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Review

Applications of Blockchain Technology in Modern Power Systems: A Brief Survey

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Abstract: In the context of modern power system development to support the evolution towards green energy and carbon-neutral emission goals, many existing problems and even challenges demand new technical solutions. In recent years, decentralized blockchain technology has been employed to address some problems in power systems, and many papers have been published. In this paper, the concept of blockchain is first introduced. A brief survey of the existing publications regarding the applications of blockchain in power systems, including power system dispatching, microgrid operation, energy trading, electricity trading settlement, transmission, and distribution system operation, is then carried out. In addition, several application scenarios of blockchain technology in power systems are also introduced. Through the discussion, we found that we still need to weigh the advantages and disadvantages, overcome its leakage, and bring its value into play if we apply blockchain technology in modern power systems in support of zero carbon goals.

Keywords: power system; blockchain; information technology; literature survey

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1. Introduction

It has been pointed out in [1] that power industry restructuring should be promoted, and the market-dominant position of the incremental distribution grid, microgrid, and distributed power supply, which is helpful for accommodating renewable energy generation, should be established.

Under the premise of the call for a dual carbon target, a high proportion of new energy is connected to the power grid in China, which leads to the security and stability of power system is affected. For example, replacing the conventional units with large-scale wind and solar power generation will reduce the overall effective inertia and the anti-disturbance capability of the system. In addition, it will require the power grid to bear a heavy power flow pressure, making frequency control more difficult compared to many other systems. Due to the large-scale off-grid system of wind power and photovoltaic generator, serious cascading failures and a large number of applications of the power electronic devices increase the risk of sub-synchronous oscillation. Therefore, the functional orientation and characteristics of each link in the modern power system will need to be greatly adjusted. The development of the system will also face many problems and even challenges that need to be solved [2]. In order to promote the accommodation of the new energy system, reduce the proportion of abandoned wind and light, and improve the coordination ability of the distributed energy and power grids, decentralized management will play an important role in future power systems.

In the engineering application represented by a power system, digital information technology has made great progress. The blockchain is an important part of information technology and has been widely used in various fields of power systems [3]. Blockchain, which is essentially a database and decentralized, is the underlying technology of Bitcoin.

It is a stream of data linked together using cryptography, each containing a batch of information about a bitcoin network transaction. It is a consensus on the current state of the books and the validity of its information can be verified as the blocks are connected to each other.

As a representative of the new generation of information technology, blockchain is a new application mode in computer science and technology that utilizes distributed data storage, consensus mechanisms, point-to-point transmission, and encryption algorithms. Due to the characteristics of blockchain technology, it can provide many advantages in the process of building a modern power system, while facing emerging challenges positively and providing solutions to the power system transformation. The specific advantages are as follows.

Due to the decentralized and immutable characteristics of blockchain technology, applicating it in the field of power systems can ensure the security of power information and transparency of the power market, and improve the management efficiency of the power system. Applying blockchain-based microgrids to the power system construction can realize remote power supply. Furthermore, it can supplement, optimize, and replace the traditional power grid, and provide a broader space for the development of new energy. Decentralized blockchain technology can provide economic incentive policies for the power grid, mobilize different power consumers to conduct energy transactions, and achieve power balance. Meanwhile, blockchain technology can motivate power consumers, save electricity, and improve the efficiency of power energy use [4].

Some publications are available regarding blockchain technology applications in power systems. In [5], two strategies of determining the bilateral transaction coefficient are proposed. The proposed platform could lower household costs, reduce total energy imports from the main grid, improve efficiency, and potentially reduce grid stress. However, the topology and consumption patterns and scale in its network configuration have not been considered and require further study. In [6], the alliance matching game model based on blockchain technology is presented for energy scheduling in a private charging pile sharing network. This study demonstrates that it is practical in improving the renewable energy generation utilization rate and enhancing consensus security but does not consider the discharge behavior of electric vehicles. A recent study [7] proposed a security acquisition algorithm for big data in a microgrid based on blockchain technology. This method can capture the operating status data of devices in a distributed real-time environment based on blockchain with good acquisition frequency and accuracy, but the data acquisition needs to meet the requirements imposed by regulatory authorities.

Some survey papers are available on the applications of blockchain technology in some areas of a modern power system, such as community energy markets and distributed energy trading. For example, the energy internet and energy blockchain are defined and the research framework of energy blockchain is presented in [8]. The key technology of energy blockchain is elaborated, but how to deeply integrate the technology with energy systems needs further study. In this paper, various possible scenarios of the applications of blockchain technology in modern power systems will be briefly surveyed, and prospects for future research outlined.

The objective of this paper is to review how blockchain technology can be applied in modern power systems and provide researchers with a summary of recent progress in this area. The structure of this paper is roughly as follows. Section 2 describes what kind of scenarios or methodology can use blockchain technology. Recent research and applications of blockchain technology in power system operation will be discussed, and the disadvantages of some existing publications identified (Sections 3–8). Finally, we draw some conclusions, and some potential research problems are prospected for promoting power industry restructuring and achieving emerging energy policy goals, such as the dual carbon goal in China (Section 9).

2. Methodology

To determine whether a certain scene of the power system can use blockchain technology, the following methods are needed:

(1) Determining whether the application domain has the characteristics of decentralization and excessive dependence on passwords;
(2) Determining whether data tampering needs to be prevented and whether consensus needs to be reached by multiple parties;
(3) Judging whether the use of blockchain technology can lead to innovation, increase transparency, and enhance the ability of auxiliary supervision [9].

If the scene meets the above criteria, blockchain technology can be used. Using this technology in the power system, existing schemes can be designed and optimized by improving algorithms, improving contract mechanisms, adding a coordination committee, improving side-chain technology, optimizing transaction mechanisms, and so on.

3. Application of Blockchain in Electric Power Dispatching

The applications of blockchain technology in power dispatching are shown in Figure 1. It can be seen from the figure that these units can be organically linked together with the grid, the power supply side, the virtual power plant, and the service provider. In addition, compared with the traditional methods, the advantages of being decentralized, distributed peer-to-peer, data block association, tamper-proof, transparent, and credible can be used in the modern power system. The current research studies on blockchain technology mainly focus on the following aspects:

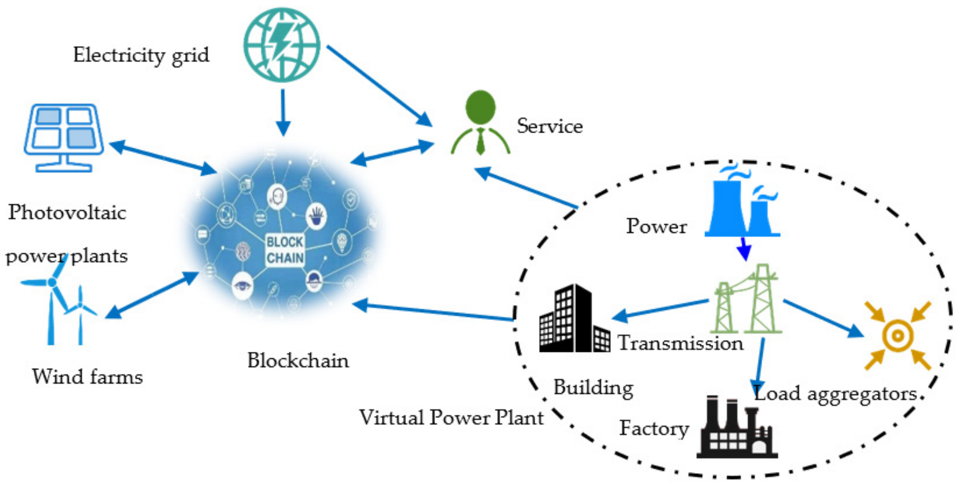

Figure 1. Application of the blockchain technology in power dispatching.

(1) Several studies have been carried out on dispatch management based on considering the dynamic electricity price. For example, a blockchain-based multi-microgrids scheduling strategy was presented in [10] with considerations of dynamic electricity price and the scheduling strategy, and a scheduling architecture based on a blockchain platform was designed. Through this scheme, the problem of the system economy and environmental pollution are improved. They used the linear programming method and improved the krill herd algorithm (KHA) with a weighted nonlinear change to solve, and blockchain technology could guarantee the security of scheduling data. A load scheduling algorithm is presented in [11] based on real-time pricing for multi-users. The algorithm can make use of real-time energy pricing information for scheduling. A case study of a distributed green energy was provided, using Hyperledger Iroha as a blockchain platform. It has been proved that the system is secure, scalable, and can ensure reliable energy transmission. The work in [12] focused on a local energy market based on blockchain. Their approach reduces the

cost of electricity using a scheduling algorithm based on critical peak price, real-time pricing, and demurrage. A scheduling algorithm was adopted and applied to a small community private chain containing photovoltaic systems. Experimental results show that this scheme can minimize energy consumption and power costs between producers and consumers, and enhance security in transactions.

(2) Scheduling schemes from the perspective of energy trading were put forth in the following studies. A peer-to-peer (P2P) energy transaction scheduling scheme (PETS) is presented in [13] based on blockchain technology. PETS is based on real-time energy consumption monitoring to balance the energy gap between the service providers (i.e., smart grid) and service consumers (i.e., electric vehicles). In PETS, a genetic algorithm was proposed to maximize the leader's profit from the leader's point of view. The simulation results show that the proposed PETS scheme is better than the most advanced one. An autonomous distributed scheduling framework was proposed in [14] for managing the power consumption in smart building clusters and the locally distributed energy. They provided an incentive mechanism based on the reputation value. The Ethereum private blockchain simulation results show that the scheduling scheme effectively reduces the scheduling cost. A distributed energy scheduling scheme is presented in [15] based on the minimum-cut-maximum-flow theory. Blockchains were used to record transactions and reach consensus. Payment and settlement of actual electricity consumption were performed using smart contracts, and a lower total power consumption cost was realized. This method was applied to a city in Guangdong province covered by China Southern Power Grid, and the result proved its feasibility.

(3) The following methods have been developed for safety. In [16], a power dispatching model based on hierarchical management and hierarchical storage was proposed, and a fully functional dispatching blockchain platform was developed. Automatic execution of dispatching evaluation was realized by using a customized smart contract, the security of the system was realized through the designed consistency check mechanism, and the scheme has been applied in practical projects. In [17], the blockchain technology is used, and a secure data aggregation model proposed based on homomorphic encryption and practical Byzantine fault tolerance (PBFT) consensus. In addition, they proposed an automatic power dispatching method based on the particle swarm optimization (PSO) algorithm and smart contract. The security and efficiency of the proposed solution are proved by safety analysis and experimental verification. A completely decentralized transaction architecture and a weakly centralized scheduling strategy are presented in [18] based on blockchain technology. A decentralized and quantified proportion of blockchain participation is defined, and a risk control model of blockchain transactions developed based on the communication credit consensus mechanism. Based on the transaction completion process, a weak centralized scheduling architecture based on an autonomous substation chain was designed, using an improved evolutionary gaming algorithm to solve the problem. A stable scheduling scheme was obtained by dynamically updating the credibility.

(4) Study from the point of view of economic dispatch includes the following: Chen et al. [19] presented the distributed security-constrained economic dispatch (SCED) algorithm based on the blockchain technique. Using a blockchain to form a coordinating committee and maintain a balance among the committee members, the proposed approach allowed for the use of a hierarchical SCED algorithm without a coordinator. The design scheme verifies the robustness of blockchain technology through digital simulation and realizes economic power dispatching.

By investigating the literatures of the past three years, we found that the application of blockchain technology in the field of power dispatching is generally included in several aspects as shown in Figure 2, and the proportion of literatures roughly reflects the heat of the corresponding research direction. At the same time, through the above discussion, we also found that in the case of electric power dispatching introducing blockchain technology can improve the degree of flexible control of electricity prices, which can improve the safety and economy.

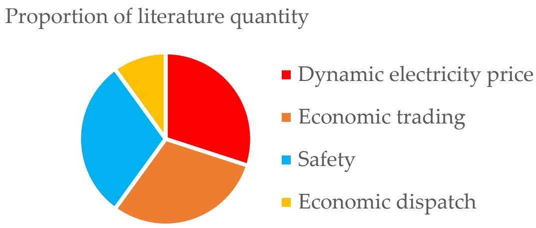

Figure 2. Application situation of blockchain in power dispatch.

However, the difficulty is the assurance of the decentralization degree of the scheduling strategy, and how to overcome it in achieving its advantage to other factors at the same time. For example, a study [17] proposed the aggregation scheme of secure data, and Formulae (1) are introduced into data reading and encryption for a smart meter.

$$RDmsg_{ijk} = \left\{cpd_{ijk} \| Id_{ijk} \| date_{ijk} \| ts_{ijk}\right\} \tag{1}$$

where $RDmsg_{ijk}$ represents legal data information, cpd_{ijk} represents encryption result, Id_{ijk} represents s_{ijk} (smart meter) identification number, $date_{ijk}$ represents date information, and ts_{ijk} represents timestamp. $\|$ represents "and", and ijk represents a smart meter under aggregator A_{ij}.

During the data aggregation and consensus process,

$$cAggRS_{ij} = \oplus_k\, cpd_{ijk}, S_{ijk} \in VS_{ij} \tag{2}$$

where $cAggRS_{ij}$ represents the aggregation result of encryption for data information, $\oplus_k$ represents aggregation of encryption results of k smart meters, VS_{ij} represents the result of a valid message, and S_{ijk} represents the result of each smart meter information under an aggregator.

The confirmed information can be expressed as:

$$TBCmsg_{ij} = VS_{ij} \| cAggRS_{ij} \| Id_{ij} \| date_{ij} \| ts_{ij} \tag{3}$$

Here, it is mentioned in this paper that the system will ignore the wrong information and only aggregate the valid information. In contrast to the latest publications, misinformation caused by deliberate acts can be punished by establishing an equal status of blockchain nodes (such as national, provincial, prefecture, and city, etc.), soft fork or hard fork can be used to modify or invalidate data, and reasonable smart contract and model data link can be used for processing.

4. Application of the Blockchain Technology in Microgrid

Figure 3 shows a schematic of the application of blockchain technology in a microgrid, which is the most important unit in the reform of electric power enterprises. The characteristics and architecture of blockchain suggest that its application in microgrids would greatly improve the intelligence and transparency of the management compared with the traditional methods. At present, the research on the use of blockchain technology in microgrids mainly includes the following aspects.

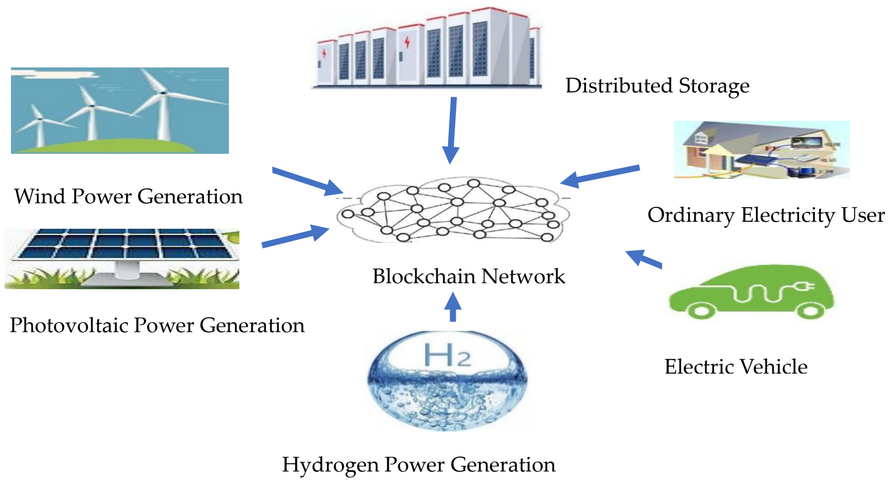

Figure 3. Schematic showing the application of the blockchain technology in microgrid.

(1) Studies from the perspective of establishing microgrid transaction models or algorithms include the following: Danalakshmi et al. [20] adopted a self-balanced differential evolution algorithm, which was used for calculating the power loss of each energy transaction. This approach was applied to the optimal reactive power dispatching (ORPD) scenario of the nine-way bus system. A case study showed that the proposed hierarchical microgrid architecture can achieve transparency and security among peers; thus, enabling reactive power optimization of the microgrid and reducing power losses. In Xu et al. [21], a coupled blockchain technology with a microgrid group transaction was described, which established a microgrid group information flow transaction model based on the blockchain technology. Based on the decentralized characteristics shared by the blockchain technology and the ant colony algorithm, an improved ant colony algorithm was proposed to solve the microgrid group, and the transaction model. Microgrid operators and distributed storage providers were taken as examples to verify the results. Yang et al. [22] proposed a blockchain consortium transaction model supporting P2P energy transactions. A power loss compensation alliance blockchain based on a smart contract transaction execution algorithm was designed. Simulation results show that the proposed blockchain model helps save users' transaction costs and could perform the technical operation of microgrid. Okoye et al. [23] proposed a network-enhanced transaction microgrid model based on the blockchain technology, and it was applied to microgrid transactions. By testing in a simulation environment, the results show that the model could enhance the robustness of energy transactions and alleviate the disaster caused by failure to deal with emergency demand events in a timely manner. Myung et al. [24] proposed an automatic power trading algorithm for a microgrid environment and applied it to transactions in microgrid environments. The algorithm has been implemented on the Ethernet blockchain platform with an executable distributed code (i.e., a smart contract). It can automate electricity transactions in a decentralized environment without user intervention. Masaud et al. [25] proposed an energy trading algorithm of two-layer isolated interconnected microgrids based on blockchain, and applied it to transactions in microgrid environments. The simulation results show that the proposed scheme can realize system reliability and improve the privacy protection of microgrid. Singla et al. [26] proposed a blockchain auction model based on a microgrid, adopting the consensus price algorithm and using geographical location as the main parameter of visibility between electricity consumers and aggregators. By applying it to transactions in microgrid environments, they aimed to create an energy transfer ecosystem. Liu et al. [27] established a microgrid transaction model based on the blockchain platform and used the optimized PSO method to solve the optimal bidding strategy in the transaction. The scheme is applied to wind storage and electric

vehicle small microgrid, and the verification results show that the scheme achieves profit optimization of each subject, realizes organic integration of blockchain and microgrid, and solves the problem of insufficient energy utilization in the microgrid game. Zhao et al. [28] established a microgrid market transaction model using the consortium blockchain technology and the Nash equilibrium in game theory. Price, trading volume, and user information were submitted to the blockchain container for transaction matching to realize the transaction. After the transaction was completed, its related information was recorded in the super ledger and called the scheduling system. The scheme was validated in microgrid transaction scenarios, and the results show that it can reduce the cost of purchasing power and improve the benefit of selling power. Chen et al. [29] proposed a prioritization algorithm based on the driving and charging behaviors of EV drivers and proposed a blockchain-based incentive mechanism for EV–EV coin. The scheme was simulated and verified by collecting solar energy data from California. The application shows that the system could effectively improve the utilization rate of the local microgrid and reduce the transmission load of the distribution network. Su et al. [30] proposed an optimized algorithm of microgrid energy management and applied it to microgrid energy management scenarios to verify the scheme. This method can reduce the inherent uncertainties in renewable energy systems by using and expanding clean energy, reducing power carbon emissions, and optimizing microgrid power management by using the energy blockchain technology.

(2) Studies on the security of microgrid transactions include the following: The authors of [31] proposed a blockchain-oriented consortium approach for solving the problem of privacy disclosure without restricting the transaction functions. This method was mainly aimed at the privacy problems of energy transaction users in smart grids. By mining different energy transaction volumes, the distribution of energy sales of sellers was screened, and its relationship with the physical location, energy use, and other information was detected. The scheme was applied to energy trading, and the security of the scheme was verified by sample selection and software environment simulation. Liu et al. [32] proposed a secure power transaction mechanism based on blockchain for smart power grids using wireless networks. By introducing a blockchain to record the power data collected by wireless networks, the designed smart contracts can make reasonable transaction decisions based on it and promote the effectiveness of the security. Wang et al. [33] proposed an artificial-intelligence-enabled blockchain-based electric vehicle integration scheme (AEBIS) for the power management of smart grid platforms. At the cost of acceptable memory and delay, the scheme was applied to the integrated power management system of the smart grid platform, and the verification results show that the scheme can achieve secure and transparent service. Khan et al. [34] proposed a Hyperledger Sawtooth Blockchain system, which realized a novel and secured distributed energy transmission node in the EPS-ledger network architecture. This approach designed, created, and deployed digital contracts for network physical energy monitoring systems. The scheme has strong renewable energy penetration capabilities and provides confidentiality and integrity in power system distribution. Zhang et al. [35] proposed a privacy protection scheme based on blockchain consortium and continuous double auction for microgrid direct electricity transactions. They used the combination way of the alliance blockchain and the continuous double auction mechanism. The results show that the proposed scheme can be applied to the microgrid direct electricity transaction scenario and can solve the demand of small scale, low cost, and high efficiency of microgrids.

(3) The following distributed transaction schemes have been proposed: Park et al. [36] proposed a scheme to implement the distributed ledger technology based on the directed acyclic graph (DAG) and applied it to the microgrid. After this, electricity transactions in a smart grid can be confirmed. Wang et al. [37] proposed a distributed P2P energy transaction method based on the double auction market, namely supply

and demand generation, pricing strategy, and distributed P2P energy transaction. The method was applied to an urban community microgrid scenario. Through test verification, the scheme can realize the coordination and complementarity of the energy resources in urban community microgrid systems.

(4) Studies from the perspective of smart contracts include the following: Younes et al. [38] discussed the detailed background of blockchain, introduced the general situation of smart grid and its technology, clarified the importance of smart contracts and their role in blockchain, and emphasized the application of blockchain in smart grid and the improvement of elasticity. Xuan et al. [39] proposed a blockchain-based power grid control method and application model, which treats both national and provincial systems as blockchain nodes. They concluded that a smart contract could establish a model data chain containing the entire network model and model maintenance ledger. It was applied to the innovative maintenance mode of the power grid. The results show that the scheme not only ensures the security and reliability of the data but can also be used for analysis, mining, and business development.

(5) Articles studied from the perspective of multi-microgrid networks include the following: The authors of [40] proposed a two-tier energy trading framework based on blockchain in multi-microgrids. This framework was applied to the transaction scenarios of eight independent microgrids. The results show that information transparency and mutual trust can be improved. Xu et al. [21] established a coupling model for the combination of blockchain technology and microgrid group transactions.

(6) Studies considering the ancillary service market include the work by Di Silvestre et al. [41], in which the auxiliary service market was considered; in particular, the voltage regulation service and a design scheme of blockchain technology in a comprehensive framework combining microgrid and economic management were proposed. The feasibility of the proposed scheme was verified by applying it to a group of energy trading examples.

For points (1)–(6), we made a summary in Figure 4. The proportion of the literature discussed roughly reflects the popularity of the corresponding research content.

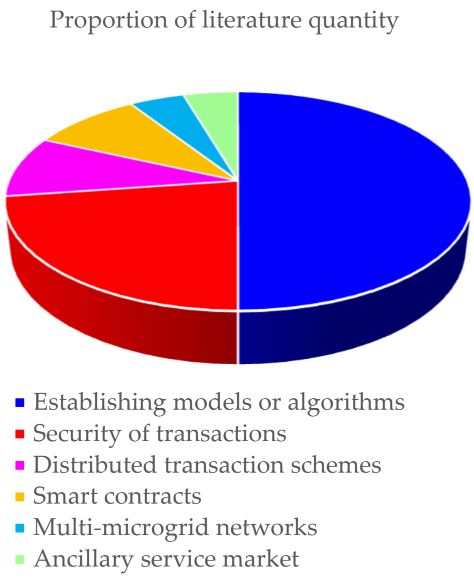

Figure 4. Application situation of blockchain in microgrid.

We can summarize the key technology approaches used in the microgrid blockchain from the above discussion. These include the adoption of the advanced algorithm, trading mechanism, and intelligent contract method. Compared with the traditional methods, these aspects will improve microgrid energy use and reduce carbon emissions. At the same time, they can improve data security and transparency. However, the bottleneck is that these applications need to be supported by a sound legal system. If the regulatory system lags, it will not be easy for it to be developed. In contrast to the latest publications, regulation can be strengthened through the establishment of coordinating committees on an equal footing, using advanced algorithms between tiers, or using advanced transaction authentication mechanisms.

5. Application of the Blockchain Technology in the Energy Market

With the development of blockchain technology, the pace of its integration into the energy market and its continuous innovation is accelerating. Figure 5 shows a schematic of the application of blockchain technology in the energy market [42]. In the future, energy blockchain will form a model of a small "physical-network + large information network + side chain auxiliary network". Energy generation enterprises, government regulatory departments, and various groups will operate in the system of the energy alliance chain [43].

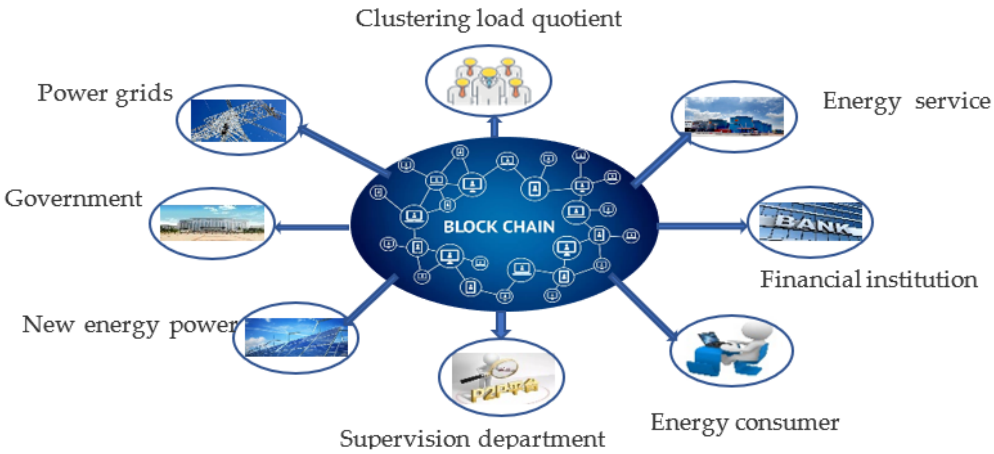

Figure 5. Application of blockchain technology in the energy market.

At present, the research on the usage of blockchain technology in the energy market mainly includes the following aspects:

(1) Various schemes have been proposed to improve its computing speed in energy trading. For example, Hu et al. [44] designed a consensus resource slice model (CRSM) in the field of energy trading. CRSM divides the consensus nodes into different consensus domains for concurrent consensus, and the storage domain only stores the block information but not consensus. It is applied to distributed energy trading scenarios. By building an experimental platform, the efficiency of CRSM was verified, which reduced the communication pressure of the blockchain system and effectively improved its consensus speed. Lu et al. [45] proposed a software-defined-networking (SDN) based distributed energy transaction scheme for an energy internet supported by blockchain technology, which was applied to a distributed energy trading scenario. Their scheme achieves reasonable matching of trading objects to protect privacy. A new distributed hash table topology was established by using the Kademlia technology, which greatly improves the speed of the route query compared to the other algorithms.

(2) The following studies on energy trading mechanism have been proposed. Che et al. [46] proposed a distributed renewable energy transaction authentication mechanism based on the alliance blockchain. Further, a certificate authority (CA) was introduced into the blockchain network to manage the users' public and private keys and certificates. This strengthened the supervision of the transaction participants over the power agencies. The solution can be applied to various platforms of blockchain consortia and energy trading markets. He et al. [47] proposed a joint operation mechanism of cross-chain transactions and combined the distributed photovoltaic power

generation and carbon markets using blockchain technology. Its novelty lies in the construction of two chains, the main chain and the side chain, which enables the two markets to share data and circulation value. In addition, the design of a two-way anchoring method can achieve the equivalence of carbon trading and electricity trading using cryptocurrencies. The results show that the scheme can increase the profit margin when applied to the cross-chain transaction scenario of distributed power generation. Xia et al. [48] proposed a decentralized power trading mode in which multiple parties participate in bidding and designed the decentralized power multi-party trading process. In addition, considering the limitations of the current blockchain technology, the user credibility model and the corresponding punishment mechanism were designed to restrict the offline point-to-point transaction after the bidding decision was completed. Using the Ethereum smart contract technology, a smart multi-party bidding contract was designed based on a decentralized power transaction process to provide privacy for users participating in the transaction and ensure that the bidding results were publicly verifiable. The scheme was applied to a distributed power trading scenario to verify the effectiveness of the power surplus trading mechanism. Zhuang et al. [49] designed a transaction mechanism and operation process for the distributed power generation market and transaction rules for distributed transactions. Based on this, the core method was used for distributing the transaction profits by taking collective rationality as the core game, and the core model of the distributed transaction cooperative game was constructed. An example verifies the feasibility of the scheme in a distributed transaction scenario. Long et al. [50] proposed a trading mechanism based on the Shapley value and a P2P energy trading algorithm. Based on the optimality and fairness of producers and consumers, a distributed energy management solution was proposed and applied to a residential community with a photovoltaic system.

(3) Various schemes have been proposed from the perspective of security in energy transactions. For example, Sheikh et al. [51] studied the energy transaction process between EVs and the distribution networks under the framework of the Byzantine blockchain consensus from the perspective of security transactions. It is applied to IEEE 33 bus system for case verification, and the results show that the scheme is feasible. Khorasany et al. [52] proposed a blockchain-supported P2P energy market trading framework, and designed the decentralized market clearing mechanism completely. This paper proposed an anonymous position certificate (A-PoL) algorithm, and applied to location-aware point-to-point transactions; the result shows that it can provide energy trading between producers and consumers, as well as security and privacy protection of the environment. Wang et al. [53] proposed a multi-blockchain power transaction data management structure based on a sovereign blockchain by taking the efficiency and security performance of the blockchain. The proposed scheme was applied to a multi-blockchain power transaction scenario for verification; the results show this data management structure improves the efficiency of power data management.

(4) The following studies on P2P energy transactions have been performed. Zhang et al. [54] studied a benchmark low-voltage microgrid case and a low-voltage microgrid case with higher node diversity using the self-designed energy trading platform "Elecbay". The results of this study show that P2P point-to-point energy trading could improve the balance of local energy production and consumption. In another study [55], a P2P energy trading scheme which adopts the alliance formation algorithm was proposed. It was applied to a residential network of 12 consumers. The case study shows that the scheme can help centralize the power system to reduce the total demand of users during peak hours. Doan et al. [56] proposed a smart electric P2P energy trading system based on the game theory and blockchain technology, which does not need to disclose private information such as the bid from each user, request, energy quantity, and user behavior. The proposed scheme is applied to a microgrid case with 10 consumers, and the security of the system is verified.

Khan et al. [57] designed a point-to-point energy transaction and charging payment system for EVs based on blockchain technology. In this system, the users can sell excess electricity to the charging stations via smart contracts, and the EV users can pay the charging fees using electronic wallets. Antal et al. [58] discussed a decentralized energy flexibility market based on blockchain. With the help of urban distribution system operators, the scheme is validated, and the results show that the scheme can enable small-scale producers to trade in a P2P manner and improve the flexibility in load modulation. Khorasany et al. [59] focused on a distributed P2P energy trading scheme. A prime-dual gradient method was applied to a small residential distribution network to verify the scheme, and a case study shows that the scheme can satisfy the direct interaction between buyers and sellers in a completely decentralized way in the electricity market.

(5) Articles studied from the perspective of the double auction market include the following: Jogunola et al. [60] developed VirtElect, a platform based on the dual auction market, to support paired interaction between consumers. Based on a case study of real microgrid data, the performance of the platform in demonstrating the potential of local energy consumption was verified. Fotia et al. [61] designed a decentralized, real-time, uniform price dual-auction energy market, which is a distributed and decentralized application, the rules of which can be specified using smart contracts. Market participants interact with smart contracts, sending their requests and offers. The distributed applications clear the market based on a uniform price economic scheduling model and realize the application in the distributed energy market.

(6) Research based on energy demand prediction includes the following: Shamsi et al. [62] proposed a conceptual framework for utilizing predictive markets on a blockchain platform with the aim of forecasting and hedging renewable energy. The potential financial benefits of applying this approach were demonstrated through a case study of a typical small wind power producer. Jamil et al. [63] proposed a predictive energy trading platform based on blockchain, which provides real-time support, one-day-ahead control, and power generation scheduling for distributed energy, and can realize point-to-point energy trading, data analysis, and predictive analysis supported by smart contracts. The energy consumption data of Jeju Island in South Korea were applied to the model for verification and analysis, and the results show that the platform has advantages in improving latency and throughput. Aloqaily et al. [64] focused on a solution combining a hybrid energy trading system with the smart contract of a collaborative power grid to create a hybrid energy trading platform on the smart contract for energy demand prediction. It was applied to the energy transaction scenario of distributed microgrid, and the results show that the scheme can efficiently reduce the utility grid's average energy cost and load.

(7) Studies based on comprehensive energy trading include the following: Hamouda et al. [65] proposed a comprehensive transactional energy market framework with linked blockchain and power system layers, a new-type market structure based on end-user marginal price, and an adaptive blockchain that adapts to the requirements of the inherent power system. The author applied it to the self-designed energy trading platform, and the results show that the scheme can make the trading price more flexible, increase the incentive effect, and improve fairness. Aloqaily et al. [64] proposed demanded forecasting content and also a solution combining a hybrid energy trading system with the smart contract of a collaborative power grid.

(8) Research based on market architecture includes the following studies: Hamouda et al. [65] proposed a new market structure based on the marginal price of end-users at the same time. Zia et al. [66] proposed the concept of a local energy market based on the existing tradable energy system architecture, critically analyzed the energy trade within the tradable energy system, reviewed and discussed the potential of the community energy market, and summarized the advantages and limitations of P2P and community energy market.

(9) Considering cross-chain technology includes the following studies: Wang et al. [67] proposed a novel two-layer energy blockchain network, which stores private transaction data and publicly available information separately. Based on the optimized cross-chain interoperability technology, the blockchain network fully considers the special attributes of the energy transactions. This method was applied to the transaction scenario of the Erlianhot distributed power market in China, and the results show that this method can improve the reliability of P2P transactions and facilitate supervision.

For points (1)–(9), we made a summary in Figure 6. The proportion of the literature discussed roughly reflects the popularity of the corresponding research content.

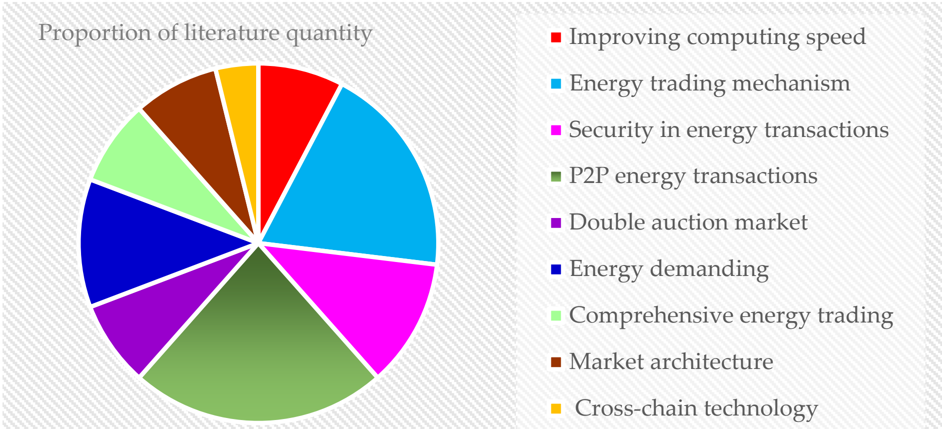

Figure 6. Research situation of blockchain in different fields of energy market.

From what has been discussed above, we can see the blockchain technology applied in the areas of energy market; by building a consensus model, using multiple chain trading mechanism, advanced technology, novel intelligent contracts blockchain network and so on, it can improve the speed of energy trading and data management efficiency, strengthen the supervision of the power mechanism, and improve the production of a consumer of optimality and fairness compared with traditional methods. However, for the private key operation, it is necessary to ensure the security of the private key; otherwise, it will have certain crackability, which will also be a potential threat to blockchain technology. In contrast to the latest research papers, we can design an advanced trading protection scheme to prevent missed energy trading.

6. Application of the Blockchain Technology in Electricity Bill Settlement

The application of blockchain technology in electricity bill settlement can efficiently realize a combination of the information flow, the energy flow, and the control flow, which can simplify the settlement process and improve the efficiency of electricity bill settlement compared with traditional methods. Figure 7 shows a schematic of the application of blockchain technology in the settlement of electricity charges [68]. Power grid companies, power generation enterprises, electricity sales companies, and electricity users can use the blockchain technology with distributed storage, consensus mechanism, smart contract, and privacy protection to carry out the settlement of electricity charges, transaction settlement, service fee settlement, and retail settlement. At present, studies on the use of blockchain technology in the settlement of electricity bills include the following:

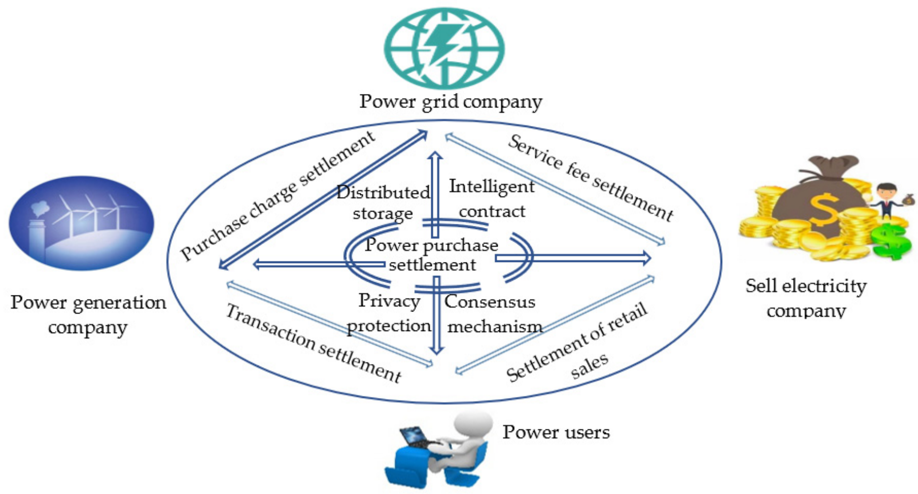

Figure 7. Application of the blockchain technology in electricity bill settlement.

(1) Research studies conducted from the perspective of security and privacy are as follows. Li et al. [69] proposed a lightweight dual blockchain privacy protection and sharing solution and designed a lightweight distributed cloud storage architecture based on dual blockchain for a smart grid smart pricing system. The scheme has the characteristics of low delay, short response time, and high security. A privacy protection estimation scheme employing the blockchain-based data acquisition and load function were proposed [70]. They estimated the power consumption behavior model of the user group using the gradient descent method, and the users who reflected the energy consumption habit of the current user group were selected as the charging node. They applied it to the scenario of multi-energy fusion system in a smart park. The results show that the scheme improves the security of the whole system and ensures the efficient operation of the energy utilization system.

(2) Studies performed from the perspective of smart contracts are as follows. In [71], smart contracts were used to automate the bidding process in trading according to smart cities' energy supply and demand. This process was applied to urban energy management, and the results show that the feasible scheme can improve the flexibility of pricing and security. Lu et al. [72] proposed a smart contract of power transaction and fee settlement of power grid enterprises based on blockchain technology and the transaction model using a smart contract. A transaction model was established and applied to an example of buying and selling electrical smart contract. The results verify the scheme can reduce the trust cost of the electricity market transaction, improve settlement efficiency, and promote the intelligence of electricity retail market.

(3) Studies on the pricing mechanism include the following: Wang et al. [73] adopted a contract model to solve the problem of cloud computing resource allocation and pricing in the mobile blockchain. An adverse selection contract solution was selected to overcome information asymmetry and applied to resource management. The verification results show that this scheme can improve user rewards and is more effective than linear pricing contracts. Wang et al. [74] proposed a multi-propensity factor pricing mechanism based on the dynamic adjustment of real-time information of the electricity/hydrogen energy market. The pricing mechanism proposed in this work can improve renewable energy's operational efficiency and consumption rate. The aforementioned scheme [69] is also intended to be applied to the pricing system. Devine et al. [75] described a framework that can simulate the price dynamics of organic token trading activities between generators and consumers. They applied it in the demurrage scenario of power transactions, and explored the relationship between the equilibrium price and time-sensitivity of bilateral transactions of blockchain tokens. Oprea et al. [76] proposed four blockchain transaction mechanisms, including classical

auction and pricing mechanisms (such as UP, PAB, GSP, and VCG), and applied them to a scenario containing 11 modern smart residential power transactions. The verification results show that this scheme can improve the flexibility and profitability of trading. Oprea et al. [77] proposed two novel and efficient P2P power exchange settlement mechanisms (global balancing settlement and split settlement), and applied them to a small residential community scenario. The verification results show that the two new mechanisms can improve the performance of classic pairwise settlement. Wang et al. [78] established a new Stackelberg game with consortium blockchain as the main body. A cost-driven and lightweight MAC layer resource allocation method was proposed and applied to multimedia transmission market scenarios. The results show that the video quality and social benefits are improved while security is ensured. A pricing model of local Partially-practical Byzantine Fault-tolerant (PBFT) consortium blockchain was proposed based on the game theory [79]. In the proposed model, the interaction between the buyers and sellers as well as between the sellers was taken into account. An example was explored to verify it, and research shows that P2P e-commerce transactions can provide more benefits for consumers. Xia et al. [80] proposed a blockchain-based vehicle-to-vehicle power transaction scheme for the internet of vehicles based on the Bayesian game pricing. Experimental results show that the scheme is safe and reliable and can obtain more benefits for vehicle users.

(4) Some authors have given recommendations on the billing system. A study [81] proposed a hybrid billing and charging framework based on blockchain distributed consensus and applied it to energy case scenarios. The verification results show that this scheme can protect user privacy and provide credit sharing functions for Internet of Things users. Khan et al. [57] also proposed a charging payment system for electric vehicles based on blockchain technology. This scheme can increase trust, transparency, and privacy among participants of electric vehicles.

For points (1)–(4), we made a summary in Figure 8. The proportion of the literature discussed roughly reflects the popularity of the corresponding research content.

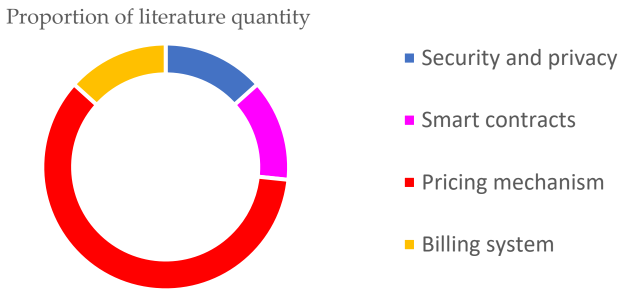

Figure 8. Research situation of blockchain in electricity bill settlement.

Through the above discussion, we find that when blockchain technology is applied to the electricity bill settlement, the system can operate efficiently by adding data collection and privacy protection schemes based on blockchain technology. Compared with the traditional methods, the operational efficiency and consumption rate of renewable energy can be improved through the adoption of reasonable smart contracts and pricing mechanisms. Still, transaction delays may occur when multiple blockchain branches exist due to the impact of low probability events. Comparing the latest research papers, advanced algorithms or consensus models can be used.

7. Application of Blockchain in Power Transmission and Distribution

Figure 9 shows a schematic of the application of blockchain technology in the field of power transmission and distribution. At present, only a few studies have been performed on the application of blockchain technology in power transmission and distribution. The research hotspots are as follows.

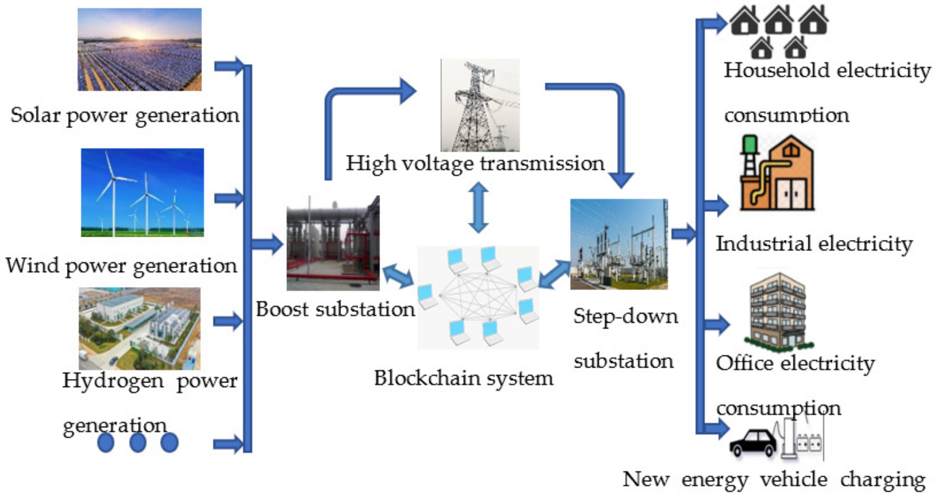

Figure 9. Application of the blockchain technology in power transmission and distribution.

(1) Optimized algorithms are used in power transmission and distribution networks. For example, in the study by Shah et al. [82], a distributed-consensus based alternate direction multiplication optimization algorithm was proposed, which contains the subproblems of private cost function and constraints. Distributed feeders were divided into low coupling subnetworks/regions, which solved the private subproblems locally and exchanged information with the adjacent regions to reach a consensus. The proposed scheme was applied to distribution networks with coupled and mixed-integer constraints. Results show that the proposed algorithm has a fast convergence speed and strong reliability. AlSkaif et al. [83] proposed a consensus-based distributed optimization algorithm using the general form of the alternate direction multiplication method, and designed a decentralized optimized power flow in the distribution network. They applied it in a private blockchain-smart contract platform, and the results show that the algorithm and framework guarantee the system's security.

(2) Some scholars have researched improving the energy efficiency of the distribution network. For example, Luo et al. [84] proposed an agent alliance mechanism to enable consumers to form an alliance and negotiate a distributed electricity trading system based on the active distribution network. Their approach adopted a transaction settlement mechanism based on blockchain. The system consisted of a two-layer network. The scheme was validated in a P2P environment with multiple numbers of consumers. Their simulation results show that the proposed power trading mechanism could effectively promote energy sharing between users and improve the energy efficiency of the distribution network. Bischi et al. [85] proposed an ad-hoc consortium blockchain based on Ethereum and designed a local low-voltage point-to-point power market. The application of this scheme can strengthen the point-to-point energy exchange, improve intelligence levels, relieve the pressure from the transmission and distribution network, and improve transmission and distribution efficiency.

(3) A few studies have been performed from the perspective of energy transactions and applied to distribution networks. Liu et al. [86] proposed a distributed P2P day-ahead transaction method under the congestion management of multiple micro-networks in active distribution networks, and analyzed the effect of the P2P transaction on the operation of the microgrids system with specific indicators. The simulation results show that network congestion as well as network loss were alleviated. In addition, the economic and technological interests of all market players were ensured. Li et al. [87] proposed a new energy trading framework that dealt with economic issues in energy trading and technical issues in the distribution system operation in a holistic manner. They applied it to IEEE 37 bus and 123 bus distributed systems for simulation

experiments, and the results show that the framework can improve the economy and voltage safety performance.

(4) Studies have been carried out on energy routers in the transmission and distribution networks. For example, Gong et al. [88] studied the operation of energy routers in the transmission and distribution networks with high permeability renewable energy access. In addition to applying blockchain technology to combine the energy flow quality of service index with the independent cooperation mode of the energy router nodes, the autonomous energy cooperative optimization mechanism and control flow of the router nodes in the power transmission and distribution network were designed. Simulation results show that this scheme can improve the output of routing nodes and optimize the transmission and distribution network.

For points (1)–(4), we made a summary in Figure 10. The proportion of the literature discussed roughly reflects the popularity of the corresponding research content.

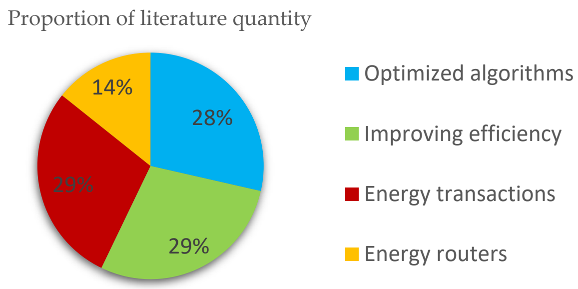

Figure 10. Research situation of blockchain in power transmission and distribution.

With the discussion above, compared to the traditional electric power transmission and distribution schemes, it can be observed that the blockchain technology with an optimized algorithm can effectively achieve decentralization. Further, based on an enhanced electricity trading mechanism and schemes, the applications of various novel blockchain can alleviate the burden of the transmission and distribution system, improving its efficiency and economy. However, if the power transmission and distribution transactions are on the public chain, the transaction data is transparent and privacy cannot be guaranteed. The property and transactions of a certain company are publicly available once its account is exposed. By comparing with the latest publications, we can adopt cloud and fog storage architecture of double blockchain or design advanced transaction mechanisms and transaction privacy protection schemes.

8. Discussion

8.1. Discussion 1

This paper reviews the application scenarios of blockchain technology in the modern power system. The Web of Science database was adopted. Keywords search references, and then references were searched. Table 1 is a statistical table of publications for the above scenarios.

From Table 1, firstly, we can see that the number of research articles about blockchain technology in the energy market is the largest in the past three years. Secondly, there are many research articles on blockchain technology in microgrid. The number of papers on blockchain in power dispatching is basically the same as in electricity billing. The amount of research articles on blockchain in power transmission and distribution is the least, which indicates that it is more difficult to carry out research on blockchain technology in power transmission and distribution. In the future, we may find a breakthrough in this direction, and further research can be carried out in the direction of power dispatching and electricity billing. At the same time, we can also refer to the latest number of papers to choose the application scenarios of blockchain technology. Among the investigated literatures, the number of research articles accounted for about 93%, while the number of review papers accounted for only 7%.

Table 1. Statistical table of various application scenarios in the publications.

Statistics	Research on Blockchain Technology in Power Dispatching	Research on Blockchain Technology in Microgrid	Research on Blockchain Technology in the Energy Market	Research on Blockchain Technology in Electricity Billing	Research on Blockchain in Power Transmission and Distribution
Number of references in recent three years	11	24	27	14	7
Database	web of science	web of science	web of science	web of science	web of science
Number of latest papers	3	1	2	1	0
Number of review	0	2	4	0	0
Number of research articles	11	22	23	14	7

8.2. Discussion 2

Due to decentralization and immutable information of blockchain technology, its application in modern power systems will have an important play due to its many advantages, such as improving the efficient operation of the system, improving the efficiency of data management and operating income, improving the insufficiency of energy utilization in microgrids, and reducing carbon emissions.

However, the use of blockchain also has drawbacks. Its immutability and irrevocability are both advantages and disadvantages. If the transfer address error occurs in the transaction, it will directly cause permanent losses and cannot be revoked, and the loss of the key will also cause permanent losses that cannot be reversed. In addition, advantages in one area may result in limitations in others. For example, [54] shows the possibility and the potential benefits of energy trading, which is integrating blockchain technology into the local power grid. However, before it becomes a reality, it will be necessary to develop a series of reforms to the existing energy policy, legal, and energy trading system. Comparing the latest work, it can improve its security and feasibility by using an optimized algorithm, secure power trading mechanism, or adding certificates for public and private keys. In another study [47], the ellipsis encryption algorithm was used to show the effectiveness of the remaining power trading mechanism; however, the process of entire data confirmation may be delayed. Comparing the latest works, the common nodes can be divided into different consensus domains and use concurrent consensus to reduce the pressure of communication so as to improve the computing speed.

9. Conclusions and Prospects

9.1. Conclusions

This paper mainly discussed the application of five scenarios on blockchain technology in modern power system, aiming to analyze the current research status of blockchain technology in the power system and provide research directions for researchers.

Naturally, the innovative application of blockchain technology goes beyond the scenarios mentioned in this article. Studies have also been performed on power enterprise management (for example, Refs. [30,46] and suggestions for improving the efficiency of power management), electricity carbon market (for example, Refs. [30,47], which also mention the linkage trading scheme of the carbon market), virtual power plant, new energy storage, new two-way interaction of load, etc. In the future, it will also play an important role in the field of ecological energy, cross-chain transparent power systems, power market trust mechanisms, and so on.

Through the above discussion, we find that we still need to conduct in-depth research on blockchain technology. It is suggested that advantages and disadvantages should be weighed in various aspects during design and application. In the future, we hope to overcome obstacles, develop advantages, and improve the defects of blockchain technology in modern power systems.

9.2. Prospects for the Applications of the Blockchain Technology in Modern Power Systems

Future applications of blockchain technology in power system development include hybrid storage, cross-chain technology, stratified consensus, built-in contract, and other aspects, which will need to be continuously optimized. In the modern power system with new energy as the main body, including the source network load storage, the use of the blockchain technology will greatly improve the flexibility of the power grid, achieve flexible adjustment, accelerate the deep integration of the digital technology with the power system, and help in achieving an intelligent and transparent power system. In particular, this can be understood as follows.

"Platform + application + ecology" has become an important development trend of the energy blockchain. The energy blockchain ecosystem will be gradually improved. With the in-depth development of blockchain technology, the blockchain standard will be gradually improved, promoting technological development and innovation, helping to realize the landing of the cross-industry ecosystem, and promoting the formation of a large ecosystem of blockchain.

Cross-chain technology can enable the communication of information between the blockchains to achieve an efficient transmission between the chains. Further, scattered island information can be communicated with others, and the circulation time can be saved. All aspects of the power system can be connected by employing the contract mechanism, and a truly transparent power system can be realized.

Blockchain technology and power field should adapt to the changes in modern power systems. With the development of high proportions of new energy, carbon emission trading, electricity market synergy, and electricity price mechanism, green electricity trading, power transaction blocking management, Power Internet of Things, electric vehicle energy management and charging pile industry ecology, cross-border business, and materials industrial finance chain on power grid combined with blockchain technology will continue to be promoted.

In the future we expect blockchain technology to be the driving force in several areas, including in the acceleration the development of energy blockchain standard system, building of a new energy digital ecology, improving the security and compatibility of the power market, exploration of a more developable application space, and creation of a new ecological pattern of the industry that will gradually come into being. In addition, blockchain technology applications in power systems will continue to be promoted and should lead to a new energy digital ecology and improve the compatibility of the electricity market [68].

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