ISSN: 2710-0588 DOI: 10.29556/FSE.202105_1(2).0015

A Stackelberg Game Model for Direct Power Purchase by Large Consumers under Consortium Blockchain Framework

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Abstract

Traditional direct power purchases by large consumers utilize a central authority to manage transactions. Centralized data storage brings problems such as low data security and a trust crisis caused by a high dependence on third-party organizations. In order to solve the above problems, this paper builds a direct power purchase transaction system under the framework of the consortium blockchain to realize the distributed storage of transaction data, the anonymity of the transaction, the unforgeability and the traceability. In addition, in response to the opaque market price signals and lack of flexibility in the existing bilateral negotiation and centralized bidding transaction models, we propose an algorithm based on reputation value and Stackelberg game. The model uses a reputation mechanism to suppress the behavior of malicious nodes to ensure the reliability of direct power purchase. Experiments show that this model can effectively reduce the power purchase cost of large consumers, expand the market share of power generators, and has better flexibility.

Keywords

Consortium Blockchain; Direct Power Purchase; Stackelberg Game; Reputation.

1. Introduction

In recent years, the rise of the Industrial Internet of Things (IIoT) has received widespread attention and has become an important part of the transformation of future industrial systems [1-2]. The IIoT promotes the development of smart grids in the direction of the Internet of Energy (IoE). IoE realizes distributed energy network by expanding smart grid [3], and at the same time, it also makes the direct power purchase by large consumers(LCs) change in the direction of distributed transaction [4]. The direct power purchase transaction model extends from 'one-to-one' bilateral negotiation to 'one-to-multi' and 'multi-to-multi' platform transactions, where both parties directly interact with each other [5].

The traditional model of direct purchase of electricity for large consumers relies on third-party trust organizations, and there are security issues such as data loss, data tampering, and information leakage, as well as trust issues with central organizations. As a 'partially decentralized' blockchain structure in the classification of blockchain, the consortium blockchain is essentially a distributed ledger database, which is a series of data blocks generated by cryptography [6]. Its decentralization, intelligence, traceability and other characteristics have strong coupling with the IoE in the three dimensions of physical-information-value. In addition, the consortium blockchain put forward certain requirements for the nodes that join the blockchain, which is highly similar to direct power purchase by large consumers with access qualifications and regulatory requirements. Secondly, compared with public blockchain, consortium blockchain have the characteristics of high efficiency, low cost, and faster transaction speed [7], which are more suitable for direct power purchase transactions by large consumers.

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The current direct power purchase transaction model is mostly based on bilateral negotiation, centralized matching, and centralized bidding. Among them, bilateral negotiation has problems such as opaque market price signals and insufficient flexibility; centralized matching relies on central agency matching. As transaction power increases, there have problems such as low transaction efficiency and decline in transaction power, and it cannot play the guiding role of market price signals. While centralized bidding is due to the completion of market matching according to the unified clearing price, and the transaction matching is compulsory according to the spread. The market choice given to users is low.

In this regard, this paper proposes a direct power purchase transaction model for large consumers based on reputation value and Stackelberg game. With power generators(PGs) as leaders and large consumers as followers, it realizes 'multi-to-multi' direct power purchase transactions for large consumers. The reputation value mechanism is used as a positive indicator to evaluate the enthusiasm of nodes to stimulate the vitality of the trading market. In the game process, large consumers can grasp market price signals in real time by receiving quotations from power generators, and have more freedom of choice and more flexible trading modes.

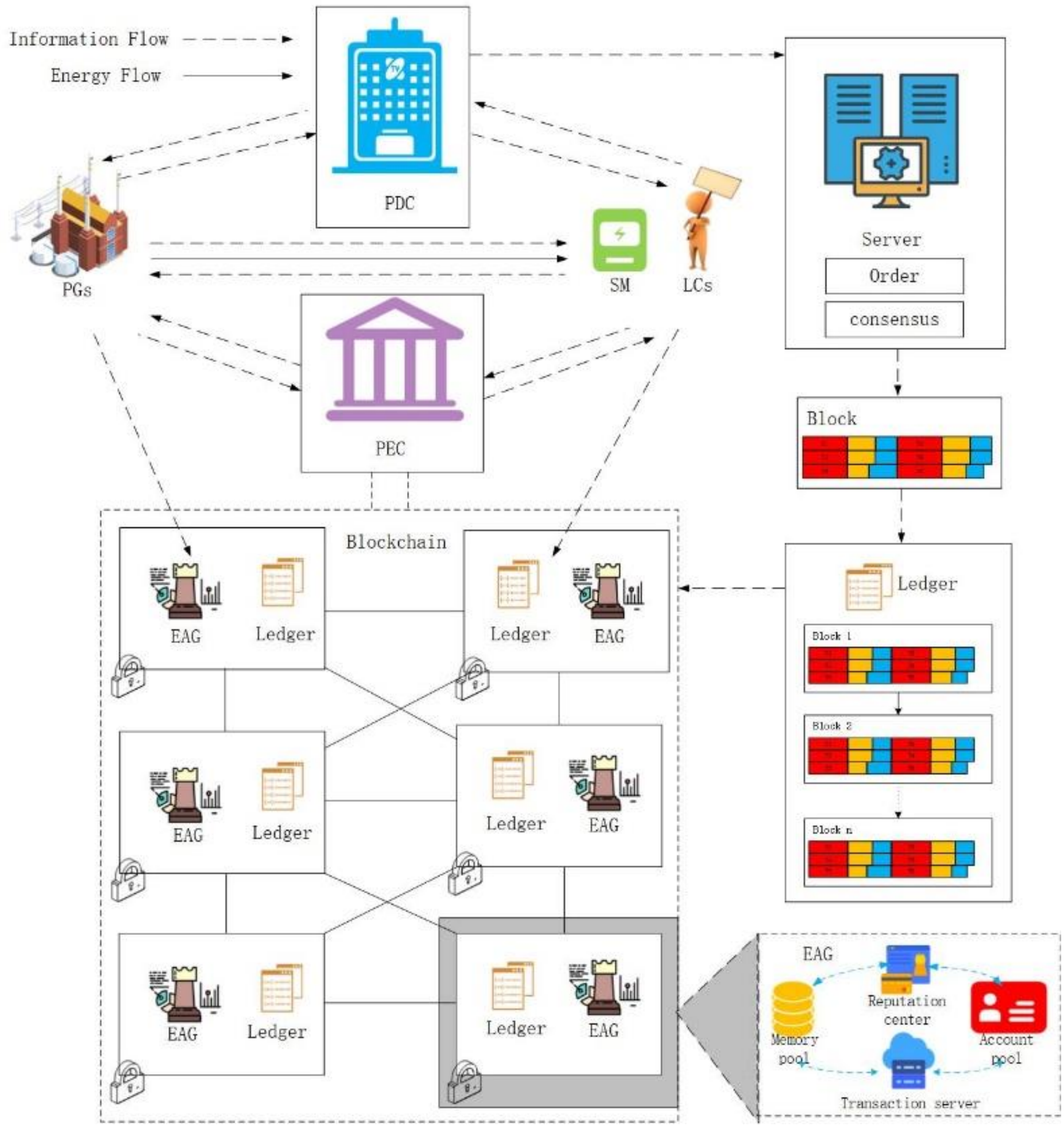

Figure 1. The system of direct power purchase by LCs under the consortium blockchain framework

ISSN: 2710-0588 DOI: 10.29556/FSE.202105_1(2).0015

2. Direct Power Purchase Trading System under Consortium Blockchain Framework

In the process of traditional direct power purchase by large consumers(LCs), it is necessary to designate a trusted third-party authority to coordinate and supervise (such as power trading center), and transaction records are mostly stored in a centralized manner. Once the system fails or is compromised, it will cause irreparable losses. At the same time, this centralized transaction model makes transaction records under the authority to be directly or indirectly accessed and accessed to a certain extent, and the security of the private data of both entities to the transaction cannot be guaranteed.

In order to solve the pain points of the existing centralized direct power purchase, and realize the true, reliable, safe and reliable, real-time delivery of the direct power purchase by LCs. This paper improves the traditional direct power purchase transaction system, and designs a system of direct power purchase by LCs under the consortium blockchain, as shown in Figure 1. There are six types of entities involved: Transaction Nodes (TNs), Power Exchange Center (PEC), Power Dispatching Center (PDC), server (Server), Energy Aggregators (EAGs), Smart Meters (SMs). The system of direct power purchase by LCs under the consortium blockchain framework is shown in Figure. 1.

TNs:PGs and LCs.

PEC: PEC reviews application materials submitted by transaction nodes, authorizes access to identity information for nodes, initializes reputation values, sets reputation value thresholds for direct power purchase transactions, and provides nodes with partial pseudo-identity information.

PDC: Responsible for the security check and congestion management of direct power purchase transactions, issue public and private keys for nodes, provide complete pseudo-identity information for transactions, and trace the true identity of nodes.

Server: Responsible for sorting the direct power purchase transaction data submitted by PDC in time series and completing consensus.

EAGs: The energy aggregator is a physical entity that connects the direct power purchase transaction nodes in the consortium blockchain, and acts as an energy broker in the direct power purchase transaction of LCs based on the consortium blockchain [8]. The main functions include transaction data storage, transaction account storage, Transaction matching services and reputation value measurement, while providing power and wireless communication services for direct power purchase transaction nodes.

3. A Stackelberg Game Model for Direct Power Purchase by Large Consumers under Consortium Blockchain Framework

In this section, based on the information transmission process of the consortium blockchain and the Stackelberg game process of direct power purchase transactions, we establish a 'sale-load' end Stackelberg game transaction mathematical model. A Stackelberg game model is designed based on the profit, cost situation and node reputation value calculation of each transaction entity, and then the consortium blockchain is introduced to establish a transaction model of each entity for the direct power purchase by LCs.

At present, the electricity trading market mainly includes a bilateral contract market and a spot trading market. The trading mechanism of the bilateral contract market is mainly a pay as bid (PAB). The trading mechanism of the spot trading market is mainly a unified market clearing price (MCP) mechanism. We define $S=\{1,2,3,\ldots,M\}$ and $L=\{1,2,3,\ldots,N\}$ to represent the collection of PGs and LCs participating in direct power purchase transactions. $T=\{1,2,3,\ldots,O\}$ represents time period collection, where $i\in S, j\in L, t\in T$.

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3.1. The mathematical model of power generators

For S_i, who receives power purchase strategy feedback from LCs through EAG. Constantly adjust their quotation to gain more market share. Under the cycle of 'quotation-feedback-quotation', PGs calculate the quotations that can get the most profit. The profit function F_i of S_i can be expressed as:

$$F_i = \sum_{j=1}^{N} (\pi_{i,j} U_{i,j}) - \xi (\sum_{j=1}^{N} U_{i,j}) - C_{S_i} \quad (1)$$

Where $\pi_{i,j}$ and $U_{i,j}$ are the unit contract electricity price and unit contract electricity of S_i with L_j in the bilateral contract market. ξ is the grid-crossing fee per unit power paid by the PG to the grid company. The grid-crossing fee is determined by the government based on the PGs' access voltage level and consumption range. C_{S_i} is the cost of power generation.

3.2. The mathematical model of large consumers

In the process of direct power purchase transactions, LCs obtain quotations from PGs in the bilateral contract market and prices in the spot market through the transaction server, formulate power purchase strategies based on their own demand for electricity, and optimize their own power purchase costs. The power purchase cost of LCs can be expressed as:

$$C_{L_j} = \sum_{i=1}^{M} \pi_{i,j} U_{i,j} + \pi_m U_{i,j}^{''} \quad (2)$$

Where π_m and $U_{i,j}^{''}$ are the electricity purchase price and electricity volume of large consumer L_j in the spot market, respectively.

3.3. The mathematical model of reputation

After each game between PGs and LCs, the reputation center in the EAG will carry out a reputation value update. As a qualification certificate for nodes to participate in direct power purchase transaction, the reputation value can effectively avoid damaging the direct power purchase transaction by nodes' malicious quotation behavior. The reputation value R_i of each node is calculated as follows:

$$R_i = \frac{\sum_{p=1}^{y} \vartheta_{i_p}}{\sum_{p=1}^{y} z_{max_p}} + \frac{y}{x} \quad (3)$$

Where x is the total number of games played, the value of x is calculated after the node registered as a legal entity of the consortium blockchain, y represents the number of games that node i successfully participated in, and p represents a certain game in which the node i participates, $p \in y$. There are at most z_{max_p} successful transaction nodes in the pth game. When the attribute of node i is a PG, $z_{max_p} = N$. When the attribute of node i is a LC, $z_{max_p} = M$. ϑ_{i_p} is the number of node i successfully traded in the pth game, $\vartheta_{i_p} \le z_{max_p}$. The reputation value R_i depends on the matching rate and participation rate of nodes in the direct power purchase transaction, where: $0 \le R_i \le 2$. Entities participating in direct power purchase transactions need to meet the threshold R' set by PEC. For transaction entities whose reputation value does not meet the standard, the difference in reputation value can be made up through time shelving or economic penalties.

3.4. System flow

3.4.1. System Initialization

PGs and LCs participating in direct power purchase first apply for registration at the PEC and apply for the qualifications to participate in direct power purchase transactions. For PGs,

ISSN: 2710-0588 DOI: 10.29556/FSE.202105_1(2).0015

materials such as unit coal consumption and carbon emissions must be submitted; for LCs, materials such as their annual power consumption, power supply voltage level, and a copy of their business license must be submitted, and they cannot be restricted or prohibited companies. After successful registration, the applicant who meets the market access conditions will obtain a legal identity ID_i and access the EAG. The power trading center initializes the reputation value R_i of the entity that has successfully registered for the first time, and transmits the reputation value of the node to the reputation center of EAG.

A direct power purchase transaction node with a real identity ID_i joins the system, and obtains its public key & private key $(pk_i \& x_i)$, the PEC computes part of the pseudo-identity information $\wp_i{}'$ of the node and transmits it to the PDC, and PDC calculates the complete pseudo-identity $\wp_i$ of the node participating in the direct power purchase transaction and sends it to the corresponding transaction node. The mapping relationship between real identities ID_i and pseudo identities $\wp_i$ is stored in the account pool of the EAG. Pseudo-identity $\wp_i$ is a pass for a node to participate in direct power purchase transactions, and it plays a role in protecting the privacy of the node. When the direct purchase node performs system initialization, the node uploads the pseudo-identity and transaction request to the transaction server of the EAG.

3.4.2. Stackelberg Game and Reputation Update

The PGs send the electricity to be sold and the initial quotation to the transaction server of the EAG. After receiving the transaction request of the PGs, the transaction server broadcasts the PGs' quotation and the sale of electricity to the EAG connected to LCs. Electricity price information in the spot market. After LCs receive the electricity price information, they formulate their own optimal power purchase strategy according to formula (2) to minimize the power purchase cost, and feed back the power purchase strategy to the EAG. The PGs obtain the purchase of LCs through the EAG. After the electricity strategy feedback, according to formula (1), each PG conducts a non-cooperative game, and modifies the quotation for each LC in accordance with the principle of maximizing their own interests. Until all PGs no longer modify their quotations, the profit of PGs will remain unchanged, and the power purchase strategy of LCs will remain unchanged. The model reaching the equilibrium point of the game. The EAGs complete the transaction matching and generate a smart contract.

Both parties in direct power purchase transactions play a Stackelberg game. PGs are modeled as upper-level leaders, and LCs are modeled as lower-level followers. The price competition among PGs is a non-cooperative game. PGs obtain more contract shares through contract quotation competition. LCs adjust their own power purchases strategies during the cycle according to the quotations of each PG and the electricity price of spot market. PGs make independent quotations for LCs. The contracted electricity price between PGs and LCs is only affected by the power purchase strategy of LCs, and the game problem between LCs is transformed into a problem of optimizing their own power purchase costs.

① Non-cooperative Game Bidding Model of PGs

The objective of PGs in the game is to maximize their profits in the bilateral contract market. The contract electricity price $\pi_{i,j}^t$ of power generator S_i to large consumer L_j in period t is

$$\pi_{i,j}^t = a_{i,j}^t + b_i U_{i,j}^t \tag{4}$$

$$\underline{\pi}_{i,j}^t < \pi_{i,j}^t < \overline{\pi}_{i,j}^t \tag{5}$$

The contract electricity $U_{i,j}^t$ signed by L_j and S_i meets the following constraints

$$\sum_{t=1}^{O} \sum_{j=1}^{N} U_{i,j}^t \le Q_i \tag{6}$$

Where $a_{i,j}^t (RMB/MW \cdot h)$ is the initial quotation of S_i to L_j at period t. $b_i (RMB/MW \cdot h)$ is the marginal quotation growth coefficient. For S_i, the marginal quotation growth coefficient b_i is

ISSN: 2710-0588 DOI: 10.29556/FSE.202105_1(2).0015

constant. In the formula, $\underline{\pi}_{i,j}^{t}$ and $\overline{\pi}_{i,j}^{t}$ are the lower and upper limits of PGs' bidding prices, respectively. Q_i is the amount of electricity that can be sold by the PG.
The power generation cost C_{S_i} of S_i is expressed as a quadratic function fitting.

$$C_{S_i} = \alpha_i U_i^2 + \beta_i U_i \tag{7}$$

$$U_i = \sum_{j=1}^{N} U_{i,j} \tag{8}$$

Where α_i, β_i are the secondary cost coefficients of power generators.
Substituting equations (7) and (8) into equation (1), the profit objective function F_i of S_i can be rewritten as

$$maxF_i = \sum_{j=1}^{N}((a_{i,j}^{t} + b_i U_{i,j}^{t})U_{i,j}^{t}) - \xi(\sum_{j=1}^{N} U_{i,j}^{t}) = (\alpha_i U_i^2 + \beta_i U_i) \tag{9}$$

② Cost Optimization Model of LCs
LCs are modeled as lower-level followers. They receive quotations provided by PGs through the transaction server in direct power purchase. The power purchase choices of LCs will affect the final profit of PGs.
Combining equations (2) and (4), the objective function of power purchase cost for L_j can be rewritten as

$$minC_{L_j} = \sum_{i=1}^{M}(a_{i,j}^{t} + b_i U_{i,j}^{t})\, U_{i,j}^{t} + \pi_m^t U_j'' \tag{10}$$

$$s.t.\ 0 \le U_{i,j}^{t} \le \overline{U}_{i,j}^{t} \tag{11}$$

$$\sum_{i=1}^{M} U_{i,j}^{t} + U_j'' = D_j^t \tag{12}$$

Where $\overline{U}_{i,j}^{t}$ is the upper limit of the contract power that L_j obtains from S_i at time t, D_j^t is the power demand of the LC at time t.
③ Reputation value update and bill generation
The reputation center of the EAG updates the node reputation value R_{i-new} according to the number of matches ϑ_{i_p-new} corresponding to each node in the game and the maximum number of matches z_{max_p-new} in the game.

$$R_{i-new} = \frac{(\sum_{p=1}^{y} \vartheta_{i_p}) + \vartheta_{i_p-new}}{(\sum_{p=1}^{y} z_{max_p}) + z_{max_p-new}} + \frac{y+1}{x+1} \tag{13}$$

After the matching is over, PGs download the latest matching information from the transaction server, generates a bill based on the matching result, and signs the bill before sending it to LCs for confirmation.

3.4.3. Security check and block construction

LCs verify the legitimacy of the received billing information, then create a transaction plan for endorsement and signature, and send it to the PDC. PDC verifies whether the signature information of the direct power purchase parties is the same, and verifies whether the direct power purchase transaction plan meets the safety check and congestion management. Then PDC sends the transaction plan and results that have passed the security check, including the

ISSN: 2710-0588 DOI: 10.29556/FSE.202105_1(2).0015

read/write set, the transaction data with the pseudo-identity information of the direct purchase parties to the server in the form of messages, and the ordering node of the server packages the transaction records into blocks according to the time series.

3.4.4. Consensus and ledger update

The server enables the sorting service to sort the direct electricity purchase transaction data Messages' in the transaction cycle, generate the block Merkel root hash, and package it into a block and broadcast it to all EAGs to carry out the consensus process of the consortium blockchain. The block header records the hash value, Merkel root, and timestamp of the previous block, and the block body records the direct power purchase transaction data within the cycle.

4. Results and Discussion

4.1. Analysis of quotation behavior of power generators

S_1, S_2, S_3, S_4 are defined as 'aggressive', 'conservative', 'conservative' and 'negative' respectively in this game. The nodes under the 'negative' attribute do not provide quotations. The experiment carried out 1000 iterations to analyze the quotation behavior of power generation companies. Figure 2 is the quotation game process curve of power generators S_1, S_2 and S_3 in the bilateral contract market in the next 500 iterations. It depicts the game quotation behavior among PGs in the bilateral contract market.

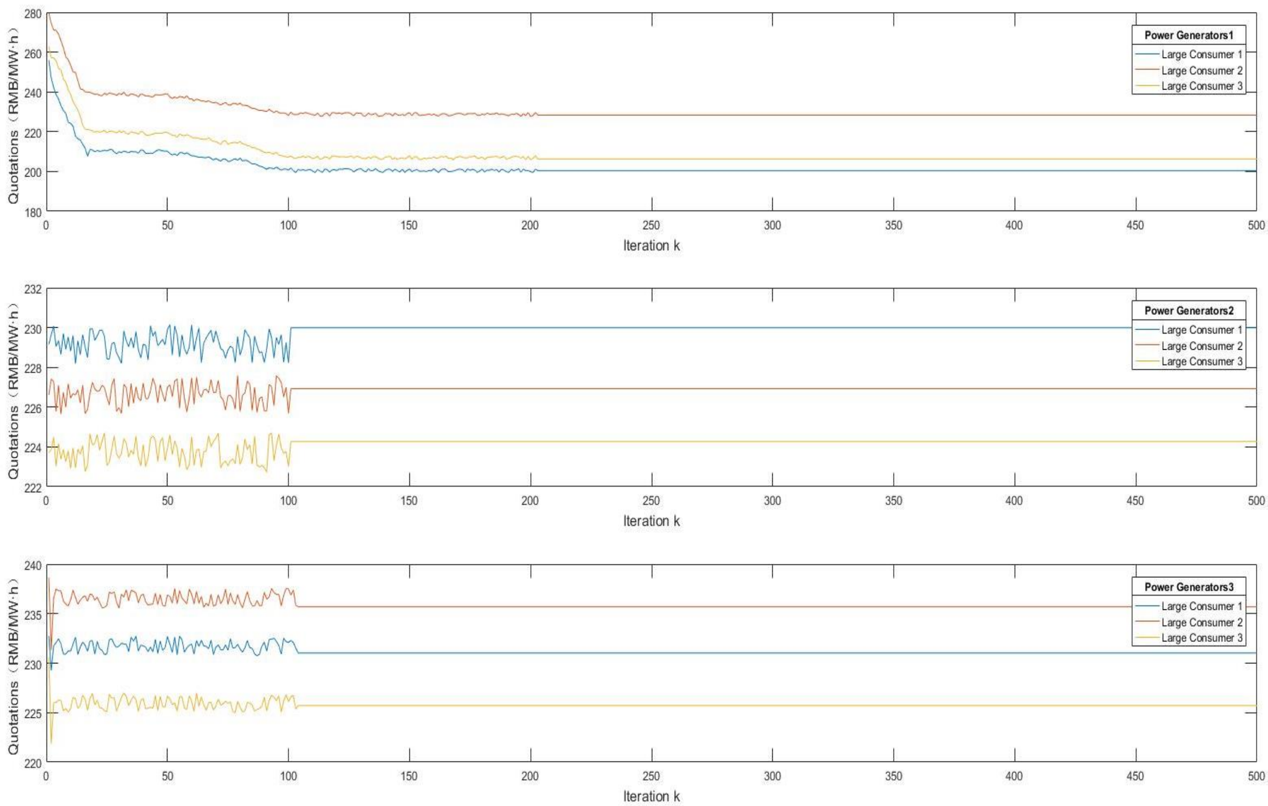

Figure 2. The non-cooperative game quotation process among PGs for the next 500 iterations

When k=203, S_1 reaches the equilibrium point, when k=101, S_2 reaches the equilibrium point, and when k=104, S_3 reaches the equilibrium point. At this time, the output quotation is the equilibrium quotation.

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It can be seen from Figure 3 that S_1 has the largest market share, S_3 is the next, and S_2 is the smallest. Because the overall quotations of PGs satisfy $\sum a_{3,j} > \sum a_{2,j} > \sum a_{1,j}$, and the marginal quotation coefficient of PGs is $b_2>b_1>b_3$ (as shown in Figure 9). Although S_1's marginal quotation coefficient is in the mid-range, it still holds the largest market share. This is due to the fact that S_1 makes full use of market price signals in the game process and effectively reduces its own quotation to bring it more market share. Even if S_3 has the lowest marginal quotation coefficient, its highest quotation will reduce its market share.

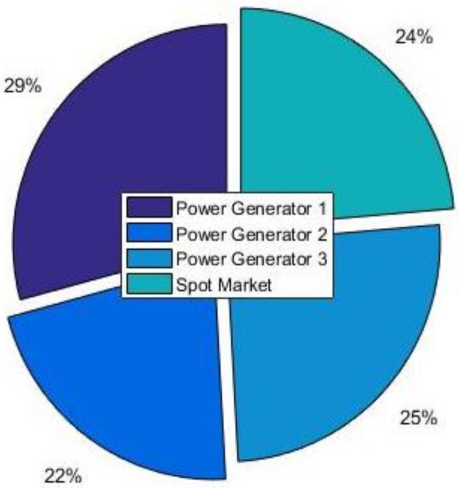

Figure 3. Market share of PGs and spot market under equilibrium quotations

4.2. Analysis of power purchase behavior of large consumers

Figure 4 shows the distribution of electricity purchased by large consumers from the bilateral contract market and the spot market in various time periods within 24 hours under the equilibrium solution.

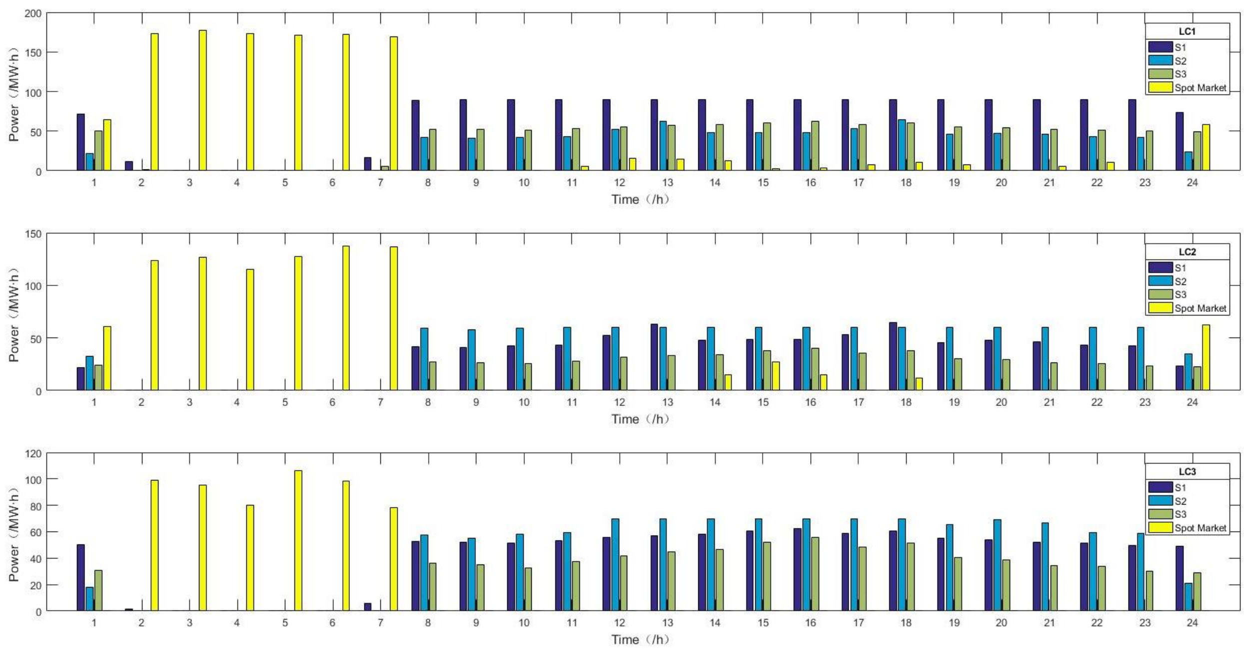

Figure 4. Power purchase strategy of large consumers under equilibrium quotations

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During the 'valley' period, the spot market electricity price is much lower than the bilateral contract market electricity price, that is, when $\pi_m^t < a_{i,j}^t$, The power purchase strategy of LCs tends to purchase power from the spot market, and when $\pi_m^t > a_{i,j}^t$, LCs are more inclined to purchase power from the bilateral contract market.

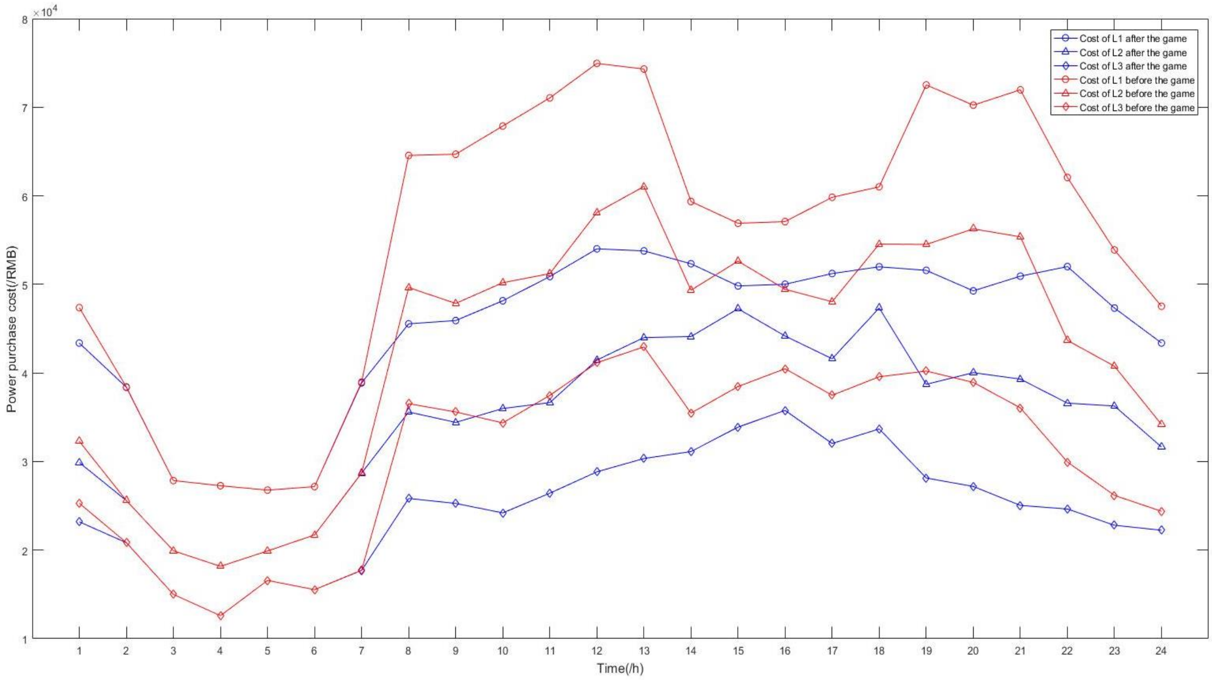

Figure 5. Power purchase cost of large consumers

According to the distribution of power purchase in Figure 4, the power purchase cost before and after the large consumers participate in the game is calculated as shown in Figure 5.

Experiments have proved that compared with large consumers directly purchasing electricity from the spot market, this model can effectively reduce the power purchase cost of large consumers. After participating in the game, the power purchase cost of L_1 was reduced by 15.11%, the power purchase cost of L_2 was reduced by 13.25%, and the power purchase cost of L_3 was reduced by 17.68%.

4.3. Analysis of reputation

After the game, the reputation center measures and updates the reputation value of each node based on the performance of each node in this direct power purchase transaction, as shown in Table 1.

Table 1. The reputation value of each node changes after participating in the game

reputation	S_1	S_2	S_3	S_4	L_1	L_2	L_3
R_n	1	1.5	1 (0.8)	1	1	1.3	2
$R_{n\text{-}new}$	2	1.55	1.17	0.5	2	1.36	2

It can be seen from Table 1 that in this game, the passive behavior of the node of S_4 leads to its matching rate $\frac{\sum_{p=1}^{y} \vartheta_{s_4 p}}{\sum_{p=1}^{y} z_{max_p}} = 0$, $x_{S_4-new} = x_{S_4} + 1$, $y_{S_4-new} = x_{S_4}$ in the direct power purchase

ISSN: 2710-0588 DOI: 10.29556/FSE.202105_1(2).0015

transaction, and its reputation value R_{S_4-new} is updated to 0.5. The remaining nodes are actively participating in the direct power purchase, and their reputation value have been improved. The negative behavior of S_4 will restrict its participation in the next direct power purchase transaction.

5. Conclusion

Direct power purchase transactions based on consortium blockchain can realize distributed storage of transaction data, and there is no need to set up third-party regulatory agencies for decentralized transactions. The model realizes the anonymity, unforgeability and traceability of direct power purchase transactions. We ensure that each node is honest and trustworthy through the reputation value mechanism, and solve the safe and efficient demand for direct power purchase transactions. The game results show that direct power purchase transactions based on the Stackelberg game can reduce the power purchase cost of large consumers by 15.35% on average, reduce their dependence on the spot market, and give large consumers the right to choose power generators. As the leader player in the game, power generators can make independent quotations to large consumers. While ensuring their own profits, they can arrange production in a planned way, which is conducive to the long-term stable development of the plants. Compared with the existing direct power purchase transaction model, the model has better flexibility and avoids compulsory matching to complete market matching.

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