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A review of energy internet research considering interactive energy: The blockchain perspective

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With the proposal of carbon peak and neutrality goals in China, new technologies such as multi-energy synergy technology, cyber physical systems, and multi-market integration technology have ushered in unprecedented opportunities and challenges. Energy Internet (EI) technology considering interactive energy has come into being. Interactive energy is a mechanism to achieve system balance by integrating economic means and power grid control technology, using "value" as a coordination method. It can promote the development and utilization of distributed renewable energy in the energy internet technology, so as to promote the clean, low-carbon, and intelligent development of energy. Blockchain can provide effective support for the development and application of EI because of its decentralized, open, autonomous, and information-immutable characteristics. In order to better cope with the challenges existing in EI, this article designs an analysis framework for EI from the blockchain perspective, which contains five dimensions, including engineering dimension, technical dimension, economic dimension, environmental dimension, and social dimension. It further refines the five dimensions aiming to comprehensively summarize the research status of the EI, which can promote its application in the development of all industries in society.

KEYWORDS

energy internet (EI), interactive energy, blockchain, carbon peak and neutrality goals, power grid

1 Introduction

With the continuous advancement of energy transformation, the access of large-scale fluctuating renewable energy and high permeability of power electronic equipment brings new challenges to the safe and stable operation of the power grid. Energy Internet can realize the efficient transmission of energy and information, but the value chain of the energy industry has not been connected. Source, network, load, storage, and other links have not been deeply integrated, and there is an extensive friction in the transaction between various links (Zhang et al., 2016; Zhou et al., 2020a).

Energy Internet is a new energy system centered on power, through a large number of new intelligent technologies, information technology, and control technology, to achieve cross-time scale coupling, multi-energy complementarity, multi-party coordination, and cooperation. It has the advantages of high-energy efficiency, high reliability, and high flexibility (Al-Ghaili et al., 2021). A strong, smart grid is the key to building a new power system with renewable energy as the main body, and Energy Internet is an important part of a clean, low-carbon, safe, and efficient energy system. With the integrated interconnection of multiple types of distributed energy, multi-type load, energy storage, and information flow, this puts forward new requirements for power transaction (Gangatharan et al., 2020; Jan et al., 2021). For example, the role of the transaction subject is constantly changing. The user subject has pure power consumers, and prosumers who can sell electricity to power grid enterprises or directly to other users. In the future, power grid enterprises may be more responsible for the operation, maintenance, upgrading, and expansion of transmission and distribution system, and collect appropriate network fees to ensure the sufficient communication capacity between the energy management system and the two parties to the dispatching agency. Moreover, the processing of a large number of energy internet subject information and power transaction data should have the requirements of being efficient, safe, and economic (Zhao et al., 2019a). Lack of trust among various market players in the energy system can easily lead to trade friction, which is generally unavoidable with a large number of participants. Blockchain technology is characterized by decentralization, openness, transparency, security, and credibility, which provides an important way to solve the transaction friction in the energy system (Yang and Wang, 2021). As an innovative and revolutionary distributed ledger technology, blockchain combines distributed data storage, peer-to-peer transmission, consistency mechanism, and encryption algorithms to allow relevant data and activity information to be recorded in verifiable ways. This is consistent with the power-trading demand under energy internet, and can provide technical support for the innovation of power-trading mode.

Interactive energy is a mechanism to achieve system balance by integrating economic and power grid control means using “value” as a coordinative means. Interactive energy is a mechanism with the dual characteristics of market and control. Compared with centralized control, it has the advantages of a distributed control system, including avoidance of large-scale data communication and heavy computing requirements; compared with the distributed control, it still retains the coordination mechanism of the market, and therefore it can support the operation goal of the group system level. The interactive energy mechanism based on blockchain technology enables the power system to realize decentralized operation and distributed multilateral transactions while maintaining the normal operation of various functions (Qi et al., 2020). The typical expression form is peer-to-peer (P2P) transactions (Ding et al., 2022).

In order to better cope with the challenges existing in the Energy Internet, we propose an analysis framework of the Energy Internet based on blockchain, which includes five dimensions: engineering dimension, technical dimension, economic dimension, environmental dimension, and social dimension. These five dimensions are further refined and classified, aiming to comprehensively summarize the research status of the Energy Internet, so as to promote its application in the development of all walks of life in the society. The respective dimensions and their corresponding reference numbers are shown in Table 1.

2 Energy internet review from the perspective of blockchain

2.1 The future of the energy internet

The framework of the Energy Internet is shown in Figure 1. The mutual transformation of various energy sources through energy hubs reflects the “horizontal breakthrough” of the multi-energy comprehensive management. At the same time, it also deepens the connection between the “source-network-load-storage” of energy, as well as realizes the “vertical breakthrough” in the operation process of energy production and consumption. The existing research deeply analyzes the value creation and business model of the Energy Internet from a technical perspective for specific application scenarios. The research of the Energy Internet value creation and business form innovation, however, should rise to the height of energy economics based on multi-energy integration, cyber-physical system (CPS), and multi-market fusion. It is necessary to explore the physical and economic mechanisms of the Energy Internet value creation, to realize the value of the Energy Internet with institutional mechanism and business model innovation, planning and promoting the strategic path of the Energy Internet (Lv et al., 2020).

2.1.1 Multi-energy integration

“Re-electrification” is a comprehensive upgrade of traditional electrification. It refers to the process of making full use of modern energy, materials, and information technology, developing and utilizing clean energy on a large scale and replacing fossil energy, and finally realizing a highly electrified society with clean energy as the main body (Xiao et al., 2021). Re-electrification is the strategic demand that renewable energy should try to replace fossil energy. The electric energy based on renewable energy will gradually replace the fossil energy for heating, cooling, and electricity for oil, gas, gradually changing the consumption structure of terminal energy by forming an energy supply based on electricity.

TABLE 1 Each dimension and its corresponding reference documents

Dimension	Ref	Contents	Expectation
Technical	Zhou et al. (2020a) Yang et al. (2021b)- Saha et al. (2022)	1, P2P Microgrid 2, Interactive Energy EMS 3, Blockchain Technology and Sustainable Development	Improving renewable, efficient, and low-cost storage of data storage
Economic	[72055]- Teng et al. (2021b)	1, The prosumer Business Model 2, Power market mechanism 3, Commercialize smart contracts	Maintaining the fairness and security of electricity trading
Engineering	Hamouda et al. (2021a)- Mei et al. (2022)	1, P2P Policy and Management 2, Power grid operation rules 3, Enterprise unit innovation (management)	Creating a safe and reliable power grid data management environment
Environmental	Abishu et al. (2022)- Wang et al. (2019)	1, Lower carbon pollution emissions 2, Higher utilization rate of renewable energy sources	Using smart technologies to strengthen and innovate management of environmental pollution
Social	Zhang et al. (2019a)- Khalid et al. (2021)	1, Social benefits (macro policy) 2, Service for smart grid equipment updates 3, Interest management of relevant subjects	Accelerating the development of a unified national electricity market and flexible market management mechanism

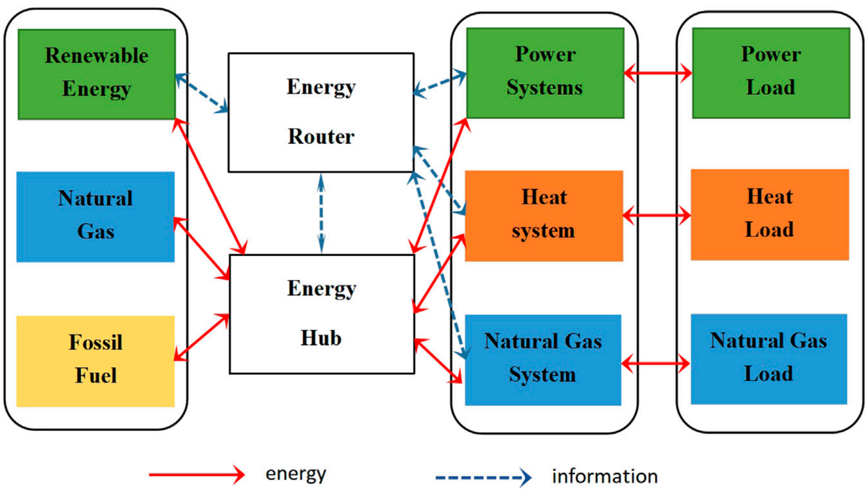

FIGURE 1
Framework map of the Energy Internet.

When electricity and heat are coupled, the low-cost energy storage advantage of the thermal system will become a flexible resource to absorb new energy, which inevitably requires the power grid to not only dispatch electricity, but also for heating and cooling systems driven by electric energy in the future (Yang et al., 2021a). Heating accounted for 50 % of the global terminal energy consumption in 2021 and 40 % of the global carbon dioxide emissions, according to the International Energy Agency. The industrial sector accounts for about 50 % of the heat consumption, buildings (mainly for space heating, hot-water supply and a small amount for cooking) account for about 46 %, and the rest for the agricultural sector. In many big cities, the air-conditioning load accounts for more than 50 % of the power load. Using the thermal insulation characteristics of buildings, it can provide a considerable amount of energy storage space for the whole power grid, so as to smoothen the volatility of new energy generation (Teng et al., 2022). Heat storage can also convert renewable energy for a relatively long time and at a low cost into heat for storage (Teng et al., 2021a). Renewable energy vehicles are also an important part of re-electrification. The re-

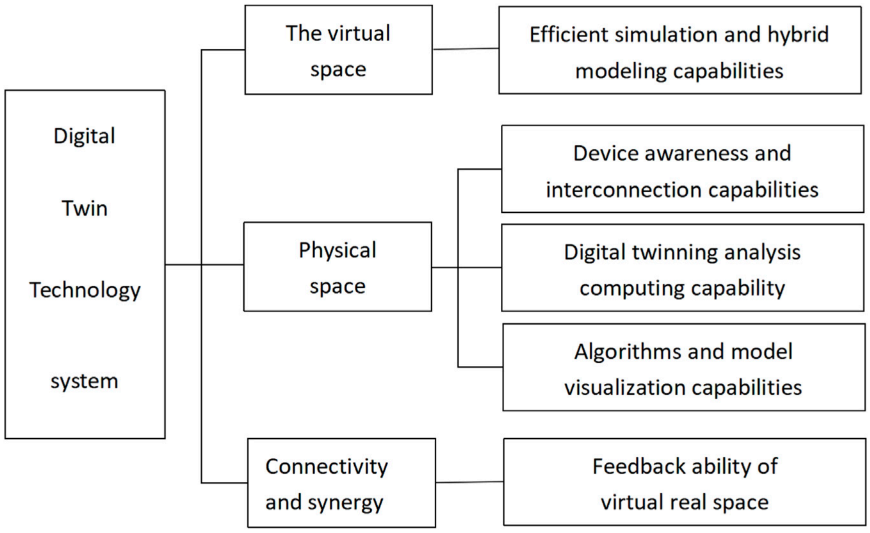

FIGURE 2
Digital twin key technology system.

electrification of energy consumption is compatible with the power structure with new energy as the main body, forming a large system of electricity, heat, and cold-integrated operations, which will become the core driving force of the Energy Internet construction (Wang et al., 2021a).

2.1.2 Information physics fusion

Artificial Intelligence (AI), in its essence, is a simulation of the information process of human thinking (Chen and Huang, 2021). Although AI has been widely used in the power system, it is preliminary and still stays in the application of load prediction, price forecast, distribution network, tide calculation, etc. These are basically improvements in the computational decision method of the power system, which is determined by the current database. The real significant value of AI depends on whether a Digital Twins (DT) system for the grid is built (Bellavista et al., 2021; Dang et al., 2022). Currently, key technologies for DT include efficient simulation, hybrid modeling, integrated data perception, transmission and lifecycle data management, etc. The technical system is shown in Figure 2.

DT is dynamic; the upstream and downstream data interactions must be achieved between the digital and physical systems. DT will solve the non-linear and uncertainty problems that cannot be solved by traditional mechanism models, and constitute an evolving system with machine learning and deep learning that will establish a DT system, constantly analyze the rules between data through AI, warn the existing risks, and optimize the operation of the system. AI can not only overcome the state fluctuations caused by human emotions, post adjustment, and other factors, but can also think and recognize the objective laws according to the data. This will substantially improve the efficiency of the Energy Internet and its essence is to greatly reduce the price paid by the uncertainty of the boundary conditions of the energy system. It can improve the synergistic benefits generated by the order of energy system operation and the security benefits brought by the security of the energy system (Lei et al., 2022). AI can predict the future operation scene of the power grid, grasp the law of the users' energy use, and remember all historical scenes. These are the key areas where AI can greatly improve the benefits of the Energy Internet.

2.1.3 Multi-market integration

Market mechanism is to generate value distribution through competition, so as to activate the enthusiasm of various market subjects. Market efficiency depends on the social welfare and transaction costs based on the transaction. The general transaction costs mainly include disseminating information, advertising, market-related transportation, and information costs such as negotiation, signing, contract-execution supervision, and other activities. Transaction costs mainly come from the information asymmetry (Liu et al., 2022). Data technology can eliminate information asymmetry and provide a means for the complete sharing of information in the energy ecosystem. Technology is only a means, however, the innovation of mechanism is needed to stimulate the full use of various elements and accurately carry out energy production, transmission, consumption, and related data-sharing. The power of sharing comes from the mechanism's accurate measurement and fair distribution of the value of participants. Only the sharing economy mechanism based on the fair distribution of value can motivate the market members to provide real information and eliminate the irrational game behavior adopted by the participants due to their fear of unfair value distribution (Bhattacharya et al., 2022). Without the market mechanism of fair distribution of value, the value that data technology can produce will be greatly reduced. Because if the value distribution is unfair, there will be no market members willing to disclose their true information and the value of data technology will inevitably be difficult to achieve.

2.2 The concept of transactive energy

Transactive energy is a mechanism to achieve system balance by integrating economic means and power grid control means using "value" as a coordinative means. The introduction and application of transactive energy in the power system provides an effective way to solve the demand-side flexible resource management and the multi-subject optimization of operation. It takes value as the driving parameter, aiming to integrate advanced communication and electronic technologies with the smart grid, innovate the traditional energy industry through advanced thinking and technology in the internet, further realize the efficient configuration of system resources making the future power system operate more safely and efficiently (Hao et al., 2020). Typical properties include the following points:

1) The transacting parties of the system supported by the transactive energy mechanism should be clear. The power system transactions generally include transmission system operators, distribution system operators, electric power company, cluster administrator, etc. The establishment of the trading body can ensure the smooth implementation of the relevant transaction behavior and incidental services;
2) Transacted commodities and transaction. In interactive energy systems, trading goods and trading behaviors must be clearly defined. For example, the traded goods can be electricity energy or related auxiliary services, demand-side flexibility, etc. While the transaction behavior should clearly define the information needed to be exchanged and the mechanism to achieve agreement;
3) Interoperability of information understanding between the transaction entities. For the interactive information in the transaction behavior, two or more parties of the transaction entities should understand its content;
4) Value discovery mechanism. The transaction subject should reach an agreement on the value of the transaction commodity, which can be reflected by the price, satisfaction degree, or other forms, but the overall goal is to form a consistent value cognition.

TABLE 2 Comparisons of major characteristics between Energy Internet and blockchain.

Energy internet Features	Blockchain Features
Intelligent equipment	Smart contract
Multi-energy collaboration	Group collaboration
Information symmetry	Parallel communication
Distributed supply and demand	Decentration
System flattening	Platform unity
Transaction opening	Open and transparent

2.3 The development of blockchain technology

The emergence of blockchain technology has provided a good opportunity for the development and application of the Energy Internet. Its characteristics of decentralization, openness, autonomy, and information tamper-proof have become the basis for the construction of "Value Energy Internet" (Saha et al., 2021). According to the six characteristics of the Energy Internet, blockchain has the corresponding characteristics or functions to match with it (Qu et al., 2021):

1) Device intelligence: Blockchain can automatically be executed on the chain through smart contracts to complete the intelligent operation required by energy equipment.
2) Multi-energy collaboration: Blockchain can realize group collaboration through the incentive mechanism, so that different types of energy sources can effectively coordinate and complement each other, which can improve the utilization efficiency of comprehensive energy and reduce energy costs.
3) Information symmetry: The network layer of blockchain is based on peer-to-peer communication technology, and each node has full backup information, which can ensure the information symmetry between different energy entities.
4) Distributed supply and demand: The core feature of blockchain is decentralization, and its distributed network architecture can be perfectly matched the characteristics of decentralized energy supply and demand.
5) System flattening: Blockchain is essentially a trusted distributed ledger which connects all participants and forms a unified underlying platform. It reduces the system process by ensuring the trusted data, and realizes the flattening of the energy business system.
6) Transaction opening: Blockchain can realize transaction information to be open and transparent to all participants, and its peer-to-peer communication mode has natural peer-to-peer transaction capability. It can open transaction services to market participants in accordance with relevant rules.

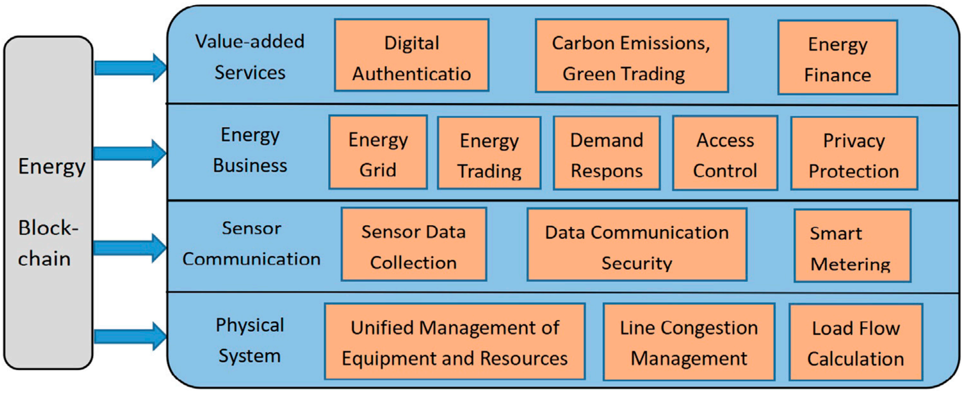

FIGURE 3
Energy blockchain application hierarchy diagram.

The main characteristics of the Energy Internet and blockchain are shown in Table 2.

3 Research method development

The EU industry believes that energy blockchain is an important application scenario of blockchain technology (Feng et al., 2022). Both Energy Internet and blockchain are characterized by distribution and decentralization. The design concept of openness, interconnection, reciprocity, and sharing emphasized by Energy Internet is highly compatible with the characteristics of blockchain decentralization, joint maintenance, status equality, and data sharing (Yang et al., 2022a). The technical architecture based on blockchain technology can ensure the equal status of individual users in the Energy Internet, and realize the P2P energy and energy-related information transactions among users (Li et al., 2021). This can realize the value drive of the Energy Internet and establish a new energy value system. We believe that the blockchain can help with the various levels of the Energy Internet to build an energy blockchain separately or jointly. The specific application scenarios are shown in Figure 3.

As one of the energy blockchain scenarios, power transaction belongs to the third level of the Energy Internet architecture—the energy business layer. In the trend of extensive decentralized access of green energy to the power grid and the gradual maturity of V2G, the demand for regional P2P trading is increasing (Yang et al., 2021b). The construction of a decentralized P2P trusted and secure regional trading platform is the developmental direction of power-trading blockchain (Yagmur et al., 2021). At the same time, with the development of the Internet of Things and sensing communication control technology, power system regulatory control of granularity gradually refined in the time and space dimensions (Wei et al., 2021). Embedding the Internet of Things, big data, AI, and other technologies into the power transaction blockchain stack in an appropriate way can automatically and quickly implement power system supervision and control to improve efficiency (Wei et al., 2022; Xie et al., 2022). From the perspective of Energy Internet, power transaction needs to use the data provided by the sensor communication layer and the results of blockchain transaction to finely control the physical system layer. Under different power grid physical architectures, the transaction requirements and characteristics are complex, which provide plentiful scenarios for research.

At present, the existing research on power transaction blockchain technology not only includes the exploration of the application mode of blockchain technology, but also the in-depth research of blockchain technology for application scenarios. This reflects the phased characteristics of the current blockchain technology stack research in the field of power trading. But, the specific application business scenarios need to be clear. The characteristic value framework has not been established, and blockchain needs to be enriched and innovated for the power transaction scenario.

4 Multi-dimensional benefit analysis

4.1 Technical dimension

4.1.1 P2P microgrid

With the advancement of power market reforms, microgrid users with distributed power supply are allowed to participate in the electricity market transaction as electricity sellers. The operational framework of P2P transaction with microgrid energy management is shown in Figure 4. The power transaction between distributed power supply and the users is

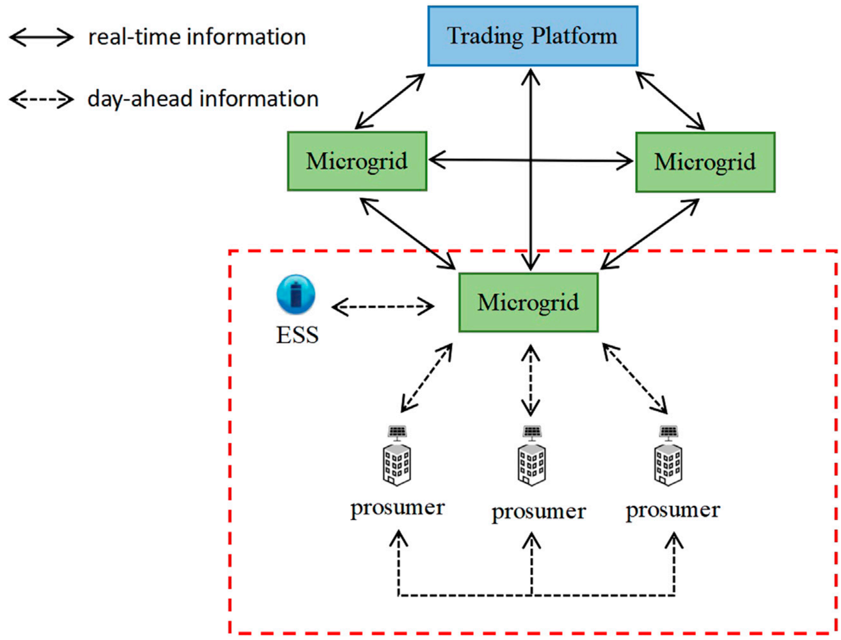

FIGURE 4
P2P operation framework of energy management of the microgrid.

characteristic of a decentralized and small scale. There are many problems in the traditional management mode of transactions through centralized institutions, such as opaque transaction price, untimely settlement, and easy disclosure of user privacy. By using asymmetric encryption, digital signature, proof of workload, and other mechanisms, blockchain technology can realize peer-to-peer transactions while ensuring data security and cost reduction.

The Ref. (Wang et al., 2018) put forward the trading mode and strategy of distributed power supply and users in the microgrid based on blockchain and continuous two-way auction mechanism, which provides reference for the construction of a microgrid power market under the new round of power reforms. The Ref. (Abdella et al., 2021) presented a unified blockchain-based P2P-ET architecture (UBETA). It integrates three different types of energy markets, providing a unified model for energy trading and payment. The Ref. (Gong et al., 2022) designed the environmental identification factor incentive mechanism of the dynamic cooperative game and the smart contract supported by the multi-objective evolution algorithm and proposed the co-governance coefficient to evaluate the effectiveness of the proposed microgrid group's operation strategy.

The main challenge in implementing P2P energy transactions is to ensure that network constraints are not violated during the energy exchange. Therefore, while focusing on the problem of P2P energy-trading, the technical constraints of the network should also be studied. The Ref. (Guerrero et al., 2019) proposed a sensitivity analysis-based approach to deploy P2P energy transactions in local markets to assess the impact of P2P transactions on networks and to ensure energy exchange without violating network constraints. The Ref. (Zhang et al., 2022a) studied the equilibrium state of the supply and demand flow in the P2P market model of residential shared energy storage units, and proposes the methods of service pricing and load allocation. Prevalent transactions between shared energy storage units and grid-based suppliers are considered, as well as the demand market based on residential consumers. A game model for characterizing the equilibrium of the market is proposed, considering the strategic behavior of individual players. The Ref. (Wang et al., 2022a) proposed a strategy based on the stochastic Cartel game to study the energy-bidding problem of power grid-oriented MMGs based on P2P energy trading under uncertain conditions.

4.1.2 The EMS of interactive energy

The multi-energy system is a high-precision self-control system, which can cooperate with the blockchain to realize the ubiquitous information interaction of the multi-energy system operation state and measurement data among multiple operating subjects. In order to make the multiple energy systems closely integrated and coordinated to form an organic whole, the Ref. (Li et al., 2018a) mainly analyzed the applicability of the blockchain in the application of the multi-energy system and the information interconnection problem brought about by the heterogeneous blockchain. It proposes the necessity and method of constructing a multi-energy system–trading system based on heterogeneous blockchain technology. The Ref. (Wei et al., 2019) proposed a multi-energy complementary security transaction model of heterogeneous energy blockchain, which better solves the problem of multi-energy complementarity and integration scheduling of distributed energy in the energy-trading system. The Ref. (Wang and Wang, 2022) proposed a multi-energy interaction agent consensus method based on the Practical Byzantine Fault Tolerance (PBFT) algorithm to realize the authenticity of multi-energy data, distributed decision-making of complex systems, trust among interaction agents, etc. The Ref. (Shen et al., 2021) had designed a consensus algorithm evaluation method including three dimensions of efficiency, fault tolerance, and operation cost, filling the gap in the quantitative analysis of energy blockchain consensus algorithm and scenario adaptability.

Due to the disadvantages of the centralized-trading service platform, including high cost, low efficiency, and lack of security guarantee, improving the energy-trading methods and management system has become a key problem facing the energy industry reform. Based on the smart contract, distributed ledger, P2P transaction, and other technologies of blockchain, the Ref. (Wang and Liu, 2022) proposed a regional energy transaction model based on smart contract so as to reduce the complexity and transaction cost of the system. The Ref. (Chen et al., 2016) designs the architecture and trading mechanism of a tradable energy system, presents the specific operation mode of the tradable energy system and analyzes the benefits of relevant subjects. The Ref. (Huang et al., 2022) proposed a new scalable blockchain-based cooperative microgrid system energy-trading framework to ensure the reliability of energy trading in the cooperative microgrid. Using the contract theory, the incentive mechanism and the reputation system under information asymmetry, the Ref. (Yahaya et al., 2020) proposed an efficient and secure blockchain-based energy transaction model, which improves the reliability and efficiency of the system.

4.1.3 Blockchain technology and sustainable development

Blockchain is a trusted system built for the first time in human history. Its core function is to improve the governance capacity of each latitude. In the past 2 years, the development and popularization of blockchain technology has shown an explosive growth trend.

The most important feature of blockchain technology is the decentralized distributed system. The traditional centralized data collection architecture has poor transparency and high data-security risks. As a new decentralized infrastructure and distributed computing paradigm, blockchain technology can lay a solid foundation of data security and trust for the development of automation and intelligence-related industries (Yuan et al., 2022). The Ref. (Yang et al., 2018a) proposed a data blockchain-generation algorithm for electric power information physical fusion system to improve the security and credibility of data interaction. In terms of information fidelity, the blockchain technology has made a great improvement to the traditional internet from the mechanism design—from the traditional centralized database to the decentralized distributed database, from the single-node-based information verification to the multi-node-based information verification (Gao et al., 2019). In Ref. (Abdelsalam et al., 2022), each prosumer uses an energy management system based on the Percent Power Change (PPC) of a day to motivate consumers to save energy and protect their privacy by using this novel blockchain-based mechanism. The Ref. (Li et al., 2020) proposed a blockchain-based energy-trading project aiming to supervise and manage the energy-trading process to build a secure energy-trading system.

With the popularization and application of blockchain technology, the emerging smart contract technology has attracted wide attention in academia and industries. Smart contracts can be effectively realized in the distrust and executable environment with the help of the decentralized infrastructure of blockchain. The Ref. (Yang et al., 2018b) made a comprehensive review of the operation mechanism, mainstream platform, key technologies, etc. The Ref. (Musleh et al., 2019) illustrated the various advantages of blockchain in power systems, and indicated that the application of blockchain in the smart grid can provide many innovative and affordable solutions. The Ref. (Saha et al., 2022) proposed a distributed hybrid access control for smart contracts that provide transparency, reliability, and robustness to existing access control mechanisms in the industrial Internet of Things. The Ref. (Hu et al., 2022) had designed a series of functional and auxiliary contracts to realize users' online demand reporting, automatic order-matching, real-time cost settlement, and other personalized functions, improving the economic benefits of production and consumers.

Blockchain technology can also well serve the construction of the Energy Internet. The Ref. (Ning et al., 2018) analyzed the coupling of the Energy Internet and blockchain technology in the dimension of "physical-information-value", and initially builds an energy blockchain framework supported by blockchain technology. The Ref. (Zhou et al., 2020a) summarized and analyzed the application of blockchain technology in the Energy Internet from three dimensions: function, theme, and attribute. The Ref. (Zhou et al., 2020b), summarized the application scenarios of six types of energy blockchain in detail, and reviewed the typical energy blockchain projects corresponding to each scenario, which provided a reference for the theoretical research and practical construction of energy blockchain. The Ref. (Zhao et al., 2019b) put forward the development ideas and suggestions of China's energy blockchain technology through the comparison of domestic and foreign application engineering in terms of energy policy and technology, combined with the current situation of China's energy development.

With the increasing amount of data storage in power systems, how to use blockchain technology to safely and reliably improve the renewable utilization, high efficiency, and low-cost storage of data storage is worth further research.

In addition, the current status of blockchain technology is that the research and development of blockchain basic technology platform or operating system is mainly in abroad, while the application and development of blockchain is mainly in China. The application development of Chinese enterprises mainly relies on the achievements of foreign open-source communities. Therefore, the core goal of promoting the healthy development of China's blockchain technology is firstly in urgent need of an advanced layout of a controllable underlying platform and independent innovation of basic technology (Zheng and Qiu, 2020).

4.2 Economic dimension

4.2.1 Prosumer business model

As an important part of a smart grid, distribution networks are also undergoing major changes. With the liberalization of the power sales side, the distribution network will have a large number of independent prosumers to participate in the power market competition. Users will not only be energy consumers, but also be energy suppliers by managing their own distributed generating units, distributed energy storage facilities, and distributed loads. The access of a large number of consumers will generate new business models, forming free bilateral trading of electricity. The increase of market participants makes it much more difficult to quantify the transaction information. Therefore, it is necessary to seek an effective way to manage power transactions.

In the operation of the distribution network, the traditional centralized management mode has the problems of high cost, low efficiency, low transparency, and high-information security risk. So, a more flexible internal-trading mechanism is inevitably needed. Blockchain technology is a distributed storage technology that can effectively solve the trust problem between both parties of the transaction. Reasonable use of the relevant characteristics of blockchain technology can provide effective technical support for the market transactions of distributed generation. Blockchain technology is used to store power transaction information in the form of smart contracts and automatically execute capital transfer to record the power data collected by smart meters. Only the center checks and manages the completed transactions safely, so that market participants can manage the transactions spontaneously. The Ref. (Yang and Wang, 2021) developed a new blockchain-based energy-trading framework for consumers, and designed a decentralized energy-trading algorithm. This algorithm improves personal income and ensures the optimal performance of the society, thus encouraging consumers to join the trading-energy platform. The Ref. (Kong et al., 2020) proposed a blockchain-based multi-chain framework to better manage and protect measurement data in power systems.

Market operations and distribution networks are becoming more complex, and P2P energy-trading markets have emerged in order to improve the efficiency of energy trading. The market is based on a P2P energy-trading model that determines a two-level pricing mechanism of transaction price and a credit rating system used to improve the quality of the P2P market, so that participants can enjoy a more acceptable transaction price and save on the cost per transaction.

4.2.2 Electricity market mechanism

With the orderly progress of the new round of power system reforms, it has become the development trend of China's power market to allow the distributed power supply and other multiple subjects to participate in the market competition. At present, there are two main ways to manage the electricity market: with the central organization as the management body and the market members managing spontaneously. The power-trading method based on the alliance chain technology can solve these problems. It can ensure high transparency, traceability, and imtamability of the transaction, retaining the regulatory authority of the trading center and providing new ideas for the weak centralized power transaction mode in the future.

For power market transactions with distributed power supply, the Ref. (Yang and Wang, 2021) proposed a multi-party transaction model of the power market with new entities based on blockchain technology, and used blockchain technology to decentralize the power market, which can ensure the safety and reliability of multi-party transactions in the market. In the case of large-scale and high-frequency energy flow and information flow in multiple user interactions, the Ref. (Liu et al., 2022) proposed a decentralized power resource allocation method based on user preferences, which can promote the nearby energy consumption and improve the resource allocation ability of the power grid. The Ref. (Wang et al., 2022b) proposed the dynamic pricing mechanism of blockchain technology in a hydrogen gas station, which has obvious advantages in improving the trading profit and renewable energy-utilization efficiency compared with the fixed energy-pricing method.

In modern smart grids, Demand Response (DR) programs can be deployed to encourage power users to schedule controllable times during off-peak periods. In order to maintain the fairness of the transaction, the information of blockchain-distributed transactions is transparent to all users so that all personnel can participate in the transaction online at any time and learn the whole process of the transaction. Each player can realize transparent information sharing and timely grasp the transformation of information resources during the

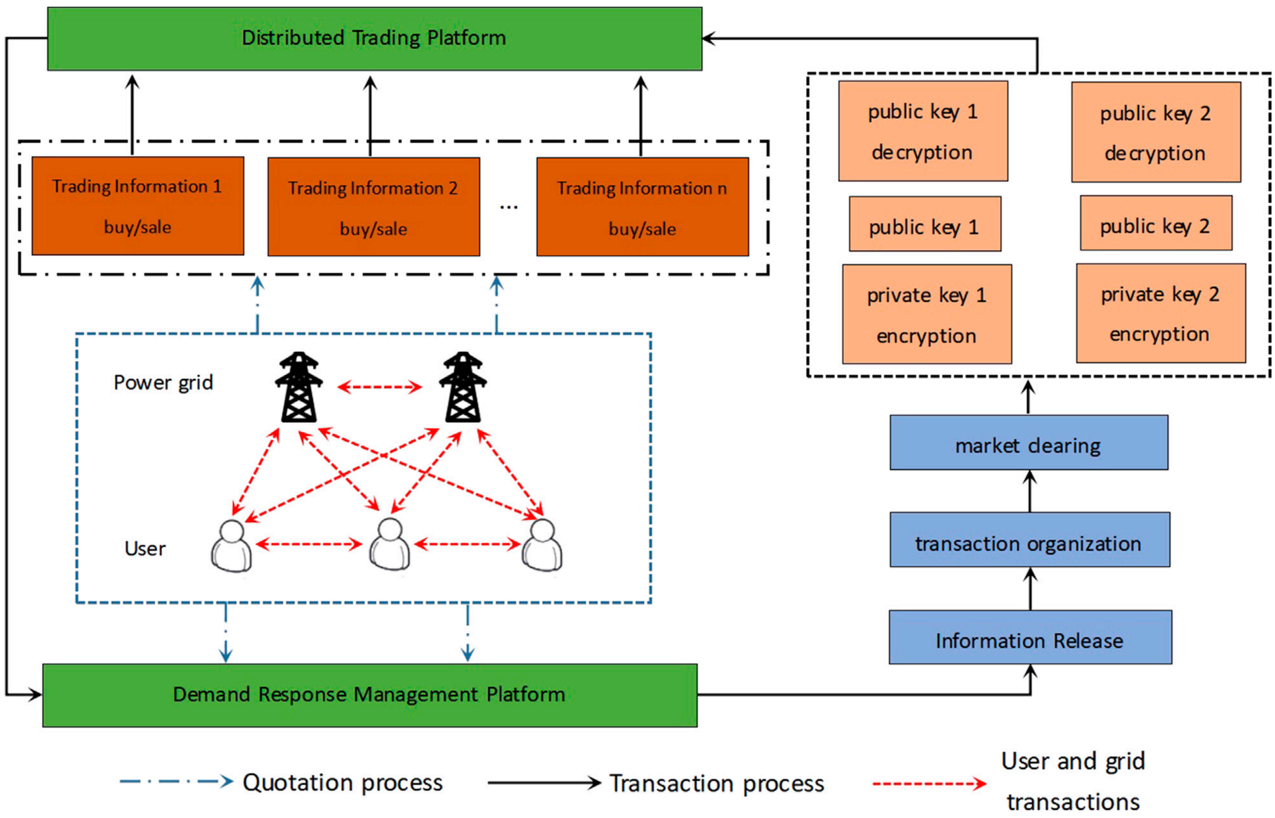

FIGURE 5
Distributed transaction process under the combination of demand response and blockchain.

transaction to guarantee high security. The distributed transaction process under combining DR and blockchain is shown in Figure 5. The dynamic balance of supply and demand has aroused great attention to the concept of DR using blockchain technology to record the data derived from the power flow computing model and electricity price customization and using smart contracts to store transaction data and automatically transfer assets. The Ref. (Tushar et al., 2020) proposed a P2P energy trading scheme that could help centralized power systems reduce the total power demand of their users during peak hours. The Ref. (Tsaousoglou et al., 2020) proposed DR architecture, where practicality of participation is enhanced via simple queries, while scalability and user privacy are preserved via a distributed implementation.

With a large number of independently decision-making electric vehicle users participating in the market competition of the power grid, it is of great significance to design an effective V2G power-trading mechanism. The decentralization, openness, and transparency of blockchain technology are consistent with the transaction demand of the distributed energy. Exploring the distributed energy transactions based on blockchain can help to absorb energy and reduce credit costs. A decentralized power-trading mechanism can effectively realize the P2P power transaction of electric vehicles. The Ref. (Baza et al., 2021) used blockchain technology to propose a privacy-preserving charging station-to-vehicle (CS2V) energy-trading scheme, introducing an anonymous and efficient blockchain payment system to protect the privacy of electric vehicle drivers. Using the security and privacy attributes of blockchain, the Ref. (Teng et al., 2021b) proposed a new blockchain-based large-scale parking vehicle-computing (BLPVC) architecture, which achieves a balance between service delay and distributed resources, while greatly reducing the cost of battery depreciation.

As a relatively independent power grid structure, microgrid is the main application scenario for distributed electric energy to participate in market transactions. In order to realize the optimal configuration of clean energy, the overall framework of blockchain-based microgrid market can be built. Data information is obtained through the blockchain management platform, combined with the model prediction and control (MPC) method, so as to realize the optimization of the microgrid market scheduling and operation. With the increased penetration rate of distributed renewable energy and the random access of electric vehicles, the traditional centralized management and power sales in the microgrid are no longer applicable. Blockchain technology is applied to the construction of a decentralized multi-microgrid system power market that can realize the high integration of physical information flow. This helps market players to make rapid decisions from massive data and improve the operation efficiency of the local power market. The Ref. (Hamouda et al., 2021a) proposed a new energy-trading strategy of an interconnected microgrid (IMG) that the self-interest-driven (SBD) behavior of power generators takes into account. This strategy defines a unique utility function for each generator, enhancing the security and transparency of the platform. At the same time, the data-trusted processing between microgrids has also become very important. At present, most research studies on microgrid data security are aimed at a specific level, while ignoring the data connection and interaction process between whole systems. The Ref. (Yang et al., 2022b) used an authoritative and private blockchain to defend against various types of network attacks, such as false data injection. This method can secure the distributed control system while ensuring the quality of control.

4.2.3 Commercial smart contracts

The emergence of blockchains has brought about the opportunity to securely automate the procedure of P2P energy-trading. A blockchain is an open and distributed ledger that records transactions between two parties efficiently and in a verifiable and permanent manner. It is noteworthy that a smart contract is one of the key elements in executing the procedure of the blockchain platform without a human interface. Smart contracts are well-suited to conduct rules for direct end-to-end transactions of energy autonomously based on local consumer preferences. The blockchain-based smart contract has the potential to enhance security and ensure fairness for decentralized energy systems' management.

Because the centralized model requires a large number of human costs for database maintenance and frequent information proof-reading with third parties, the trading center is vulnerable to attacks. The security of information storage is poor and user privacy is difficult to guarantee. The Ref. (Dong et al., 2020) proposed an innovative blockchain platform framework which significantly increased the security and fairness of energy transactions as smart contracts strictly enforced transaction and payment rules.

With the introduction of social capital, there will be more DR aggregators and electricity sales service providers to participate in the interaction of the power grid. If DR still follows the existing centralized information security management methods, there will be major risks. Most of the existing blockchain technology research studies in the business field stay in the conceptual design stage. In order to explore the application method of blockchain smart contracts in demand-responsive bidding transactions, the Ref. (Cui et al., 2022a) proposed the Energy Imbalance Market (EIM). The market promotes the real-time supply and demand balance in the power system better by rewarding market participants for better prediction of market conditions. The Ref. (Zhang et al., 2022b) proposed a smart contract micro-service architecture for load aggregators to solve the technical bottleneck of applying smart contract to load aggregators to participate in demand response.

4.3 Engineering dimension

From the perspective of engineering dimension, the application of blockchain technology in the field of Energy Internet is affected by Chinese and international policies, standards, norms, and other aspects. On 19 December, 2019, the State Grid Technology Corporation organized the first Energy Blockchain Ecology Conference to actively explore and promote the application of blockchain technology in the energy and power industry. The key laboratory of blockchain technology and data security, the UN Network Blockchain Company, has set up a power application working group, which has played a significant role in promoting the development of blockchain technology and industrial innovation.

Compared with traditional energy, renewable energy has the characteristics of a diversified main body and a long industrial chain. Integrating blockchain consensus mechanism and smart contract technology, adopting continuous bilateral auction mechanism can effectively solve the problem of the lack of trust caused by information asymmetry between power transactions through P2P transactions. In addition, the use of blockchain technology can also achieve enterprise innovation through the management of the power grid data, to create a safe and reliable power grid environment.

4.3.1 P2P strategy and management

In order to realize more secure and stable transactions in the power market, the power transactions based on blockchain need certain laws and regulations to restrain and regulate theselves. The Ref. (Mengelkamp et al., 2018) pointed out that current regulations do not allow the operation of local peer energy markets in most countries or regions, and electricity cannot be legally traded. In addition, as the blockchain scale continues to expand, the government should provide stricter regulations to regulate the development of the power industry.

In the electricity market, the traditional centralized management mode has the problems of high cost and low trust. P2P transactions are realized through the asymmetric encryption, digital signature, and proof of workload of blockchain technology, which can effectively solve the problems in the centralized management mode and provide a feasible way for the direct transaction of energy. The Ref. (Li et al., 2018b) used alliance blockchain technology to propose a secure energy-trading system called energy blockchain which can be widely used in the general situation of P2P energy-trading to get rid of the trust intermediary. The Ref. (Zhou et al., 2022a) proposed a credit-based P2P power transaction model in the

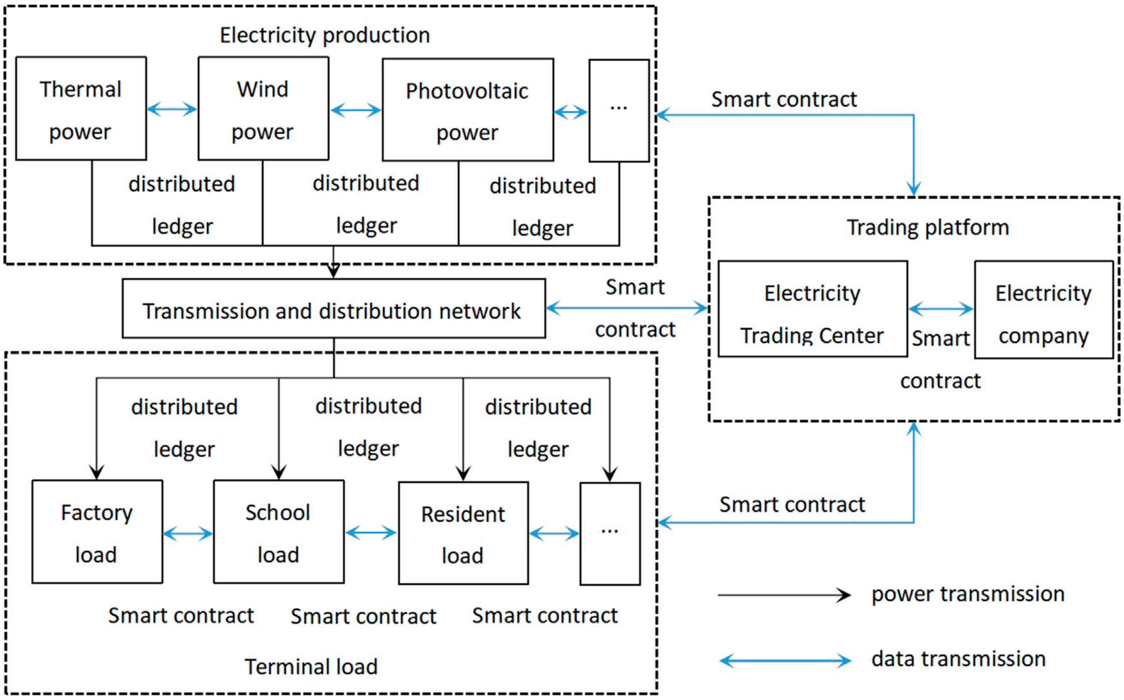

FIGURE 6
Improved smart contract electricity transaction model.

blockchain environment, and introduced credit management to manage the default behavior of users. The model is conducive to reducing the cost of blockchain users, realizing credit management in P2P power transactions, so as to improve the stability and efficiency of transactions. The Ref. (AlAshery et al., 2021) proposed a P2P energy-trading framework supported by blockchain, integrating bilateral contract, e-commerce platform, etc.

4.3.2 Power grid operation rules

With the opening of the electricity sales-side and the deepening of the concept of Energy Internet, a large number of distributed generation, distributed energy storage, intelligent electricity load, and other subjects have started participating in the power market competition. The electricity market structure is becoming more and more diversified. Therefore, it is of great significance to realize the benefit of each subject in the power market (Liu et al., 2020a). However, under the traditional centralized energy management, there are great problems of data tampering, information asymmetry, and high transaction cost between various subjects and power-dispatching centers. As an emerging distributed database technology, blockchain technology has the characteristics of decentralization, intelligence, contracts, and so on. It has great applicational potential in the future of Energy Internet. In order to solve the problem of high operation and maintenance costs in the process of power transaction, to ensure the security and efficiency of the power transaction, the smart contract is deployed in the blockchain. The improved smart contract power-trading model is built for the power transaction scenario, as shown in Figure 6. As energy trading may seriously affect the operation of power systems, the Ref. (Esfahani and Mohammed, 2018) introduced a blockchain-based energy-trading framework. The results showed that the proposed framework was more reliable than the traditional centralized and improved decentralized energy-trading framework. The Ref. (Hamouda et al., 2021b) established a power market model integrating the blockchain and the power system layer. This model will benefit all system users, and will alleviate the demand response and peak rebound problems. The Ref. (Chen et al., 2022) proposed a distributed security constraint of the economic scheduling optimization algorithm based on the blockchain, to ensure the safety and reliability of the power system.

In the electricity market, the two-way energy trading of electric vehicles can be used to mitigate the impact of the mismatch between supply and demand. The Ref. (Mei et al., 2022) proposed a blockchain-based terminal security access scheme which could effectively combat the single-point risk of the renewable energy power grid security scheme. The Ref. (Abishu et al., 2022) proposed a new consensus mechanism that takes advantage of practical PBFT and proof of reputation (PoR) and employs an incentive mechanism based on the Stackelberg game model to optimize the utility of the seller, buyer, and verifier nodes. The Ref. (Aggarwal et al., 2021) proposed an energy-trading scheme with blockchain among the three communication parties (i. e, electric vehicles, charging stations, and service centers). The proposed scheme had better security for electricity transactions in V2G networks, less communication overhead, and computational time.

Direct electricity purchase by large users is a necessary stage for the power industry to shift from regulation to opening up, and then establish a market mechanism. The application of blockchain technology to direct the power purchase by large users will not only contribute to the promotion of the power market reform and the development of the power system to the Energy Internet, but also promote the practicality of blockchain technology. The Ref. (Xu et al., 2022) discussed the reform of introducing blockchain into the demand side of the power market. The reform initially constructs the access mechanism and transaction framework for direct power purchase by large users of blockchain technology.

4.3.3 Enterprise innovation (management)

With the continuous advancement of enterprise information level, the value of data plays a very important role in the process of enterprise development. Due to the wide range of enterprise data sources and large structural differences, the blockchain technology is just suitable for the analysis and processing of complex data. Therefore, blockchain technology is expected to solve the problems of weak security and low precision of smart grid data management. The Ref. (Cui et al., 2022b) used the characteristics of distributed storage, asymmetric encryption, consensus mechanism, etc., of blockchain technology to solve the problems of power grid data storage and application. At present, the application of blockchain technology in the smart grid data management platform in China is still in the exploratory stage, and there are few experiences to draw lessons from. Therefore, it is still necessary to carry out continuous technological innovation and experience exploration. The Ref. (Ghorbanian et al., 2020) introduced the problems and challenges of smart grids in the presence of blockchain-based cryptocurrencies and proposed some innovative ways to effectively integrate and manage blockchain-based cryptocurrencies in smart grids.

4.4 Environmental dimension

4.4.1 Lower carbon pollution emissions

In recent years, the global environmental quality has declined seriously, causing various direct or indirect threats to nature and human society. Therefore, to continuously explore the use of intelligent technology to strengthen and innovate environmental pollution control is the essence of promoting the modernization of the national governance system and governance capacity (Rui, 2020).

As a Chinese industry with a priority of inclusion in the carbon-trading system, the power industry has become the largest carbon emission source in the global energy sector, and is the main force of energy conservation and emission reduction. Blockchain, as an emerging distributed ledger technology, can effectively solve the problems of data security and operation efficiency in the carbon-trading system. Therefore, it is significant to explore the application of blockchain technology in the field of environmental sustainable development. In view of a series of problems existing in the operation of the current carbon-trading system, the Ref. (Du et al., 2020) designed the overall framework of the carbon-trading system in the power industry based on blockchain technology. It also constructs carbon quota cost-decision model, emission reduction reward and punishment model, and carbon trading-matching model to optimize the carbon trading system of the whole power industry. The Ref. (Yan et al., 2021) proposed a blockchain application for processing energy and carbon quotas in microgrids, using an external cooperative game to simulate the market behavior of networked manufacturing systems, and encouraging generators to trade the effectiveness of energy and carbon quotas. After the analysis of energy trading and distributed energy, the Ref. (Su et al., 2021) showed that energy blockchain technology is a valuable asset for expanding the use of clean energy, reducing carbon emissions in power, and optimizing power management in a microgrid.

As more and more market members participate in the electricity market, the market management becomes more difficult. The Ref. (Wang et al., 2019) combines blockchain technology with microgrid-grid power market transactions, proposing a new transaction-clearing model considering low-carbon benefits, which can ensure the safe, efficient, and low-cost operation of the system. The Ref. (Zhang et al., 2019a) built a green power-trading system with core capabilities such as efficient consensus, on-chain trading, and identity authentication, so as to meet the needs of building a credible and efficient trading environment to meet the demands of credibility and timeliness of large-scale multi-subject transactions.

4.4.2 The utilization rate improvement of renewable energy

As global energy and environmental problems become increasingly serious, it is a general trend to vigorously promote renewable energy. As an effective form to realize complementary advantages, efficient consumption, and remote transmission, microgrid has been widely paid attention and studied. In order to realize the operation optimization of the microgrid market, the Ref. (Zhou et al., 2022b) designed the overall framework of the microgrid market, and introduced game theory for study. The Ref.

(Zhao et al., 2020) proposed a multi-layer framework of multi-microgrid energy transaction based on blockchain to provide the decentralized transaction, information transparency, and mutual trust system of each node in the trading market. This framework effectively reduced the transaction volume with the main grid and improved the energy utilization rate.

In addition, the current energy system is facing a revolutionary shift in both supply and demand, where their technology developments will lead to a surge in load management solutions such as DR. The Ref. (Li et al., 2019) proposed a hierarchical framework for energy demand-side management through P2P energy information exchange in the real-time market. By correctly designing the blockchain implementation, the security, transparency, and overall benefits of the whole system can be greatly improved. The Ref. (Afzal et al., 2020) proposed a distributed demand-side management system in multiple community microgrids to reduce the cost of electricity and total energy consumption for each user in the microgrid.

4.5 Social dimension

4.5.1 Social benefits (macro policy)

In February 2020, State Grid Corporation, Ltd. issued key work arrangements for reforms in 2020, explicitly mentioning key tasks such as accelerating the construction of a national unified power market and establishing efficient market-oriented operation mechanisms. In recent years, the German government has accelerated its layout in the field of blockchain, promoting the research and development of related technologies and products. This has further enhanced its international influence, which is of positive significance to the development of China's blockchain technology.

Today, blockchain technology has the characteristics of decentralization, detrust, and high reliability. It has become a key area in many countries. The Ref. (Li et al., 2022a) carried out the demand analysis of blockchain-based power transaction standardization, aiming to promote the standardization development of the entire energy blockchain industry. But at the same time, the application of blockchain technology in the power system also faces technical, economic, social, political, and other challenges.

4.5.2 Service for smart grid equipment updates

Smart grid is a new grid system integrating traditional network and existing communication technology, it can realize the best transmission and power distribution between grid operators and users. Intelligent devices play a very important role in the smart grid. Once the equipment fails or runs abnormally, it will have a significant impact on the safe and stable operation of the power system. The safety diagnosis of smart grid equipment is essential. The design of a perfect smart grid privacy-protection scheme can not only promote the development and application of the power grid, but also make the power producers and sellers benefit a lot.

Nowadays, smart meters are one of the most important current and future trends in the development of smart grids, providing real-time energy consumption information for utilities. As modern distribution networks are rapidly developing complex cyber-physical systems, data tampering in smart meters is a big problem for utilities and users. The Ref. (Olivares-Rojas et al., 2020) proposed an advanced network security architecture for the blockchain-based intelligent metering system to significantly enhance data security. The Ref. (Keshk et al., 2020) proposed a privacy protection framework that could effectively protect data from smart grids and discover abnormal behaviors to achieve privacy and security in smart power networks. The Ref. (Gai et al., 2019) proposed an alliance chain-oriented approach to address the privacy leakage problem without limiting transaction functionality. The Ref. (Wang et al., 2021b) proposed a secure private data-sharing (SPDS) scheme in the smart grid data processing and service mode. Compared with the traditional scheme, the proposed SPDS can effectively improve the benefits of the participants. The Ref. (Zhang et al., 2019b) designed a novel key management scheme of the smart grid system to enable secure communication between service providers and smart meters. The Ref. (Liu et al., 2020b) proposed a blockchain-based secure power-trading mechanism. The dual-chain structure composed of local energy transaction blockchain and renewable energy transaction blockchain improved the efficiency of power trading and renewable energy consumption. The Ref. (Khalid et al., 2021) proposed a trust management method for agents in a blockchain-based multi-agent system, realizing the trust, cooperation, and privacy among agents.

In addition, energy storage units, including home batteries and electric vehicles, are a powerful emergency backup device in the smart grid that can effectively enhance the resilience of the grid, but their uncoordinated charging puts a lot of pressure on the power system. Use blockchain and smart contracts to build a decentralized fee coordination mechanism to achieve decentralized fee coordination, so as to avoid the aforementioned problems.

4.5.3 Interest management of relevant subjects

With the gradual opening of China's electricity sales side market, there will be more trading entities in the power market, such as: power grid enterprises, load integrators, service providers, third-party organizations, etc. The liberalization of the electricity sales-side market is one of the key tasks of China's new round of power system reforms, and the central government requires the steady promotion of the electricity sales-side reform. Combined with foreign experience, the future construction of China's electricity sales-side market should focus on the opening up of the electricity sales-side market, adhere to the legislation first, gradually cultivate the market-oriented electricity sales subject, and ensure the orderly progress of the reform of the electricity sales-side.

To counter the current high cost, low efficiency, and information security problems that currently rely on centers or third parties, blockchain, as a brand-new decentralized infrastructure and distributed computing paradigm, is of great significance to break through the bottleneck of the lack of trust among the participants of the Energy Internet. Based on the demand analysis of the existing automatic DR services, the Ref. (Li et al., 2022b) proposed the application based on blockchain technology, and analyzed the key problems of the blockchain in the automatic DR system from many aspects. The Ref. (Dang et al., 2019) proposed a new market structure (i. e, trading rules) under the existing blockchain power-trading platform, focusing on the optimal load management of specific industrial users. The Ref. (Zhao et al., 2021) proposed a privacy protection model for regulatory blockchain transactions to solve the weaknesses of the traditional blockchain application model in both transaction data concealment and regulation.

4.5.4 Community participation

Traditionally, electricity is generated mainly by large, centralized power plants, not only accelerating global warming, but also causing energy losses in power transmission systems. The Ref. (Afzal et al., 2019) proposed a community microgrid optimization model which uses renewable energy to perform the scheduling of household appliances in community microgrids, minimizing the total operating costs of the entire community. The Ref. (Cui et al., 2020) proposed a new, equitable P2P energy-sharing framework to achieve economical, sustainable building communities.

5 Conclusion

We propose the analysis framework of the Energy Internet based on the blockchain, which includes five dimensions: engineering dimension, technical dimension, economic dimension, environmental dimension, and social dimension. These five dimensions are further refined and classified, aiming to comprehensively summarize the research status of Energy Internet. The classification content of the various dimensions in the review framework of this study should consider the actual national conditions of the local region/country, and it can be slightly adjusted according to the actual situation.

It can be seen that blockchain is all-dimensional and multi-dimensional for the improvement of the Energy Internet. A variety of key technologies forming the power transaction blockchain can play its role from the bottom-up, which is expected to fundamentally solve the various challenges facing the current power transaction. However, at present, the Energy Internet power transaction blockchain still has a lot to explore. In order to truly realize the landing application, in addition to a more in-depth research from the aspect of technical theory, we also need to carry out more extensive practice in the industry. Blockchain thinking is used to promote public policy formation and social progress in the smart grid field.

6 Expectation

Energy blockchain is in a stage of rapid development, but there are many factors restricting the development of energy blockchains. On one hand, the current research on energy blockchain lacks in-depth exploration and application of Frontier blockchain technologies; on the other hand, most energy blockchain solutions remain in the design and prototype stage and lack effective practical feedback. Energy blockchain will deeply integrate blockchain with the energy industry, which will profoundly affect all aspects of energy production, transmission, storage, and consumption in the future. It is expected to play an important role in data sharing and energy ecological construction in the near future.

Author contributions

GW: Methodology, Writing–original draft. YL: Investigation, Conceptualization. CZ: Writing–review; editing. YZ: Resources, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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