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Research on Distributed Energy Transaction Based on Blockchain

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Abstract

In the current stage of clean, low-carbon energy development needs, distributed energy, mainly renewable energy such as solar, wind, and tidal, is the primary energy source for the future energy Internet. Energy blockchain technology is expected to become an important breakthrough to solve the bottleneck of the development of the energy Internet, and its most widely used scenario is distributed energy trading. Distributed energy trading has the characteristics of decentralization, small scale, multiple stakeholders, complex operation status, and diverse control objectives. It coincides with the blockchain's decentralization, openness, transparency, immutability, and traceability. This article summarizes the application of blockchain technology in distributed energy transactions. First, it analyzes the feasibility of the combined application of the two; at the same time, it summarizes the application of blockchain technology in distributed energy transactions in different scenarios. It also analyzes two different distributed energy transaction modes in blockchain. Secondly, it summarizes the method of increasing the throughput performance of the blockchain network.

Keywords: *Blockchain, Distributed energy transaction, Transaction mode, Application scenarios*

1. The feasibility of applying blockchain technology in distributed energy transactions

In developing distributed energy transactions, its control structure has gradually developed from centralized control to entirely decentralized. Blockchain has the characteristics of decentralization. It can ensure that all participating nodes in the network have the same status through a consensus algorithm and jointly complete computing tasks. At the same time, distributed energy sources and terminal load points are multi-faceted, power sources are diverse, operating conditions are complex, grid control objectives are diverse, coordinated control is complex, and controllability is insufficient. Blockchain technology has collective coordination capabilities and uses specific incentive mechanisms to ensure that each block participates in data block verification and competition process and promotes its independent coordination and cooperation.

As an important part of the energy network, distributed energy realizes the interconnection with power generation measurement, power demand side, power trading market, and grid regulation market through two-way communication technology. At the same time, it integrates, optimizes, and dispatches data information at all levels and participates in power market dispatch. However, distributed energy participants are diverse. Power generation and

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user-side distributed energy have a small capacity, a large number, and a geographically dispersed position. Related stakeholders are complex. With the opening of policies, market participants are becoming more active, and the demands of different stakeholders are intertwined [1]. The interaction between clusters (microgrids, aggregators, virtual power plants) and between the grid and other nodes is expensive, and the benefit distribution mechanism is not open and transparent to all market participants. Distributed energy and power grids and clusters cannot form a symmetrical two-way choice of information, which increases the cost of credit in the transaction process. Blockchain technology has advantages in transaction applications due to its characteristics. First of all, all nodes in the network jointly participate in the recording of transactions, and the decentralized transaction organization reduces transaction costs. At the same time, as a decentralized distributed ledger, the blockchain stores all the information in the system. All transaction records cannot be tampered with privately and can be traced back, ensuring the safety and reliability of transaction data. Also, the blockchain provides fair information reading permissions for many nodes, and block information can be read and written at any time. The power grid and users can grasp the changes in schedulable resources during the transaction in time, which is convenient for adjusting the transaction strategy. Therefore, the information in the blockchain is open, transparent, and authentic, ensuring the safety and reliability of transactions.

2. Application scenarios of distributed energy trading based on blockchain

2.1. Virtual power plant power trading

The virtual power plant utilizes fragmented resources such as a large number of distributed resources, energy storage resources, and community users scattered in large numbers, forming a bottom-up management and control structure. Take homes, buildings, communities, parks, etc., as the unit construction, realize interconnection transactions through source-load collaboration, and simultaneously provide auxiliary services to the grid. However, traditional virtual power plants have problems such as non-open and transparent benefit distribution mechanisms, so the cost of trust required for power transactions is relatively high. The literature proposes a semi-centralized blockchain with the characteristics of both private and public chains. It improves the blockchain's Proof of Work (POW) consensus mechanism to improve the optimal scheduling of virtual power plants—computational efficiency. The literature introduces the energy blockchain network model into the operation scheduling process of the virtual power plant so that distributed energy can effectively participate in the power market transaction. With the help of cryptographic characteristics, the virtual power plant can obtain transaction information security.

2.2. Microgrid grid-connected power generation transaction

A Microgrid is a small power generation and distribution system combining distributed energy, energy storage equipment, energy conversion equipment, control, protection equipment, and loads through power electronic technology. The advantage is to improve power supply reliability and reduce feeder losses, but there are certain physical limitations. Because the blockchain and the microgrid market have similar distributed topological structures, blockchain technology can simplify the transaction mode, realize point-to-point transactions, promote nearby distributed energy consumption, and reduce power transaction costs [2]. The literature designed the overall framework of the microgrid market based on the blockchain and made up for the lack of a game model for obtaining global information. It introduced a reward and punishment mechanism to ensure the fairness of individual participation in trading so that the game results tended to optimize the optimal solution. The literature studies microgrid economic dispatch based on the energy blockchain network, then considers energy storage and user-side response and proposes a multi-time scale microgrid economic dispatch method based on smart contracts to improve the information transparency and data security of the microgrid system and storage security. The literature proposes a direct power transaction mode and strategy between distributed power sources and users in the microgrid based on the blockchain and continuous double auction mechanism. It verifies that the method can meet the decentralized, small-scale, and low-cost microgrid power transaction cases—cost of transaction requirements.

2.3. Automatic demand response transactions

In the context of the Energy Internet, as the penetration rate of distributed energy continues to increase, more demand response resources will emerge. Automatic demand response can realize the adjustment of both ends of "source-network-load" to ensure the real-time balance of the power grid making full use of the real-time adjustable potential of the load. However, the traditional centralized trading model of the electricity market has made achieving low-cost, safe, and efficient user interaction difficult. Blockchain technology can guarantee the traceability and tamper-proof of transaction information and realize decentralized and credible transactions [3]. Literature [4] proposed a design idea of an integrated information platform based on blockchain protocol standards centered on information monitoring collection, entry, and statistics. It is based on demand response servers, load integrators, and user groups so that the security is not limited to a central point of failure. Literature [5] proposed a framework for comprehensive demand response resource transactions based on blockchain technology and analyzed the key issues in market transactions under the framework. Literature [6] uses distributed energy's demand response transaction as an example to illustrate the detailed transaction process and designs. It deploys the smart contract of the transaction on the Ethereum private blockchain to verify the effectiveness of the proposed transaction plan. Literature [7] explored the application method of blockchain smart contracts in demand response bidding transactions. It proposed a multi-level demand response management scheme based on technical support for blockchain smart contracts from the technical level. It can guarantee the support of demand response bidding—business security transactions.

2.4. Electric vehicle charging and discharging transactions

In recent years, in response to the call for energy conservation, emission reduction, and environmental protection, many countries have actively promoted the development of new energy vehicles, and their ownership has gradually increased. Still, problems include inconsistent charging standards and user privacy leakage [8]. Blockchain technology uses decentralization and trustless methods to realize the secure transaction of digital assets. Literature [9] proposed a charging pile-sharing scheme based on blockchain technology. The charging alliance chain eliminated the trust barrier between electric vehicle companies and charging pile operators. Literature [10] constructed a blockchain-based charging rights transaction mechanism and model. The smart contract executors in the blockchain network fairly distribute the initial charging rights to achieve peer-to-peer digital asset transactions to avoid overloading power transmission and transformation equipment.

At present, blockchain technology has preliminary practical applications in the field of distributed energy transactions at home and abroad and has achieved certain results. A typical example of blockchain-distributed energy transactions is shown in [Table 1].

Table 1. Typical cases of blockchain-distributed energy transactions

Project name	Region	Core Technology
Power Ledger solar trading	Australia	P2P transactions between producers and consumers who own distributed energy and other users are realized through smart contracts, but the internal private chain is used, which has poor scalability
TransActiveGrid distributed photovoltaic power sales	United States	Provide a distributed energy trading platform in the Brooklyn community. Smart meters collect users' electricity consumption and transaction data and record them on the blockchain, but the scale of the project application is relatively small.
Share & Charge Electric Vehicle Charging Platform	Germany	Platform users look for charging piles on the client side and use smart contracts to achieve transaction settlement between users and charging pile operators. Still, the tokens issued by the platform are not promotional.
BittWatt blockchain project	United Kingdom	Establish an intelligent demand response platform based on Ethereum, where generators and consumers can match transactions through smart contracts.
Fortum Energy System	Finland	Build a demand response platform based on the blockchain, with the help of smart contracts, to enable the subject to respond automatically to the compensation demand proposed by the system.
Scanergy blockchain project	European Union	Based on the smart contract of Ethereum to realize P2P direct transactions, the smart contract generates corresponding virtual currency. It provides it to the green power producer, but the economic model, transaction security, data privacy, and other project aspects need improvement.
Sun Exchange Solar Equipment Crowdfunding Project	Africa	Raise external funds with the help of the blockchain platform to help African countries build photovoltaic projects. Still, the project has relatively little correlation with energy-distributed trading, optimized operation, etc.
De La Salle University Project	Philippines	The project is based on the De La Salle University campus microgrid project. The decentralized characteristics of the blockchain can support users in different buildings in conducting P2P power direct transactions, but the project is small in scale and the experimental stage.
WePower Green Energy Trading Platform	Gibraltar	Build a blockchain platform, issue energy tokens to raise funds, and promote the development of global renewable energy
Smart microgrid project	Israel	A microgrid pilot project based on blockchain technology and artificial intelligence has been built to achieve green power certification, power trading, regional energy optimization management, and P2P functions.
Shekou Energy Blockchain Project	China	Users can select the type of electric energy they want through the trading platform to realize the P2P renewable energy transaction between the user and the power station. Still, the reward mechanism needs to be improved.

Zhejiang Electric Power Marketing Contract Management Application Project	China	Using blockchain technology to ensure the consistency of the electronic contract data information stored by the various stakeholders in the power market, the project has a relatively single application scenario for the blockchain.
TenneT Home Energy Storage Project	Europe	Combine home storage batteries with blockchain to perform real-time charge and discharge management to alleviate congestion, but the degree of decentralization is low.

3. Distributed energy trading model based on blockchain

Blockchain-based distributed energy transaction settlement models mainly include P2P transactions and centralized clearing. There are differences in the transaction process between the two modes. [Table 2] compares P2P transactions and the centralized clearing transaction process. The most significant difference between the two is that in P2P transactions, users with electricity trading qualifications and distributed energy generators have completed transaction matching at the application layer through the website or DAPP in Phase 1 without matching in the blockchain. In the centralized clearing mode, the block link in stage 3 will match the buyers and sellers after receiving the quotations from the buyers and sellers.

3.1. P2P transaction

Blockchain-based P2P transactions take advantage of the decentralization and traceability characteristics of the blockchain. Based on the P2P structure of the blockchain, there are only buyers and sellers when conducting electricity transactions, and there is no central node [10]. Before the transaction, the buyer and the seller agree on the contract's content. During the transaction, the smart contract is automatically executed according to the quotation of both parties, and the buyer and the seller do not need to negotiate a price. Literature [11] proposed a photovoltaic transaction mechanism based on blockchain incentives, which can encourage free, flexible, and single transaction settlement among users. Users can obtain more satisfactory transactions under the trading mechanism using reputation value. Literature [12] proposed a demand response framework for decentralized cooperation. Through the complete decentralization of blockchain technology, a trusted communication medium can be established between participants, and autonomous monitoring and billing can be implemented through smart contracts without relying on centralized aggregators or utilities. Literature [13] established a competition game model for market entities based on blockchain. In this model, the information of energy storage entities does not need to be fed back to the control center; it is point-to-point information interaction and asset transfer with other entities. Literature [14] proposes a distributed energy trading model based on contract orders, and users' matching transactions are all realized through contract orders.

Table 2. Comparison of P2P transaction and centralized clearing transaction process

Transaction mode	Stage 1	Stage 2	Stage 3
P2P transaction	Request for purchase and sale of electricity to request transaction matching between buyers and sellers	Information transfer to the blockchain	Transaction clearing stores transaction information
Centralized clearing	Request for purchase and sale of electricity	Information transfer to the blockchain	Buyer and seller transaction matching transaction clearing storage transaction information

3.2. Centralized clearing

The centralized clearing model mainly refers to the use of the decentralized characteristics of the blockchain to gather the quotations and needs of market participants for matching, forming a supply-demand curve, and then clearing. According to different quotation methods, it is mainly divided into collections, Bidding, and continuous bilateral auctions.

In the in-call auction, after buyers and sellers give quotations, the blockchain platform selects according to the quotations and demand of the buyers and sellers to reach the transaction. Literature [15] used the Vickrey Clarke Groves (VCG) auction rules to motivate producers and consumers to make rational quotations. The quotations of users and distributed energy were submitted to the blockchain platform in a confidential state before the start of the trading cycle. When the quotation information is public, all valid quotations will be entered into the clearing queue from low to high until the deviation power balance constraint is met. The literature [14] encodes the bidding rules into smart contracts by the demander of electricity and the generator of electricity, and it is simulated and implemented on the Ethereum blockchain platform. Although the transaction efficiency of a call auction is higher than that of a CAD auction, and it eliminates the game cost of producers and consumers, the quotations given by buyers and sellers cannot be modified, so it isn't easy to coordinate to achieve the optimal. The participants may not obtain the maximum benefit [16].

Continuous bilateral auction refers to a situation where buyers and sellers exist in many-to-many forms, market participants can submit quotations at any time, and the quotations are submitted to the auction center to be responsible for matching. Buyers and sellers are sorted and matched according to the "price first, time first" principle. To illustrate the above auction mechanism, the auction process of each node is illustrated with examples. Suppose the user node is the buyer, and define the vector $A = [A_1^{t_1}$ $, A2t2, A3t3, A_4^{t_4}]$, where Atik indicates that user k has completed the purchase price of electricity at time t_i, The distributed energy service provider node is the seller, and the definition vector is $B = [B_1^{t_1}$ $, B2t2, B3t3, B_4^{t_4}]$, where Btij represents the distributed energy service provider j in t_i complete the electricity sales quotation at any time, here assume $t_1 < t_2 < t_3 < t_4$. The quotation information of buyers and sellers is shown in Table 3, and the order of quotations and transaction matching are shown in Table 4. Buyers are sorted in descending order of bids, and sellers are sorted in ascending order of selling prices. Matching occurs when the selling price is higher than the selling price, and the selling price is the average price of the two. In the literature [17], buyers and sellers first complete transaction matching through a continuous two-way auction mechanism and propose an adaptive and aggressive trading strategy so that the transaction parties can adjust their quotations in time according to market changes. Literature [18] Two-way auction and P2P trading mechanisms introduce the charging rights market. For the part where the buyer's price is higher than the seller's price, the two-way auction market is used to match the transaction; the part where the buyer's price is lower than the seller's price is through the P2P trading market Listing transactions to maximize the optimal allocation of charging resources.

Table 3. Quotation information of buyers and sellers

Buyer	Bid	Seller	Selling price
$A_1^{t_1}$	80.00	$B_1^{t_1}$	84.00
$A_2^{t_2}$	86.00	$B_2^{t_2}$	80.00
$A_3^{t_3}$	82.00	$B_3^{t_3}$	84.00
$A_4^{t_4}$	80.00	$B_4^{t_4}$	81.00

Table 4. Quotation order and transaction matching

Buyer descending	Bid	Seller ascending	Selling price	Does it match	Final price
$A_1^{t_1}$	80.00	$B_2^{t_2}$	80.00	Y	80.00
$A_4^{t_4}$	80.00	$B_4^{t_4}$	81.00	Y	80.50
$A_3^{t_3}$	82.00	$B_1^{t_1}$	84.00	Y	83.00
$A_2^{t_2}$	86.00	$B_1^{t_1}$	84.00	N	-

4. Blockchain technology to improve transaction network throughput performance

Blockchain technology inherently exists in the trilemma. That is, it cannot simultaneously have the three characteristics of decentralization, security, and efficient operation. As the number of participating nodes and running time increase, the data storage system of the blockchain will face greater capacity and maintenance pressure. This will lower the throughput of transactions and limit the speed of transactions. In order to solve these problems, developers mainly improve the processing performance of the blockchain from several aspects, such as the design of the consensus algorithm, the expansion of the chain, and the cross-chain technology.

4.1. Improvement of the consensus mechanism

The consensus mechanism is the core issue of blockchain technology in a decentralized environment. Currently, most of the theoretical assumptions of the electricity trading market are based on the operation model of the public chain and the POW consensus mechanism. The world's most famous public chain projects are Bitcoin, Ethereum, and Enterprise Operating System (EOS), so you can see the status quo of public chains by studying them.

Bitcoin adopts the POW consensus mechanism. With the emergence of more powerful ASIC mining machines, the entire network's computing power is almost monopolized by several major mining pools, so the decentralization of Bitcoin has declined. Bitcoin's system throughput (TPS) is only about seven transactions per second, unsuitable for daily high-frequency, small-value transfers. But Bitcoin is the best in terms of security.

Ethereum also uses the POW consensus mechanism, but to solve the problem of computing power monopoly, the Proof of Stake (POS) consensus mechanism will be adopted. Ethereum's TPS is slightly higher than Bitcoin's, with 7-15 transactions per second. Still, because Ethereum is a smart contract platform, its application scenarios are more complicated and more prone to congestion than Bitcoin ones. In addition, Ethereum is second only to Bitcoin in terms of security [70].

The consensus mechanism of Proof of Share Authorization (DPOS) was adopted in the first edition of the EOS white paper. It has been changed to Byzantine Fault Tolerance (BFT)-Byzantine Fault Tolerant Equity Delegated Consensus Mechanism (DPOS). Its TPS is the highest among the three public chains, reaching 3000～ 4000 pens. However, the EOS network has only 21 nodes, which is also the worst regarding security.

Table 5. Comparison of characteristics of 5 typical consensus mechanisms

Characteristic	POW	POS	DPOS	PBFT	RBFT
Energy consumption	High	Low	Low	Low	Low
Node management	Public	Public	Public	Accurate mechanism	Access mechanism
Block production speed	Slow speed, unable to meet the needs of high-frequency small transactions	Faster	Reaching second-level consensus verification	Slow speed, suitable for private chain or consortium chain	Fast speed, TPS≥104
Data throughput	Low	High	High	High	High
safety	Higher can only withstand less than 50% of the hash rate attack	High, can only withstand less than 50% equity attacks	High, can only withstand less than 50% of verification attacks	Low, can only withstand no more than 1 /3 of the nodes to do evil	Low, can only withstand no more than 1 /3 of the nodes to do evil
Is there a professional bookkeeper	No	No	Yes	Yes	Yes
Scalability	Great	Great	Great	Difference	Difference

To shorten the time to reach a consensus on distributed energy transactions on the blockchain, there are currently two main ways to grant nodes different permissions and change the consensus mechanism. Literature [6] uses an improved indirect verification method to verify the workload proof. A certain number of third-party nodes are used for verification, which can improve computational efficiency and effectively avoid the Byzantine Generals problem.

Literature [19] based on credit-based rewards and punishments and voting results to choose and optimize two core solutions and proposed an improved DPOS consensus mechanism, which can significantly reduce the probability of abnormal nodes acquiring the identity of proxy nodes and shorten the time for abnormal proxy nodes to be kicked out of the proxy. Thereby weakening the influence of abnormal nodes on the system and enhancing its security. In a weakly centralized blockchain, the number of light nodes exceeds the number of full nodes. The verification form of the MPT (Merkle Patricia Tree) tree is adopted, and the path of the tree is stored in an encoding method. Literature [20] uses the consensus mechanism of MPT; the transaction Merkel tree retains all the transaction information, and the state Merkel tree retains the state changes of the transaction. If a new node is added to the block, only the leaf nodes of the state tree need to be added. The consensus mechanism of the new research includes the sharding algorithm and the combination of PBFT and POS consensus to form a new Proof of Stake Velocity (POSV) consensus mechanism, etc.

4.2. Off-chain expansion

The improvement to the consensus algorithm is called Layer 1 on-chain extension, but recording every transaction on the blockchain network into the blockchain is very time-consuming. Now, a new Layer 2 solution is proposed, called off-chain extension. Off-chain expansion technology mainly includes side-chain assistance, multi-chain fusion, and state channels. The side chain separates a chain from the public chain and returns to the main chain after a series of transactions are completed to protect privacy by isolating blockchain data. The solution of transaction matching or distributed optimization algorithm can be placed under the chain, and the main chain is only responsible for the arbitration or recording of transaction results [21]. The Lightning Network transfers transactions to off-chain processing without consensus confirmation on the main chain, thereby improving transaction efficiency. Ethereum Plasma uses POS off-chain, and users can collectively run DAPP through a peer-to-peer network [22]. With multi-chain integration, transaction nodes in the blockchain network can establish their private chain or sub-chain, place transaction matching in the private chain, and store data with higher security requirements in the main chain. Literature [23] designed a new hybrid blockchain storage mode, combining the security of public chains with the efficiency of private chains and using the efficiency of private chains to solve the inefficiency of the initial blockchain. At the same time, it inherits the security and immutability of the initial blockchain. Literature [24] designed a blockchain with the characteristics of both public and private chains, which effectively controls energy grid connection and uses a decentralized platform to ensure fair participation of all subjects. The channel is on the private blockchain, and both parties have all the information, and each communication needs to be verified and signed.

5. Future development of distributed energy trading based on blockchain

5.1. Development challenges

With the development of energy blockchain, full nodes in the network need to store more transaction data, requiring blocks to have enough storage space. Blockchain network communication will also face delay problems, leading to bifurcation. And the underlying blockchain network cannot support the development of higher systems.

Blockchain technology guarantees the automatic execution of smart contracts and facilitates the smooth progress of distributed energy transactions. If the contract has a coding error, it is usually difficult to perform a rollback or fork. Smart contracts will also have problems such as missing responsible parties, timestamp attacks, and reentry vulnerabilities. In distributed energy transactions, the participant is a virtual account, and the issue of accountability is likely to result in the lack of a responsible entity [25]. Some malicious nodes will use the timestamp in the contract as a trigger condition to obtain improper income. In addition, when one contract calls another contract, the current contract will be rolled back and suspended, which will cause the contract to be called multiple times, causing security issues.

Security and privacy have always been the core issue of blockchain technology. It mainly includes double-spending attacks and mining pool attacks. A double-spend attack refers to spending a single amount of money multiple times because there will be a delay in the consensus process of network nodes, and malicious nodes will use a single amount of money to trade with multiple nodes simultaneously. A mining pool attack is a classic blockchain attack. A malicious mining pool deliberately hides new blocks without publishing them and continues to mine on the hidden blockchain, causing it to fork.

To deploy distributed energy transactions between users to the actual grid operator, the physical model of the grid operator cannot be constructed, but the blockchain is difficult to integrate well with the complex physical model. In addition, integrating locally distributed energy into the power grid should consider the user-building model, which can take advantage of the flexibility provided by various entities commonly found in buildings. However, there is currently no innovative general framework that can be used in local distributed energy production. Manage energy in a flexible smart building community. Therefore, to realize distributed energy trading, we must continue exploring distributed clearing methods that consider the constraints of building models and physical topology.

5.2. Development prospects

Currently, the carbon emission market has the problem of a large workload of carbon emission rights certification, and the issuance and tracking of green certificates are difficult. With the help of the blockchain's non-tamperable, traceable, open, and transparent features, a safe and reliable distributed trading platform can be established. The platform can simplify the carbon emission right certification process, effectively avoid fraud in carbon emissions, reduce the certification cost of green certificates, and improve the liquidity of certificates.

6. Conclusion

This article systematically summarizes the application of blockchain technology in distributed energy transactions. Blockchain technology realizes distributed energy P2P transactions and ensures centralized and adequate supervision. With the increase of distributed energy transaction nodes, the throughput performance of the blockchain is bound to decline. The design of a practical consensus mechanism and off-chain expansion processing technology can improve the efficiency of network transactions. On this basis, the two transaction modes and four typical scenarios of the energy blockchain are analyzed and summarized. Finally, the problems that urgently need to be solved in the future development of blockchain distributed energy trading are put forward, and its development prospects are pointed out. This article will provide a technical reference for the theoretical research and engineering practice demonstration of blockchain-distributed energy transactions.

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