid is connected to the main grid, allowing users to conduct transactions with either

Table 1 Blockchain utilized for recording transactions

Block	Hash and Data	Event
Block 1	fa1743f48649cff069e71484d802446f13d17aa902880dae96d39a360f82af9c	Genesis Block
Block 2	Timestamp = '1,011,143,150' Previous Hash = 'fa1743f48649cff069e71484d802446f13d17aa902880dae96d39a360f82af9c' 'ID0212 = −3.167' Self-hash = '5b4b5ca1774f5bd0da08032670595e1c7edbd93878f64ce4ad86c93102d8cf72'	Publish sales information
Block 3	Timestamp = 1,011,143,221 Previous Hash = '5b4b5ca1774f5bd0da08032670595e1c7edbd93878f64ce4ad86c93102d8cf72' 'ID0245 = + 2.424' Self-hash = 'c2cc2ff48e279945fde2a821beede5951898299cc1fdee7bd5fb5d2546ba1807'	Publish purchase information
Block 4	Timestamp = '1,011,143,250' Previous Hash = 'c2cc2ff48e279945fde2a821beede5951898299cc1fdee7bd5fb5d2546ba1807' 'ID0129 = + 1.342' Self-hash = '92426c2b7347d6561232f69336832037649600e157b9fcbd7cc50e635e89e18e'	Publish purchase information
Block 5	Timestamp = '1,011,143,255' Previous Hash = '92426c2b7347d6561232f69336832037649600e157b9fcbd7cc50e635e89e18e' "ID116 = −1.234" Self-hash = '258d9f97ed0c2dc8232933fb5161b220a2de68dd371f586803241859bbc95ad4'	Publish sales information
Block 6	Timestamp = 1,011,143,340 Previous Hash = '258d9f97ed0c2dc8232933fb5161b220a2de68dd371f586803241859bbc95ad4' 'ID154 = + 2.751' Self-hash = 'ff79d50884a6b622232c2669ef2481560f5ab285f866f303f9f747032e77def8'	Publish purchase information
Block 7	Timestamp = '1,011,143,850' Previous Hash = 'ff79d50884a6b622232c2669ef2481560f5ab285f866f303f9f747032e77def8' 'ID0212:ID0245 = 2.424; ID0212: ID0129 = 0.743; ID116: ID0129 = 0.599; ID116: ID154 = 0.635' Self-hash = '8ba0075f8e9b83c8441eb68bed5abf5a7cbc2114bae92198530f1f668abf2580'	Energy trading
…	…	…

their peers or the main grid. Each consumer has a solar photovoltaic system installed, with capacities ranging from 100 to 400 kW. The simulation is structured over a 24-h period, divided into 24 time steps, denoted as $T = \{1,2, \cdots, 24\}$. It is assumed that the users do not have energy storage facilities. Figure 5 illustrates the energy demand profiles of the five prosumers at various times throughout the day.

We randomly select a value from the interval [5:00, 10:00] to represent a_i^t and set the value of β as 0.5. We employ dynamic, time-varying electricity prices as the benchmark for our research. Figure 5 indicates that P2P energy trading is particularly active between 9:00 and 15:00, and we focus primarily on this period for our analysis. Based on the value of SDR(t), prosumers can assume the roles of sellers or buyers throughout the day. We select 11:00 to validate the performance of the proposed pricing model. At this time step, prosumers 3 and 5 act as sellers, while the others act as buyers. Peer-to-grid (P2G) scenarios refer to the absence of P2P transactions, where required energy must be purchased solely from the grid, and excess energy can only be sold directly to the grid.

The primary objectives of our proposed pricing model are twofold: (1) to leverage non-cooperative game theory among sellers for price competition, and (2) to employ the Stackelberg game for negotiations between buyers and sellers. As the sellers take the roles of leaders in the game, the Stackelberg solution optimally responds to the buyers. Figure 6 illustrates the convergence properties of prosumer prices towards the Nash equilibrium. When the sellers' prices approach the Nash equilibrium point, the buyers' demand for electricity from the sellers also converges to a certain extent. This process confirms the existence of a Nash equilibrium in the transaction process. Figure 7 displays the equilibrium prices that prosumers ultimately agree upon at different times. From Fig. 7, it is evident that the final convergent prices of prosumers are not only related to the selling and recycling prices of the main network at that time but are also significantly influenced by the supply and demand dynamics of the network.

Figure 8 illustrates the interactions between prosumers and the power grid under various transaction modes. Analysis of Fig. 8 reveals that, compared to P2G transactions, the volume of electricity bought and sold by prosumers through the grid is diminished under P2P transactions. This reduction indicates that P2P transactions can mitigate the impact of user electricity consumption on the power grid, potentially enabling prosumers to reduce or even eliminate their reliance on grid power for certain periods.

Table 2 presents the expenditures and incomes of prosumers and marketers. Examination of Table 2 demonstrates that at different times, the overall expenditures of users decrease, while their overall incomes as sellers increase. Consequently,

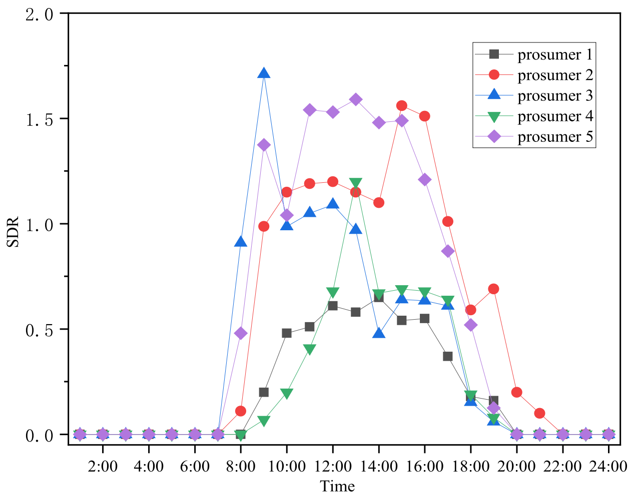


Fig. 5 SDR of prosumers

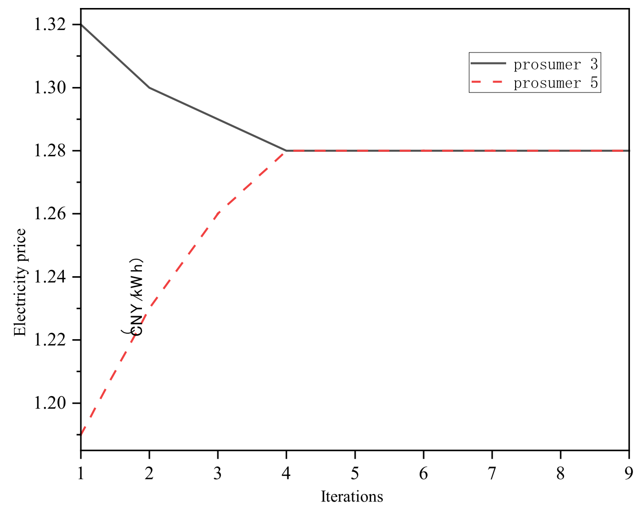


Fig. 6 Convergence of price of sellers at $t = 11$

the proposed pricing model is effective in managing P2P energy transactions, offering economic benefits to participants.

5.3.2 Analysis of regional energy regulation

In this section, we analyze the regional energy regulation capabilities of the proposed method. The introduction of P2P energy trading in microgrids serves two purposes: (1) to enhance energy utilization efficiency; (2) to achieve load balancing within the microgrid, thereby reducing the impact on the upper-tier power grid. We conduct an analysis of regional regulatory capabilities under the following five scenarios: (1) P2G only; (2) P2G with P2P; (3) P2G with Battery Storage Systems (BSS); (4) P2G with P2P and BSS; (5) P2G with P2P, BSS, and SDR. We assume that all prosumers have a storage capacity of 1 kW·h. Intuitively, we analyze the regional energy regulation capabilities using a practical example of actual energy consumption within an area with 100 users, as illustrated in Fig. 9.

Figure 9 (a), (b), and (c) respectively illustrate the inflow, outflow, and total flow of energy within the microgrid. As depicted in Fig. 9 (a), while increasing solar energy can enhance energy utilization rates, it paradoxically increases the load on the upper-tier power grid. Figure 9 reveals that with the introduction of P2P energy trading, the energy sold by prosumers to the grid is significantly reduced, indicating that P2P energy trading can alleviate the load on the upper-tier power grid. The sales and purchases of the microgrid to the overall power grid are close to zero, demonstrating that P2P transactions among prosumers can meet their demands, thereby reducing the reliance on the power grid and the impact of photovoltaic generation on it. Furthermore, in Scenario 5, the energy purchase and sale volumes are minimal, resulting in a reduced impact on the upper-tier power grid, which validates the effectiveness of the strategies proposed in this paper. Consequently, the P2P energy trading method proposed here can better achieve self-sufficiency in energy, mitigate the impact on the upper-tier power grid, and possess superior regulatory capabilities.

We conducted a visual comparison across four key aspects of regional microgrid energy: daily total energy input, daily total energy output, daily peak electricity demand, average daily electricity consumption, and load factor. The comparison results are presented in Table 3. Specifically, the daily total energy input refers to the total energy purchased from the grid, which is the energy flowing into the microgrid from the grid on that day; the daily total energy output is the total energy sold to the grid, representing the energy flowing from the microgrid into the grid on that day; the daily peak

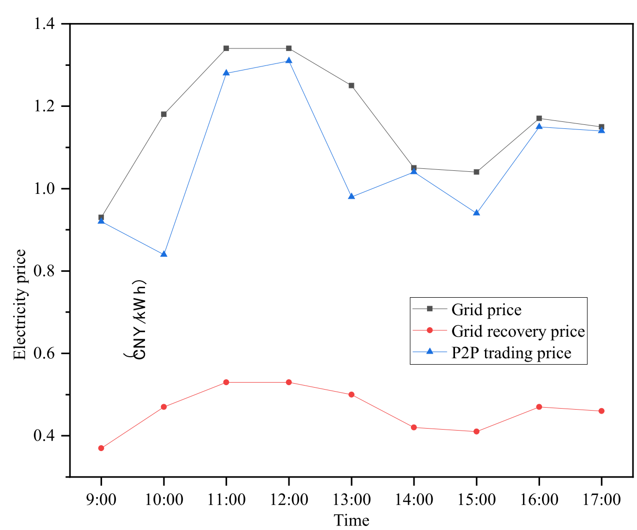


Fig. 7 Hourly P2P trading price

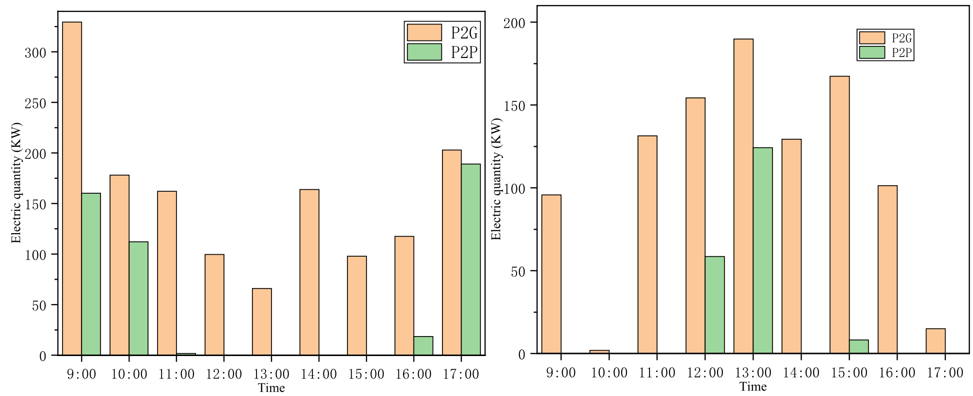


Fig. 8 Energy exchange between prosumers and the grid. (**a**) The total electricity input from the grid; (**b**) The total electricity output to the grid

Table 2 Expenditure/income

Time	Expenditure		Saving percentage	Income		Increasing percentage
	P2G	P2P		P2G	P2P	
9:00	306.32	237.05	29.22%	35.40	88.03	148.67%
10:00	210.09	133.96	56.83%	0.89	1.60	79.78%
11:00	217.11	170.55	27.30%	69.63	168.17	141.52%
12:00	133.60	125.456	6.49%	81.79	156.50	91.34%
13:00	82.35	64.14	28.39%	94.88	126.29	33.11%
14:00	172.00	134.58	27.81%	54.35	134.58	147.62%
15:00	101.84	92.04	10.65%	68.62	95.4	39.30%
16:00	137.49	135.5	1.47%	47.63	113.98	139.78%
17:00	233.42	233.28	0.06%	6.86	15.90	131.78%

electricity demand is the highest value of energy input from the grid; the average daily electricity consumption is the mean value of electricity usage per hour; and the load factor is the ratio of the average net electricity load to the maximum electricity load, with a lower load factor indicating more stable operation. As shown in Table 3, the proposed method excels in the first four metrics but underperforms in the last, due to the introduction of SDR, which shifts the load to peak electricity demand times to maximize profits.

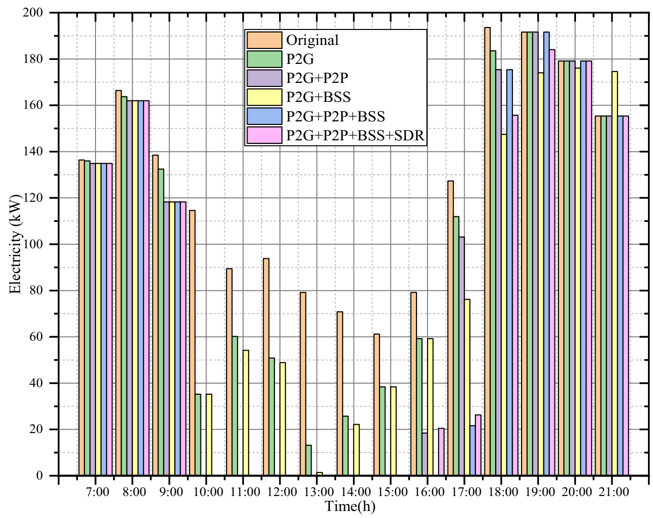
As evident from Fig. 9 and Table 3, Scenario 5 exhibits a significant reduction in peak values, thereby demonstrating the effectiveness of the proposed method in peak load shifting. Consequently, the method presented in this paper enhances the stability of the power grid, improves the utilization of energy resources, and mitigates the impact on the upper-tier power grid.

6 Conclusion

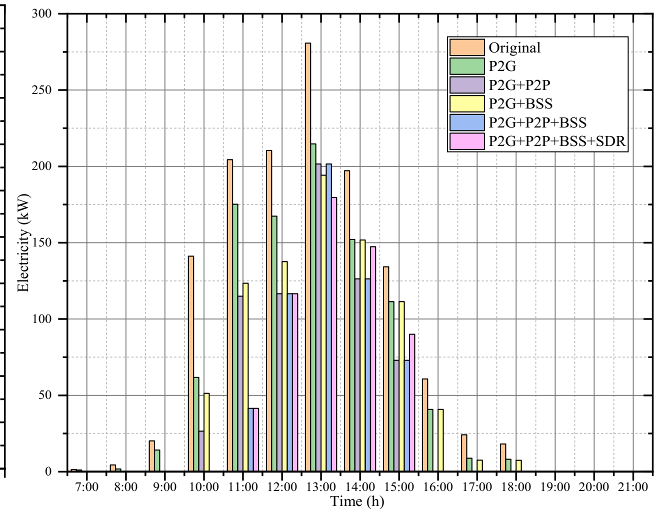
This paper aims to enhance energy utilization efficiency on the user side by increasing user revenue through the development of a blockchain-based P2P energy trading system. By leveraging blockchain technology, energy transaction data becomes more transparent, reducing risks and saving significant workforce and material resources. Smart contracts are utilized to create a new automated workflow, further reducing manpower and material costs. Additionally, this paper designs a pricing model tailored for the system. This model encourages users to participate in energy buying and selling, improving energy utilization and promoting the construction of a new energy system.

However, the research has certain limitations. The experimental validation was carried out in a simulated environment with a restricted node scale, which might not fully reflect real—world operational complexities. The energy storage component within the trading system requires more refined modeling to address temporal mismatches between supply and demand.

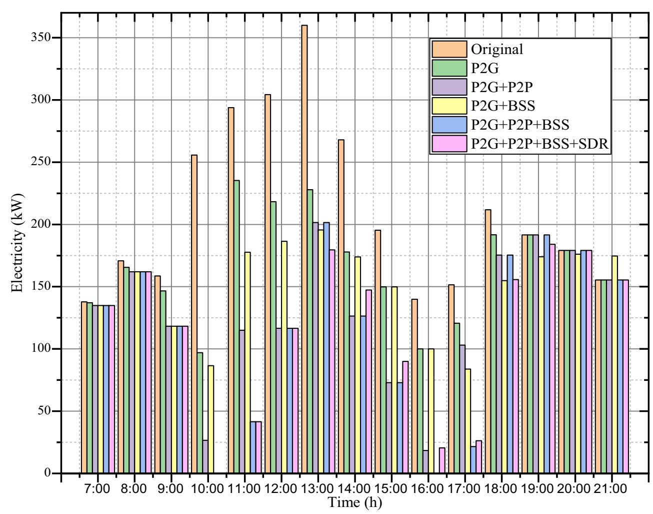
Future research directions should focus on: (1) Implementing large—scale field trials with actual energy infrastructure to verify system robustness; (2) Developing adaptive pricing mechanisms that integrate machine learning predictions with real—time grid conditions; (3) Exploring hybrid blockchain architectures to optimize the balance between transaction throughput and energy consumption. It is also recommended to investigate regulatory



(a) Energy flowing into microgrids



(b) Energy flowing out of microgrids



(c) The total energy inflow and outflow of microgrids

Fig. 9 Energy flow in regional microgrids. (**a**) Energy flowing into microgrids (**b**) Energy flowing out of microgrids (**c**) The total energy inflow and outflow of microgrids

Table 3 Load variations in microgrid under different scenarios

	Daily total energy input	Daily total energy output	Average daily electricity consumption	Load factor
Original	1876.45	359.91	211.58	0.6462
P2G	1536.66	235.37	166.27	0.5347
P2G + P2P	1238.25	201.58	126.48	0.4308
P2G + BSS	1423.09	195.59	149.91	0.5388
P2G + P2P + BSS	1138.25	201.58	113.15	0.3960
P2G + P2P + BSS + SDR	1156.21	184.05	114.08	0.4117
Comparison with the original	**39.45%**	**48.9%**	**46.1%**	**−36.31%**

frameworks and standardization protocols to facilitate practical implementation.

Although the application of blockchain in energy trading services is still in its initial phase, this study has demonstrated technical feasibility through systematic design and preliminary testing. It is expected that this paper will offer valuable insights and a foundation for subsequent research into blockchain—enabled energy trading systems.

Author contribution Jingya Dong conceptualized this study, wrote the original draft, and curated the data. Peiming Ning conducted the formal analysis and provided the software. Han Zhao was responsible for validation and visualization. Chunhe Song acquired the funding and provided supervision. All authors revised the manuscript.

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Data availability Data will be made available on reasonable request to the corresponding author.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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