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Survey on the Application of Blockchain in Enhancing Mutual Trust in Smart Grid Transactions

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Abstract: The characteristics of blockchain technology, such as decentralization, traceability, and tamper-proof, are in line with many scenarios in smart grid transactions, and the application of blockchain technology in smart grid power transactions has attracted wide attention. In view of the increasing complexity of smart grid transactions and possible misunderstandings and contradictions or distrust between participants, this paper summarizes and analyzes the application research of blockchain in enhancing mutual trust in smart grid from three aspects: data privacy protection based on blockchain-based data aggregation technology, encryption technology to ensure data security, and smart contract to ensure fair transactions. It provides a valuable reference for the future application of blockchain in the field of smart grid.

Keywords: Blockchain; Smart Grid; Electricity Trading; Mutual Trust Issues.

1. Introduction

Smart grid is a highly automated power system, which uses advanced communication and control technologies, as well as data analysis and management systems to achieve more intelligent and efficient management of the power system. On April 3, 2024, the company issued a notice on policies and measures to support the green, low-carbon and high-quality development of Inner Mongolia, proposing to strengthen the construction of power grid infrastructure, actively develop smart microgrids, and promote the construction of Hohhot, Ordos and other smart grid comprehensive demonstration zones[1]. Smart grid plays an important role in coping with global climate change, promoting energy conservation and emission reduction, and developing a low-carbon economy. It is proposed that by 2030, the digital transformation of distribution network will be basically completed, massive resources will be aggregated and interactive, and the integrated development of distributed smart grid and large grid will be effectively promoted[2]. With the frequent occurrence of data leaks, network attacks and other incidents, people's attention to data security has gradually increased, and smart grid transaction security has also received more attention and attention.

With the deepening of the marketization degree of smart grid and the increasing number of participating members, there are more and more trust issues between participants in smart grid transactions. Blockchain distributed storage of data can enable multi-point backup of data, prevent data loss, ensure data integrity, and increase the trust of parties to contracts through identity authentication and smart contracts. Blockchain also integrates asymmetric encryption, data aggregation and other technologies, with transparent and reliable, traceable, tamper-proof and other characteristics, can better solve some trust problems in smart grid transactions.

Enhancing mutual trust among transaction participants is conducive to the healthy development of the electricity market. The research on enhancing mutual trust in the smart grid is conducive to facilitating the power trade, better distribution of power resources, and promote the establishment of an open, transparent, stable and secure power market in China.

In recent years, many domestic and foreign scholars have studied the application of blockchain in the smart grid and power grid market. Literature[3] proposes a scheme to enhance mutual trust in electricity market transactions based on hybrid blockchain. Public information is stored in alliance blockchain, private information is stored in private blockchain, and access records of private information are stored in alliance chain so that participants can supervise each other. Literature[4] sorted out three blockchain-related algorithms of security protection, data synchronization and consensus, and analyzed them in combination with trial scenarios. Literature[5] proposes a blockchain-based credit management method for distributed energy transactions. Literature[6] proposes a novel three-tier peer-to-peer power transaction architecture to protect private information submitted to the blockchain through a new privacy-protecting transaction strategy, and also proposes an on-chain data protection method based on homomorphic encryption and secure multi-party computing.

To sum up, smart grid greatly facilitates the participants in the power grid, but due to the characteristics of smart grid online transactions, there is a lack of trust between participants in the power trading market. Many characteristics of blockchain technology are in line with many scenarios in smart grid transactions. At present, many scholars have studied the application of blockchain in various aspects of smart grid, such as privacy protection of electricity price settlement, encryption of sensitive information, legality and verifiability of transactions, etc. However, there is no systematic explanation of the problems of mutual trust between participants in the electricity market and the solutions. Therefore, this paper summarizes the experience of the predecessors and systematically expounds the problems of mutual trust between the participants in the electricity market and the solutions. The main organizational structure of this paper is as follows: the first part mainly introduces the application of blockchain technology in smart grid, the second part mainly describes various mutual trust issues between central institutions and participating users, the third part analyzes the current ways to enhance trust between central institutions and participating users, the fourth part discusses and looks forward to, and the fifth part summarizes this paper.

2. Features of Blockchain and its Potential Applications in Smart Grids

2.1. Basic Principles and Characteristics of Blockchain Technology

Blockchain is a distributed database technology where data is stored in the form of blocks, each block containing transaction information and hash values pointing to the previous block, forming an immutable chain structure, as shown in Figure 1 below. Data is stored in a distributed manner on multiple computer nodes, each of which holds a complete copy of the data. At the same time, blockchain adopts cryptography technology to ensure the security and integrity of data and protect transaction information from tampering or theft[7]. The transaction record on the blockchain is public and can be viewed by all participants, but it does not disclose the identity information of both parties involved in the transaction. Blockchain technology enables smart contracts, which are self-executing contracts written in code that are capable of performing pre-set actions under certain conditions[8]. Blockchain technology ensures the security and integrity of data by storing it in a decentralized manner.

These characteristics make blockchain have a wide range of application prospects in various fields, including finance, supply chain management, voting, real estate registration and so on.

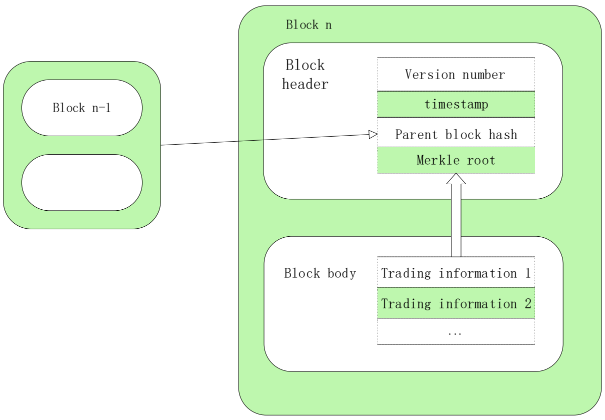

Fig 1. Blockchain chain structure

2.2. Advantages and Potential Applications of Blockchain in Smart Grid

Blockchain has many potential applications and advantages in smart grids that could support peer-to-peer energy trading, allowing consumers to buy and sell energy directly without middlemen. Smart contracts are an important part of blockchain, ensuring transparency and reliability of transactions and promoting the use of renewable energy. Blockchain can also be used to track energy assets, such as solar panels, ensuring that the power resources they generate are accurately recorded and tracked. The encryption technology of blockchain can protect the data in the smart grid, ensure the security of transactions and electricity usage information, and also improve the transparency of the electricity market, ensuring that electricity prices and transaction information are publicly visible to all participants, thereby increasing the fairness of the market[9].

The combination of blockchain and smart contract can automatically execute the electric energy transaction and transfer according to the preset conditions[10], automatically execute the terms set in the contract, the agreed content and execution of the contract and the record viewing are recorded in the public ledger, realizing the real-time transfer and settlement of electric energy, which can not only reduce the occurrence of human errors, but also simplify the transaction process and improve efficiency. At the same time, because the contract details are completely stored in the blockchain, the details are traceable, reducing judicial litigation.

The decentralized characteristics of blockchain combined with the advanced metering architecture security framework can reduce the risk of attacks or single points of failure of smart grid systems and improve the security and stability of the system[11].

These advantages and application potential make blockchain a powerful tool for improving smart grid infrastructure, increasing efficiency, and promoting renewable energy use and energy market development.

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3. The Importance of Mutual Trust and Trust Issues in Smart Grid Transactions

3.1. The Key Role of Mutual Trust in Smart Grid

Smart grid greatly enriches and facilitate people's lives, if the privacy of users in smart grid is not effectively protected, it will greatly affect the promotion. Mutual trust establishes the basis for cooperation, and all parties need to trust and cooperate with each other to maintain the stability and reliability of the power system. For example, during peak demand, power generation companies need the assistance of customers to reduce the use of electricity, or power companies need to coordinate the allocation of resources to meet demand. The composition of the participants in the electricity market is shown in Figure 2 below. In smart grid systems, solving the trust problem requires a powerful combination of technology, policy, and cooperation. Only by establishing good mutual trust can all links work together better to achieve sustainable development and optimized operation of the power system.

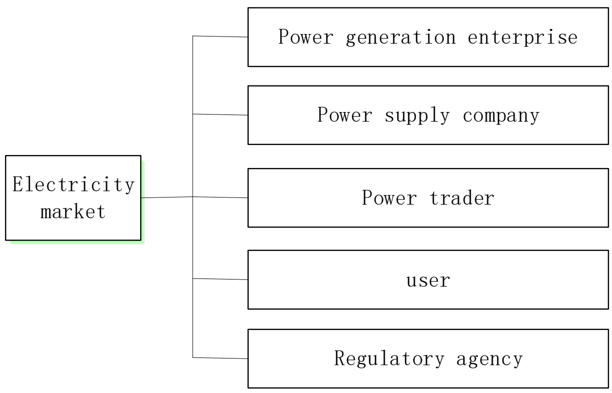

Fig 2. Participants in the electricity market

3.2. Challenges Faced by Blockchain in Solving Trust Issues

3.2.1. Leakage of Personal Information in Power Grid Transactions

There may be a lack of transparency in how smart grid systems operate and how data is used, leaving users unclear about how data is collected, analyzed, and applied, resulting in a lack of understanding of how the entire system works. Users may be concerned about personal information being leaked, and users lack the right information about how smart grids work and their benefits, leading to doubts about their functionality and benefits.

3.2.2. The Safety of the Electric Energy Data on the Meter

The data of smart meters may be stolen and tampered with by hackers during transmission [12], and may also be attacked by hackers during storage. The data recorded by smart meters involves the privacy of the entire home. Users may be concerned about the collection and use of personal electricity consumption data and the misuse or unauthorized access of such data, resulting in an invasion of personal privacy.

3.2.3. Sensitive and Critical Information among Market Participants

Sensitive and private information among participants in the smart grid includes power transaction information, such as transaction records of power purchases and sales, which is crucial to the business strategy and national decision-making of market participants. It also includes market trading contracts, rules and policy information, which is related to the rights and interests of the participating members of the market, and the authenticity, accuracy and effectiveness of the information in the process of publishing and declaring such information is crucial.

4. Application of Blockchain Technology to Enhance Mutual Trust in Smart Grid Transactions

The transparency and traceability of smart grid transactions can enhance trust between participants and facilitate more cooperation and transactions. Blockchain technology can provide a decentralized transaction recording system that records the details and history of all electricity transactions. This decentralized nature makes data more secure and reliable, reduces the risk of a single point of failure, and improves transparency and traceability throughout the trading system. The following will analyze the application of blockchain technology to enhance mutual trust in smart grid transactions from three aspects: data aggregation to protect privacy, encryption technology to ensure data security, and smart contracts to ensure fair transactions.

4.1. Data Aggregation Protects Privacy

In the smart grid, data aggregation technology is often used to prevent the privacy of users caused by the transmission of electricity data. The performance of several blockchain-based data aggregation schemes is shown in Figure 3 below.

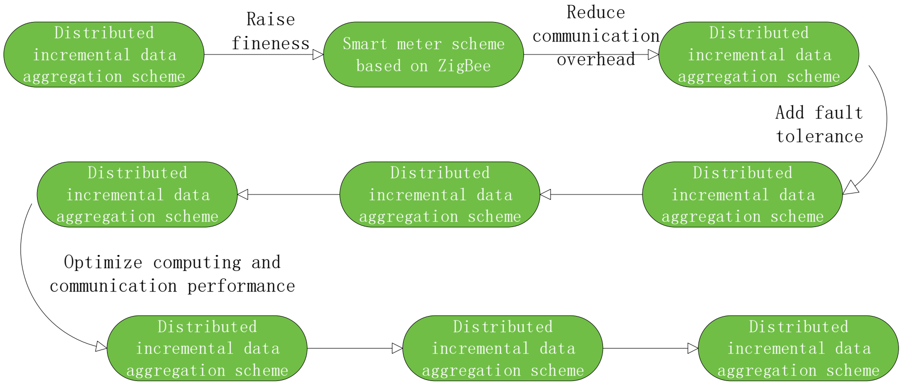

Fig 3. Performance of several blockchain-based data aggregation schemes

The distributed incremental data aggregation method proposed by FLi et al. [13] is to carry out data aggregation on all smart meters participating in data routing. The aggregated route covers the entire local neighborhood or any group of specified nodes with minimum overhead, and then adopts homomorphic encryption technology to protect the data during transmission. The advantage is that it can reduce the workload of smart meters through data aggregation technology. However, this scheme only has the overall power consumption data, and cannot calculate the specific power consumption of each device or each user. To solve this problem, Pasdar A[14] proposed a new wireless communication technology to design and implement a ZigBee-based smart energy meter. The multi-dimensional data aggregation scheme combining the digital energy meter with ZigBee networking can not only improve the efficiency of smart grid data fusion, but also meet the requirements of fine-granularity analysis. However, computing and communication costs are high. Therefore, Yang Ming et al. [15] proposed an efficient multidimensional data aggregation scheme, P2MDA, which uses hyperincreasing sequence and ElGamal encryption technology to enable smart meters to classify power consumption data based on energy supply devices, so as to achieve multidimensional aggregation. The scheme does not require bilinear pairs and map-to-point hashing. Improved efficiency.

These are lightweight data aggregation schemes that protect user privacy to a certain extent. However, if the meter fails or the network is interrupted, the control center will not be able to get the correct aggregation results, and there is no fault tolerance function. Xue and Kaiping[16] proposed a highly robust non-trusted authority data fusion scheme for smart grid, and Xiaodi Wang[17] proposed a fault-tolerant multi-subset data fusion scheme that aggregates total power consumption and obtains the number of users and total power consumption in different value ranges without relying on a trusted third party. Lingjuan Lyu et al.[18] proposed an efficient privacy protection aggregation algorithm. With the help of fog computing architecture, the system enables intermediate fog nodes to periodically collect data from nearby smart meters and accurately export aggregate statistics as fine-grained fog level aggregation. These three schemes are different from the above lightweight schemes, solve some fault tolerance problems, but bring additional computing overhead or communication overhead to the system.

Xie Jinhong and Chen Jianwei et al.[19] proposed a new data aggregation scheme for privacy protection that supports fault tolerance, which uses the logarithmic difficulty problem of elliptic curves to construct an efficient signature authentication method to ensure data integrity. When electricity meter data cannot be sent normally or some cloud servers are attacked, this scheme can still perform data aggregation and has better computing and communication performance. In addition, some aggregation schemes also consider the data security and privacy protection of the edge layer. Weifeng Lu et al.[20] proposed an edge blockchain-assisted smart grid lightweight privacy protection data aggregation scheme, uploading the data monitored by smart meters to a local edge server, where the edge server conducts local aggregation. The information is then globally aggregated and added to the blockchain by a specific edge server. The control center can obtain the global aggregate plaintext by reading the information in the blockchain. The architecture supports a two-level data aggregation scheme with higher efficiency and security.

Based on the above scholars' research on using data aggregation to enhance trust in smart grid, data aggregation has many advantages for blockchain-based smart grid transactions. It can not only reduce the workload of smart meters, improve the efficiency of smart grid data fusion, meet the requirements of fine-grained analysis, but also help eliminate data inconsistencies and errors, and improve the credibility and accuracy of data. However, in a blockchain-based smart grid, each blockchain node needs to store and transmit a large amount of data. Data aggregation may increase the cost of data transmission and storage or increase the complexity of the system. Especially in large-scale smart grid systems, data aggregation needs to take into account the data management and coordination of multiple nodes, which increases the difficulty of system design and maintenance.

4.2. Encryption Technology to Ensure Data Security

Encryption is a technology that converts raw data (plain text) into an unreadable form (ciphertext) by using cryptographic algorithms to protect the security and privacy of data. Cryptography plays a key role in blockchain-based electricity transactions, protecting data from unauthorized access or tampering during transmission, storage and processing. The encryption technologies commonly used in blockchain-based power transactions include asymmetric encryption, hash algorithm, zero-knowledge proof, homomorphic encryption, multiple signatures and other technologies, whose functions and applications are shown in Table 1.

Some strategies employ asymmetric encryption techniques, like state encryption. However, asymmetric encryption technology will make the ciphertext content larger, and the computing time and cost will increase[21]. Ma Yiping, Zhang Junqiang et al.[22] proposed a reading acquisition strategy based on symmetric encryption and hash operation. Masks were added to the reading collection of electric meters so that all readings could be aggregated to eliminate masks. In this way, the data on a meter cannot be obtained separately, which protects the user's privacy and ensures the security of the user's power data, but the fault tolerance rate is low. A sharing scheme combining BGN homologous encryption algorithm and Shamir secrets can ensure the privacy of power data and also support fault tolerance[19]. It also uses a scheme combining attribute-based encryption and symmetric encryption algorithms, which not only protects user privacy, but also realizes the confidentiality of power data and fine-grained access control[23].

Table 1. Several common cryptographic technologies combined with blockchain

Encryption technology	Feature	Application in combination with blockchain in electricity trading
Asymmetric encryption algorithm	Digital signature, key exchange	Verify the identity of the participant
Hash function	Generate a unique identification of the transaction data	Verify that data has been tampered with or falsified
Zero-knowledge proof	Prove that you have certain information without disclosing specific information	Do not disclose specific transaction content and personal information to protect user privacy and data confidentiality
Homomorphic encryption	Data computation while protecting data privacy	Encrypt the transaction data without knowing the specific power data
Multiple signature	Make sure multiple parties agree	Ensure that transactions need to be confirmed by multiple parties before they can be executed, preventing malicious behavior and tampering.

Power transaction data can easily be tampered with by any internal or external attackers, thus destroying the value of the data. While ensuring the verifiability of shared data, it is crucial to protect the privacy of customers. A bilinear mapping accumulator based readable signature scheme is a solution to this problem[24]. In addition, Liang Jie et al.[25] proposed a security verification mode for power transaction data based on trustworthiness and blockchain in order to prevent the identification of internal attackers from certification authorities, using hash-based encryption and zero-knowledge proof verification methods to avoid abnormal access to internal blocks. In addition to protecting the privacy of sensitive data, it is also necessary to ensure that electricity bills are properly settled. Li Da et al.[26] proposed a privacy-protecting electricity bill settlement mechanism by combining cryptography technologies such as blockchain and Pedersen promise.

Cryptography plays a key role in blockchain, guaranteeing the security, privacy and trust of transactions and communications. Through the application of these encryption technologies, blockchain can achieve distributed, secure and trusted data storage and transmission, which has promoted the development and application of blockchain technology in various fields.

4.3. Smart Contracts Guarantee Fair Transactions

A smart contract is an automated computer program executed on a blockchain whose function is to automatically perform a certain action or behavior when pre-set conditions are met. The functions of smart contracts and their role in the power trading system are shown in Table 2.

Table 2. Functions of smart contracts and their role in power trading systems

Feature	Effect
Automatic settlement and payment	No third party involved
Decentralization of transactions	No need to rely on traditional intermediaries
Dynamic pricing and trading rules	We will promote the rational allocation and utilization of resources
Energy sharing and community trading	Realize the sharing and mutual assistance of energy resources

After the birth of blockchain technology, due to its programmable, decentralized, and high transparency characteristics, it is regarded as a natural support technology for smart contracts. Literature[27] introduced the formulation of smart contracts based on blockchain technology, and concluded that the application of blockchain technology in the direct power purchase of large users can ensure the automatic and strict implementation of transaction rules, and the relevant information is more transparent, while improving the timeliness and fairness of settlement. Tai Xue et al.[28] used blockchain and smart contracts to complete power transactions, which ensured the security of power grid data, realized the self-management of all participants in the power market, and solved the trust problem among some participants. There is also a plan to chain electricity market transactions and combine them with smart contracts to ensure the reliability of transactions and the real-time and accuracy of big data transactions[29]. The literature[30] also proposes a blockchain consensus mechanism that allows for secure information exchange, as well as the signing of smart contracts that allow the formalization of relationships between various market participants, thus ensuring transparency of the entire process, and the use of smart contracts in electricity transaction pricing mechanisms to improve the transparency of electricity prices. In addition, Ma Teng et al.[31] proposed a blockchain-based power distribution side multi-microgrid decentralized transaction model, which embedded a two-way auction pricing mechanism in smart contracts, and realized a safe and efficient decentralized transaction of electric energy.

Based on blockchain technology, smart contracts can be traded and executed directly between participants without the need to trust intermediaries or third parties, reducing the cost of trust in the transaction process. The execution process of smart contracts is open and transparent, and all participants can view the code and execution results of the contract, ensuring the credibility and transparency of the transaction, promoting the fairness of the transaction, and thus enhancing the trust of the transaction.

5. Discussion and Prospect

The application of blockchain in smart grid transactions is expected to solve several problems, especially the challenges of mutual trust and data security. Smart grid transactions require highly reliable data exchange and management to enable collaborative work among participants, and blockchain technology can provide a decentralized, secure and reliable data storage and transmission solution. On the one hand, the decentralized nature of blockchain can prevent single points of failure and data tampering, enhancing the security and transparency of data. On the other hand, there are multiple players involved in a smart grid, and blockchain can provide a trusted mechanism for transactions and contracts, helping to build trust and increase transparency. With smart contracts, energy trading and management can be automated, increasing efficiency and reducing costs.

In the future, as blockchain technology continues to develop and mature, smart grids can better utilize this technology to optimize energy distribution and improve the resilience and stability of the system. At the same time, artificial intelligence and Internet of Things technologies can also be combined to achieve more intelligent and efficient energy management and promote the integration and utilization of renewable energy. However, the application of blockchain in the smart grid will also need to address challenges such as performance scaling, energy consumption and standardization, which will require continued technological innovation and industry collaboration to drive development. Of course, all this is built on the basis of better integration of blockchain and smart grid development.

6. Closing Remarks

To sum up, trust issues in smart grid transactions involve user data privacy, power data security and decision-making information fairness. Protecting data privacy through data aggregation technology, ensuring data security through encryption technology, and ensuring fair transactions through smart contracts can address these issues, thereby enhancing trust between smart grid participants and achieving the goal of smart grid reliability, security, economy, and efficiency.

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