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Keywords
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Path of Digital Technology Promoting Realization of Carbon Neutrality Goal in China's Energy Industry

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Abstract: In the era of digital economy, digital technology is the best tool to achieve China's goal of carbon neutrality. The energy industry is the largest source of carbon emissions in China, and how to use digital technology to peak the carbon dioxide emissions and achieve carbon neutrality goal in energy industry has attracted widespread attention. The article first explains the important strategic role of digital technology in carbon neutrality, and then analyzes the related theoretical research and application progress of digital technology and carbon emission reduction in the literature, revealing the problems of current digital technology applied to carbon neutrality in energy industry. Finally, the article puts forward the general guidelines of digital technology to promote China's carbon neutrality process, as well as the main path of implementation of digital technologies, such as big data, digital twins, artificial intelligence, and blockchain, to assist the realization of carbon neutrality in China's energy industry.
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As climate change imposes increasingly severe challenges to human survival and development, a global consensus has been reached on protection of the earth by achieving carbon peak and carbon neutrality in a timely manner. According to the United Nations Framework Convention on Climate Change (UNFCCC), as of September 2019, 60 countries have been committed to net zero carbon emissions by 2050, with all the major economies in the world except the United States and India committed to reducing their carbon emissions [1]. It can be seen from the China-US Joint Announcement on Climate Change in 2014, the 75th UN General Assembly in 2020, to the Central Economic Working Conference in 2021 and the 14th Five-Year Plan that the Chinese leaders have been giving high priority to carbon peak and carbon neutrality together with definite requirements. Nevertheless, since China has proposed a much narrower time window from carbon peak to carbon neutrality than the developed countries, it will entail great endeavors from China.

With the intensive incorporation and innovative application of digital technology in the sectors of resources, energy and environment, the role of digital technology in reaching carbon neutrality has received increasing attention. Developed in parallel with computer science, digital technology converts all sorts of information into computer-recognizable binary data that will be further computed, processed, stored, transferred, distributed, and restored, aiming to improve information-based intelligent application as well as the efficiency of resource allocation across the society [2]. Despite the threats to human survival and development imposed by climate change, manufacturing and livelihood maintain an ever increasing demand for energy and minerals. In 2020, fossil energy accounted for as high as 84.1% of primary energy consumption in China, and the annual carbon emissions from energy consumption are around 9.8 billion tons, nearly 90% of total carbon emissions nationwide [3]. Digital technology is pivotal in solving the conflict between utilization of energy and minerals and demand from manufacturing and livelihood. With the rapid growth of digital communication technology, digital technologies such as smart sensors, cloud computing, big data, and Internet of Things (IoT) have the potential to reshape the energy system. Intensive integration of digital technology with carbon footprint and carbon sequestration can facilitate digital surveillance, precise gauging and prediction of emissions, and efficient planning and implementation, thus significantly increasing the efficiency of energy use and directly or indirectly decreasing carbon emissions from the energy industry [4]. Furthermore, the new business forms and models led by digital technology will help change the idea about energy consumption, restructure the energy business model, and facilitate fulfillment of carbon peak and carbon neutrality in China.

Therefore, in response to the national goal of achieving carbon peak and carbon neutrality, this study explored the role of digital technology in enabling the fulfillment of

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carbon neutrality, with special focus on the pathways of the digital technologies such as big data, artificial intelligence (AI), blockchain, and digital twin in promoting carbon neutrality in the Chinese energy industry in terms of precise gauging of carbon sequestration, efficient dispatching of energy, operation of energy market, precise planning for carbon neutrality, etc.

1 Strategic significance of digital technology in carbon neutrality

Carbon peak and carbon neutrality are essentially challenged by two uncertainties: (1) uncertain impacts from economic activities; (2) uncertain pathways for emission reduction. The two uncertainties originate from asymmetric information, inadequate data, and poor performance in precise prediction, which can be tackled exactly with digital technology. Therefore, against the backdrop of continued advocacy of digital transformation in the energy sector by the government, it will be strategically significant to achieve the goal of carbon neutrality to intensify the incorporation, innovation, and application of digital technology in the energy industry.

(1) Digital technology can improve the balance between energy supply and consumption. On the supply side, digital technologies including IoT, cloud computing, and big data are able to enhance the efficiency of energy tapping and inter-connectivity and to enable integrated, refined, and data-driven supply, thus laying a safe, robust technological foundation for energy production. On the consumption side, digital technologies including AI will transform the traditional mindsets about energy consumption, introduce new ways of energy consumption, drive the energy shift across a variety of sectors and reduce energy consumption and energy intensity [5].

(2) Intensified application of digital technology in energy industry bolsters clean energy production. As the technological revolution and industrial transformation expedite, digital economy has come to take the lead in value creation. Governments around the world are proactively deploying shift toward digitization by applying the digital technologies such as cloud computing, AI, IoT, and distributed management to energy production, transportation, transaction, consumption, and regulation [6].

(3) Digital technology innovates energy models and business forms and promotes green energy consumption. Over a long time, China has developed an energy consumption system centered on electricity, petroleum, and natural gas. The system is characterized by increasingly strengthened rigid correlation inside while strong independence as a whole, resulting in an overall low efficiency which hinders the energy industry from transformation, upgrade, and restructuring. Application of digital technology can optimize and consolidate energy-related services by breaking the "energy shaft" as well as to enable multi-energy integration for improved efficiency of the whole industrial chain.

In summary, digital technology plays a crucial role in reaching the goal of carbon peak and carbon neutrality for China. It is imperative to actively grab and lead a new wave of information technology revolution, adapt the philosophy of manufacturing and management for all-round shift toward digitization from energy production, supply, management to services, push forward the shift to green energy, and strive to explore the effective approaches by which digital technology can facilitate fulfillment of carbon neutrality in China.

2 Advances and issues in the research on how digital technology impacts carbon emissions

With the increasing studies on the impacts of digital technology on carbon emissions, we will brief the advances and shortcomings of the existing studies and applications in terms of carbon footprint and carbon sequestration.

2.1 Impact of digital technology on carbon footprint

Digital technology has both upsides and downsides on carbon footprint. On one hand, digital technology can bring efficiency benefit by promoting safe, green and intelligent tapping of energy and mineral resources as well as their clean, efficient low-carbon utilization, which is conducive to balanced energy supply and demand and reduced carbon footprint. On the other hand, digital technology itself is likely to incur high energy consumption, particularly a large demand for electrical energy.

(1) Development of Energy Internet is a major attempt to apply digital technology to carbon emission. The efficient integration of digital technologies, distributed energy production and utilization, and energy storage technologies makes energy measurable, controllable and predictable from production and transmission on the supply side to consumption and services on the demand side, making Energy Internet an important strategic resource and platform for the energy system [7,8]. Energy Internet will enable interactions between the supply end and demand end of energy and make carbon footprint locatable and traceable. Researchers have studied the key concepts and framework of Energy Internet, the design and operation of Energy Internet systems, and the involved IT infrastructure and future planning, which include energy producers and consumers, microgrids, virtual power plants, smart grids, and security framework for energy network [9–14]. For example, smart grids combined with digital network on the platform of communicated information will enable informatization, automation, and human-machine interaction in power generation, transmission, transformation, distribution, consumption, and dispatching. Through the direct or indirect mechanisms such as cutting cost of energy adoption, reducing waste of electrical power, and

mitigating oil dependence, smart grids can decrease the carbon footprint of traditional power grids by at least 12% [15].

(2) Coal mining is another major sector into which digital technology can be incorporated. As one of the most consumed energy resources in the Chinese energy structure, coal has laid a solid foundation for the economic growth and energy security while causing massive emissions of greenhouse gases and environmental pollution in China. With the application of digital technology and state-of-the-art coal development technologies, intelligence has been implemented in general mining equipment, tunneling equipment, and transporting equipment, which has preliminarily realized intelligent coal mining and reduced carbon emissions [16,17]. For example, digital twin and 5G telecommunication will enable unmanned, visualized precise surveying and mining and all-round intelligent surveillance, which not only boosts the efficiency of mining but also minimizes the harm to the environment [18,19]. In addition, IoT technologies have enabled real-time data collection, processing, and analysis during coal mining. Therefore, safety and environmental risks can be whittled by deployment of smart devices [20].

(3) Digital technology can continuously improve the corporate efficiency of carbon emissions by assisting the transformation of business administration. According to the 2019 Global Digital Transformation Benefits Report, among 230 customer projects accomplished by Schneider Electric and its partners across 41 countries around the globe, those companies that deployed digital technology platforms gained consumption reduction by up to 85%, with an average of 24%; their energy cost was saved by up to 80% with an average of 28%; carbon dioxide (CO_2) footprint was optimized by up to 50% and by 20% on average①. Maximizing Return on Digital Investments Executive Summary released by the World Economic Forum in collaboration with Accenture shows that the incorporation of cutting-edge digital technologies into production increases productivity by up to 70%, whereas those companies with the slower deployment of digital technologies have an increase of only 30% in productivity ②. It can be seen that digital technology can not only provide productivity gain but also facilitate low-carbon production.

(4) Typical energy-intensive digital technologies like data centers and Bitcoin will potentially take up some share of energy consumption, leading to an extra carbon footprint which will compromise green, sustainable development of energy. Studies have demonstrated that in parallel with the convenience created by smart devices, enormous energy is being consumed by data centers underlying the transfer and distant processing of massive volumes of data [21,22]. In 2014, the data centers in the United States consumed 2% of total electricity usage, surpassing the consumption by the energy-intensive paper industry [23]. According to the studies about the energy consumption of the Chinese data centers and the potential use of renewable energy, in 2018 the Chinese data centers consumed 160 billion KWH of electricity in total, equivalent to the total production of the Three Gorges Hydroelectric Plant in that year ③. Moreover, since the invention of Bitcoin in 2008, its energy-intensive design has imposed great threats upon energy development [24]. Without intervention from external policy, the Bitcoin industry in China is projected to consume 296.59 TWH with approximately 130.5 million tons of carbon emission in 2024, making it a big obstacle to China's goal of carbon neutrality [25].

2.2 Impact of digital technology on carbon sequestration

The past-emitted CO_2 needs to be carbon-neutralized via the negative emission technologies such as agricultural carbon sequestration, marine carbon sequestration, carbon capture, utilization, and storage (CCUS), bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC). Digitized collection, storage, and analysis of the environmental elements including soil, crop, and forest has become a major application of digital technology in carbon sequestration.

The digital forest resource monitoring system built upon visualized simulation, IoT, and smart decision-making is capable of high-fidelity, high-precision dynamic monitoring of forest resources. For example, precise collection of information about grasslands with satellite remote sensing and land monitoring devices can lead to a good command of fundamental data on grassland environment, which in turn will be applied to ecological recovery and harnessing of grasslands for its improved role as carbon sequestration [26].

(2) Featuring a high efficiency of carbon sequestration and prolonged storage, marine carbon sequestration has gained support in policy and stimulated scientific research worldwide. Based on the big data technologies such as measured on-site data, remotely sensed data, and data on maritime economy as well as the IoT technologies including radio frequency identification and wireless sensing, the Smart Ocean initiative has achieved ecological protection, economic development, and disaster prevention for the ocean [27]. However, it is still at an early exploratory stage how to orient

① https://www.schneider-electric.cn/zh/work/campaign/roi-report/

② http://reports.weforum.org/digital-transformation/files/2018/05/201805-DTI-Maximizing-the-Return-on-Digital-Investments.pdf.

③ https://www.greenpeace.org.cn/wp-content/uploads/2019/09/%E7%82%B9%E4%BA%AE%E7%BB%BF%E8%89%B2%E4%BA%91%E7%AB%AF% EF%BC%9A%E4%B8%AD%E5%9B%BD%E6%95%B0%E6%8D%AE%E4%B8%AD%E5%BF%83%E8%83%BD%E8%80%97%E4%B8%8E%E5%8F%AF%E5%86%8D%E7%94%9F%E8%83%BD%E6%BA%90%E4%BD%BF%E7%94%A8%E6%BD%9C%E5%8A%9B%E7%A0%94%E7%A9%B6.pdf the Smart Ocean technologies toward accounting and calculation of carbon sequestration.

(3) CCUS is deemed an important option to achieve carbon peak and carbon neutrality. Since CCUS was introduced into China in 2000, a preliminary technological system has been established for it over the last 20 years. Currently, CCUS focuses on theories in physics, chemistry, and geology as well as technological solutions to the capture, utilization, and storage of carbon emissions [28] without initiating research on the intensive integration with digital technology. In the application of BECCS, preliminary explorations have been made on biomass power generation and how to combine it with biomass gases, biomass fuels, and bioliquids [29].

2.3 Issues concerning the application of digital technology to carbon neutrality in the energy industry

Overall, it is at an early exploratory stage to research how to apply the rapidly growing digital technology to the achievement of carbon neutrality in the energy industry. Reviewing major papers reveals at least four areas that have yet to be further explored in terms of theory and application.

(1) Studies and applications of such technologies as big data, IoT, and digital twin are far from enough in the monitoring of carbon footprint and the measurement of carbon sequestration. An integrated mode has not been established for carbon footprint monitoring. The platforms monitoring carbon in the space, on the ground, and in cities remain isolated instead of being consolidated. In other words, a holistic research mode integrating space, air, and ground has not been established [30].

(2) Digital consolidation of energy network lags behind and it has yet to be further investigated how to maintain balance between supply and demand of energy flow and its efficient operation with cloud computing and cloud storage. Due to asymmetric information, when the huge system of Energy Internet adapts to and coordinates the integrated network, there are still such issues as uncoordinated information consolidation and failure to timely screen for and process useful information under heavy load [31]. The digital computation methods including high-efficiency computing, model simplification, and assisted solutions remain the key technologies and research trends for efficient operation of Energy Internet.

(3) There is larger room to improve for digital technology research on carbon sequestration than on carbon footprint. Despite a considerable volume of studies about the role of agriculture, forestry, and ocean in carbon sequestration, a digitized intelligent observation and appraisal system that is measurable, reportable, and auditable has not taken shape [32]. It is in urgent need to investigate how to establish a more tangible monitoring mechanism for stock, formation mechanisms, and functions of carbon sequestration with the help of such technologies as big data and AI, and to incorporate them into the carbon neutrality network of energy.

(4) In view of the new requirements created by the goal of carbon peak and carbon neutrality, traditional calculation and prediction of carbon emissions and absorption suffer from low precision and poor performance. On one hand, the system of carbon emission factors remains to be optimized. Because of the complexity and diversity of the factors that influence carbon emissions, simple representation of carbon emission factors by such indices as gross domestic product (GDP) per capita, population, urbanization rate, technological level, and secondary industry's percentage [33] is unable to support comprehensive, precise calculation of carbon emissions and absorption. On the other hand, the performance of prediction has yet to be further improved. Subjected to uncertainties such as long time span and potential policy change, economic activities of different divisions in different regions are intricately correlated, thereby making it difficult to predict the process of carbon peak and carbon neutrality in different scenarios and time periods.

3 Paths of digital technology promoting realization of carbon neutrality goal in energy industry

Based on the aforementioned studies, this study focused on data monitoring, calculation of carbon emissions and absorption, process prediction, paths, and policy planning and implementation for carbon peak and carbon neutrality. Specifically, we explored the primary paths to carbon neutrality for the energy sector with the application of such technologies as big data, digital twin, AI, and blockchain (Figure 1).

3.1 Big data technology realize precise calculation and prediction of carbon emissions

It is a sophisticated systematical project to calculate and predict the process of carbon peak and carbon neutrality in the energy industry and to compare that at different technological conditions and in different policy scenarios. The project involves the calculation of carbon emissions from economic activities of various divisions in the energy industry, the estimation of the carbon absorption in nature, the deduction of economic development in the society, and the like [34]. The application of big data technology and methodology can address the poor precision and improve the performance in the prediction of carbon emissions and absorption.

(1) Optimization and adaption of emission factors with big data technology. During the estimation of carbon emissions from economic activities of various divisions in the energy industry, dynamic adjustment of emission factors is necessary to preclude interference from uncertain factors. The big data technology will be used to analyze the trend of variations in the CO_2 concentration and net emissions, and to determine the impacts of emission factor settings on the trend difference. Next, the correlations between factors will be determined via clustering analysis and Association Rules analysis.

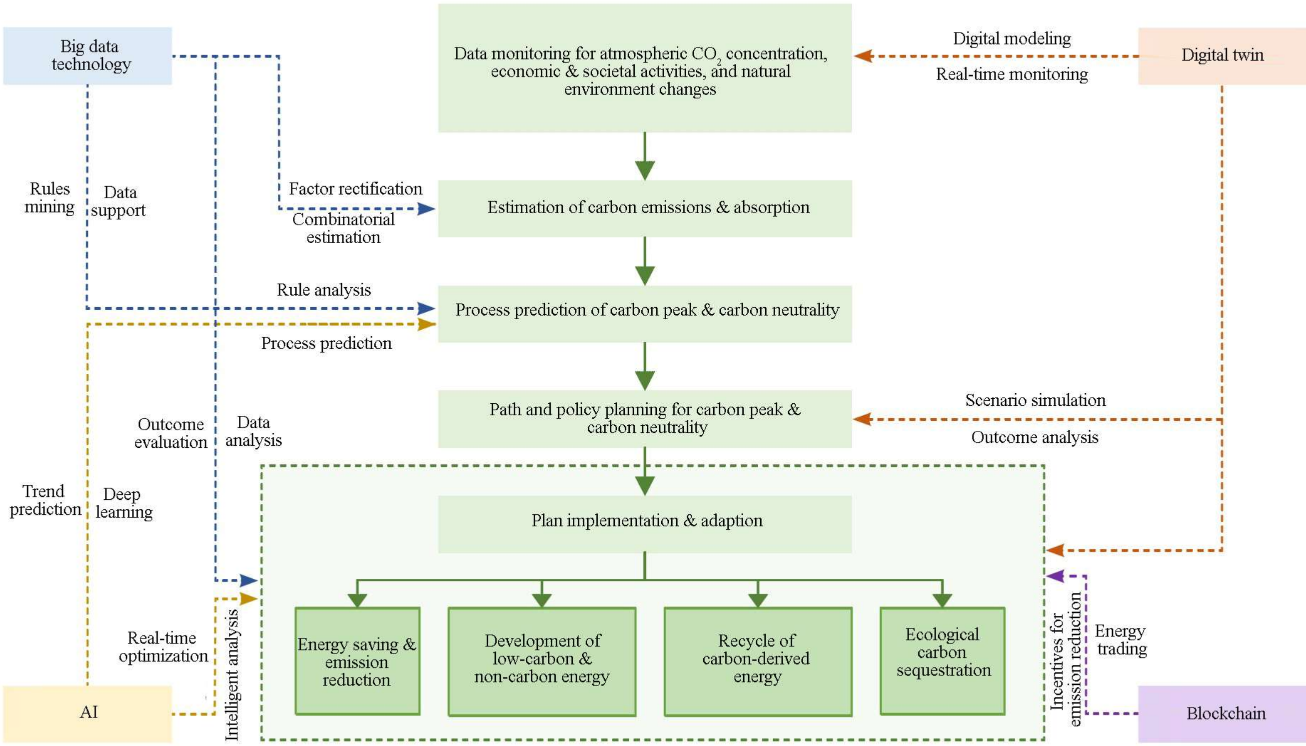

Figure 1 General framework of digital technology promoting carbon neutralization process in China

The regions with similar features will then be clustered into one group to create optimal combinations of emission factors that can minimize the difference, thus making the system of carbon emission factors in the energy sector work in a concerted, efficient way.

(2) Comprehensive and precise calculation of carbon emissions and absorption with the big data technology. The big data technology enables daily and monthly dynamic monitoring and accounting of carbon emissions in the energy sector, which shortens the analysis cycle, improves the precision and efficiency, and reduces the cost of calculation [35]. The analysis of carbon emission data in different areas and of different stakeholders can reveal the dynamic trend of carbon emissions. The associations of carbon emissions with carbon capture and storage can be analyzed to monitor and track CO_2 variations in the full life cycle [36]. The inversion of atmospheric CO_2 concentration and trend based on the evolution laws of carbon emissions and absorption in combination with changes in geography and environment enables the comprehensive and precise calculation of carbon emissions and carbon absorption.

(3) Precise prediction of the process of carbon peak and carbon neutrality in multiple scenarios with big data technology. With the integrated advantages of big data, a prediction and simulation system can be constructed for carbon emissions in the energy industry, which can track and predict carbon emissions in the long run. Energy consumption in manufacturing is traceable through simulation of variations in energy consumption by sectors in various regions under different technological conditions and in different policy scenarios. The time of carbon peak and carbon neutrality can be precisely predicted by analyzing how economic activities evolve and calculating annual changes in net carbon emissions from human activities and nature in multiple scenarios [33].

3.2 AI facilitates efficient dispatching and utilization of energy

AI is an effective means to tackle issues in controlling complex systems and decision-making. The intensive application of AI in the energy industry will help drive clean energy production and cut carbon emissions for shift from high-carbon to low-carbon and then to carbon neutral. In the energy industry, reducing cost in energy consumption is as important as reducing discharge of pollutants [37]. Hence, in parallel with a reliable high-quality supply of energy, using AI for efficient dispatching and utilization of energy has become an important measure adopted worldwide for carbon emission reduction.

(1) Carbon neutrality requires intelligent dispatching of energy. The modern energy system features a large scale and sophisticated structure. Intelligent dispatching in the context of carbon neutrality is expected to keep the system securely and steadily running and improve its cost-effectiveness. The development of AI has created higher requirements in energy dispatching, e.g., detection of abnormal conveyors during coal transportation, status monitoring of power lines and flexible dispatching during power transmission, for efficient

use of electricity, safety surveillance during storage and transportation of oil and gas, and effective energy dispatching at public emergencies. Economic and social development, improved quality of life, and restrictions imposed by carbon neutrality require intelligent and efficient energy dispatching.

(2) AI facilitates precise dispatching of energy. The development of AI makes efficient intelligent dispatching of energy feasible. Intelligent algorithms based on machine learning, such as sine cosine algorithm [38] and soft actor-critic-based deep reinforcement learning [39], are widely used to pursue optimal solutions to energy dispatching, which improves the dispatching accuracy and effectiveness. For example, in power transmission, machine vision is used for real-time monitoring and full evaluation of the safety of transmission channels; in coal transportation, smart conveying equipment is used to recognize foreign objects on the conveyor, coal pile-up at transfer points and the like; in oil/gas storage and transportation, object detection can be employed to detect the flaws in welding seams on oil pipelines to prevent unnecessary waste during oil transportation.

(3) AI enables efficient utilization of energy. AI applications by energy companies have inspired the utilization of energy. Grid Edge in the United Kingdom saved energy and prevented overload by operating VPN connections and analyzing users' energy consumption data. Kansai Electric Power Co. Inc. in Japan summarized the data from smart electricity meters based on machine learning and optimized multi-mode electricity usage with high-precision AI algorithms. In China, China Datang Corporation built a 3D virtual power plant with state-of-the-art telecommunication technologies and software architecture for aggregation and coordination of geographically scattered locations. Its intelligent control system can manage and control the process of power generation in real time and accomplish storage and reasonable deployment of energy. Zhongshan Power Supply Bureau affiliated to China Southern Power Grid Co., Ltd. conducted lean management with integrated adjustment and control based on smart grids, by which the technologies such as big data, machine learning, and deep learning are incorporated into the power grid to build a demonstration zone for intelligent technologies with integrated adjustment and control. South China University of Technology is working on the next generation of energy and electricity system which will be integrated with the Energy Internet to construct the robot of energy control. The researchers are focusing on digital transformation of the energy service system for automated dispatching of energy [40].

3.3 Blockchain technology enables efficient operation of the energy market and incites low-carbon practices

In the future the energy trading market will feature multiple stakeholders, modes, and rules, which will call for and challenge the transparency, real-timeness, and data security of transactions in the energy market. The "Both Ends Open" services for the energy trading market require commensurate stakeholders, intelligent mutual trust, transparent transactions, and information sharing. In response to the above requirements and in combination with the four major features (decentralization, transparency and security, immutability, and traceability) of blockchain technology, a novel distributed energy trading market will form, thereby providing concrete means for the fulfillment of China's goal of carbon neutrality.

(1) Blockchain technology drives innovation of distributed energy market. (1) Blockchain enables secure and trustworthy transactions and efficient settlement for the energy trading market. The blockchain technology can be used to create distributed ledgers of energy and input transaction data on the supply end, marketing data, and users' usage data in the energy market into the block chain, leading to distributed accountancy and bookkeeping. Owing to the immutability of record keeping on the block chain, the process of data input and storage can be streamlined and human errors and malicious manipulation circumvented. The workflows such as transaction and liquidation can be automated with smart contracts, thus rendering transaction as settlement to reduce errors and frictions during liquidation. (2) Blockchain automates business processing in the energy trading market. Transactions and other energy-related workflows can be automatically executed according to smart contracts. Energy is priced in real time based on the real-time relationship between supply of and demand for energy. Energy transmission and control are triggered upon completion of transactions for balanced dispatching of energy across the power grid. (3) Blockchain optimizes deployment of resources in the energy trading market. Overall coordinated operation is feasible from formulating rules for energy trading and dispatching through blockchain code and smart contracts, treating stakeholders in a unified way, and aggregating different types of distributed power supply. The consumption of clean energy will account for a higher percentage in trade volumes through customized pricing and optimized dispatching of integrated energy, thereby promoting reasonable consumption and absorption of energy.

(2) Blockchain technology optimizes the architecture of energy market and the process of transactions. ① Blockchain technology optimizes the fundamental architecture of distributed energy market. The blockchain-based energy market enables interconnection of heterogeneous devices and transaction information during energy trading as well as efficient interaction between distinctive stakeholders, hardware devices and the trading system. The overall architecture consists of four layers: foundation layer, engine layer, business layer, and application layer (Figure 2). With low-level data blocks encapsulated, the foundation layer provides support as the fundamental architecture of the trading platform, and it also encapsulates such technologies as data encryption and time stamp for off-chain data storage. Consensus algorithms for nodes are encapsulated in the engine layer in support of

the construction of smart contracts for energy trading, energy pricing, and energy dispatching, which will in turn support business need from blockchain-based distributed energy market. At the business layer, business in the energy market is fulfilled via smart contracts. A variety of scenarios and use cases are encapsulated in the application layer. ② Blockchain technology improves the process of transactions in the energy market (Figure 3). First, the user on the supply end (seller) will publish the information of electricity supply. The pricing contract on the platform will set a price according to the situations of the supplier and supply and input it onto the block chain. Next, the user on the consumption end (buyer) will publish the information of demand and be matched to the seller by the platform or directly enter into a deal after querying for the power supply on the supply end. The transaction will activate the trading contract on the platform. After both ends' credentials are checked and requirements are met, the trading contract will be triggered and the buyer's account locked. The contract will be verified on the backend and the user notified upon failure. The successfully verified contract will be stored on the block chain and trigger the dispatching contract which will be responsible for energy dispatching and transmission. The government can intervene in the operation of the trading market by participating in formulating policy on carbon neutrality at any stage of trading. In addition to the supply end and consumption end, the trading involves those parties with roles in energy transmission and regulation such as the power grid and the government.

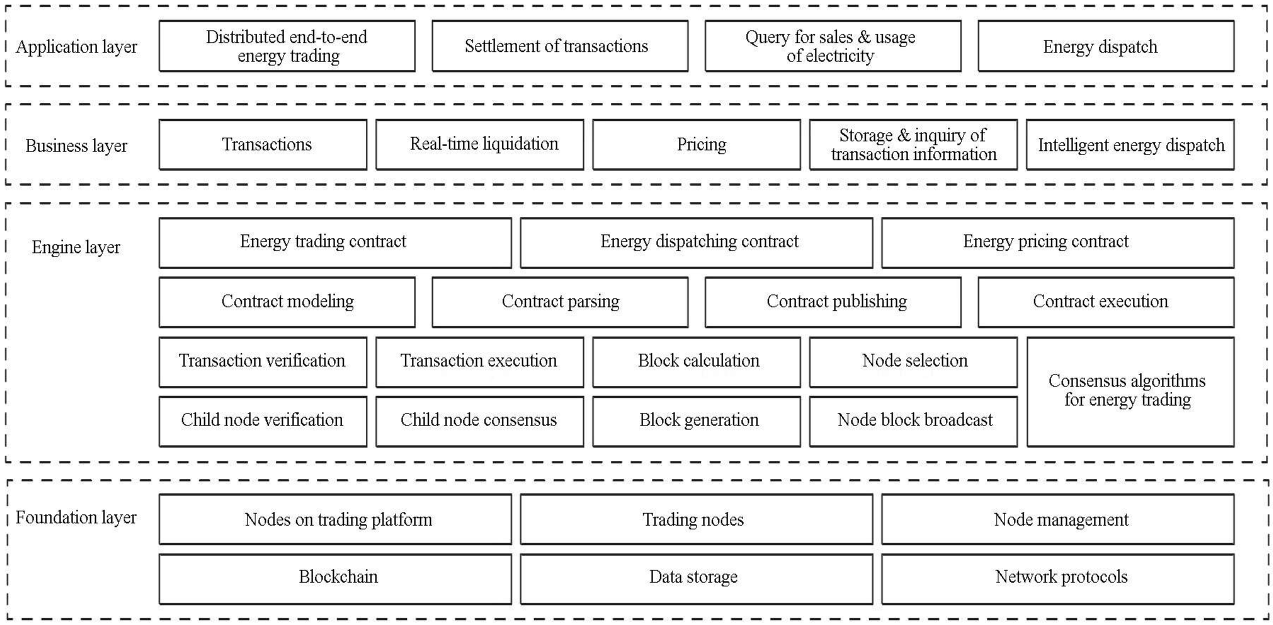

Figure 2 System architecture diagram

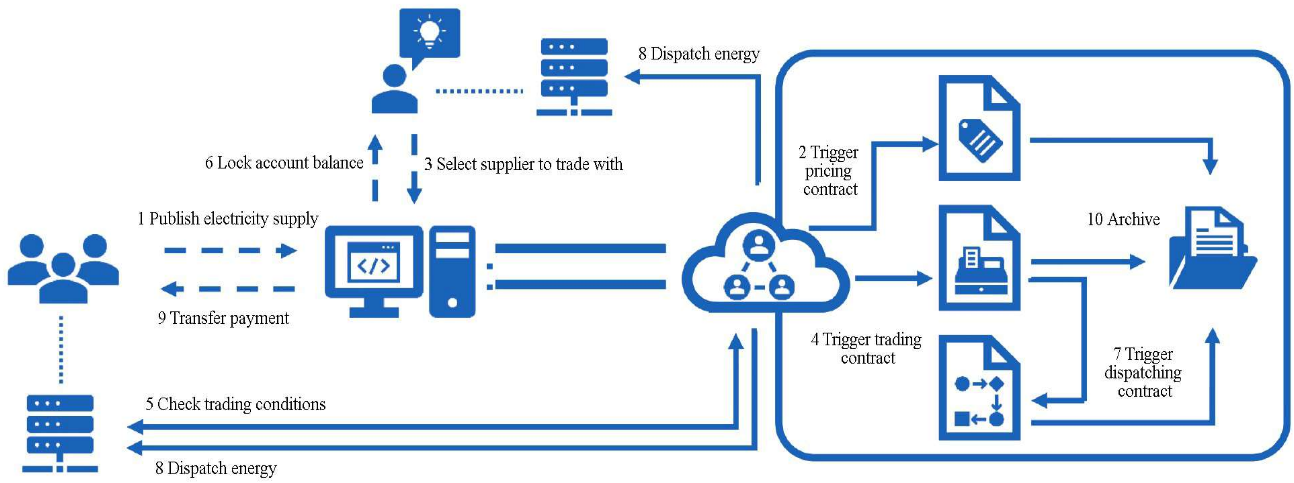

Figure 3 Transaction flow chart

(3) Blockchain technology provides incentives for low-carbon practices. When the energy trading market is built with the blockchain and an incentive mechanism, low-carbon practices will be effectively stimulated. The token economy in the energy market is usually realized with the blockchain token to enhance the economic benefits attached to low-carbon practices. In addition, smart contracts are used to reward low-carbon practices with prioritized dispatching in accordance with incentive rules and patterns, which can also encourage low-carbon practices. The specific measures are as follows. ① Energy-saving-oriented dispatching of electricity. The principle of even dispatching is to be forgone. The cost of transmitting renewable energy and the power supply with higher energy efficiency and less pollutant discharge is to be relieved or exempted. Alternatively, such energy should be dispatched with higher priority. ② Low-carbon incentives at the demand end. Consumers' overall demand for energy can be reduced through incentives, and demand can shift between peaks and troughs in a controlled way. With incentives, consumers are encouraged to use power-intensive appliances with higher efficiency in favor of carbon neutrality. ③ Trading low-carbon tokens. Similar to trading pollution rights, market-stimulated low-carbon practices can overcome environmental externality caused by carbon emissions.

3.4 Digital twin boosts precise planning of carbon emission reduction and carbon neutrality

Digital twin is a key technology that maps the physical environment to a digital model in the information domain. It creates a virtual counterpart of a physical object in a digital way to simulate, verify, predict, and control the full life cycle of the physical object which can be reflected in distinctive real scenarios by making full use of the sensors deployed across the physical system for data analysis and modeling of the physical object [41].

In the endeavor toward carbon peak and carbon neutrality for the energy industry, a big ongoing challenge is how to establish a system for real-time tracking of carbon footprint and evaluation of the full life cycle. It is important to finalize digital management over the full life cycle from data capture and monitoring of carbon emissions to precise planning of carbon neutrality. Therefore, 2D or 3D visualization model of the carbon map can be built based on the digital twin technology. Thus, clear pathways to monitoring, regulating and planning carbon emissions, and implementing strategies can be established by acquiring the capabilities of tracking the drivers for carbon emissions, dynamic simulation and extrapolation of emission reduction as well as alerting, detecting and analyzing energy consumption.

(1) Digital twin technology realizes precise monitoring and calculation of carbon emissions by the general public and enterprises. As an important grip to advance comprehensive digital transformation of enterprises and urban governance and to facilitate reduction of carbon emissions, digital twin technology plays a vital role in green product design, green manufacturing, green smart cities, and green construction projects. As far as precise monitoring and calculation of carbon emissions is concerned, the relevant study is more developed in the United States and European Union. In 2015, the Environmental Protection Agency conducted continuous monitoring on 73.9% of the thermoelectric generators in the United States by using CEMS data and digital twin technology, simulated and emulated their running status in full workflow, and conducted data monitoring on carbon emissions. In the carbon trading system of the European Union, digital twin technology is used in Germany, France, and the Czech Republic to develop novel carbon monitoring systems for real-time, precise, and automatic accounting of carbon emissions. In the development of China's carbon market, the ever-updated technological process will make regulation more difficult for the regulatory agencies and keep escalating regulatory standards, which will in turn require more flexible, precise and real-time monitoring of carbon emissions. Therefore, online monitoring of carbon emissions based on the digital twin technology has begun to be gradually put into practice in China. China Southern Power Grid Co., Ltd. monitors the programs, specifications, installation requirements, and ways for data capture, processing and their quality assurance by using carbon dioxide emission monitoring system (CDEMS) and visualizing digital twins. It is feasible to monitor and manage the emissions of greenhouse gases by setting up a digital regulatory system that incorporates instructions, standards, and safeguard.

(2) Digital twin technology helps implement precise planning of carbon emission reduction and carbon neutrality. ① Carbon emissions during operation are simulated via modeling of digital twins, laying a solid foundation for carbon management. Those emissions include carbon emissions by enterprises' offices, carbon footprint of their products and services, and carbon emissions from value chains upstream and downstream. Enterprises' own products and services can also bring about the potential for carbon emission reduction. ② Digital twin technology can be adopted to reckon and analyze the paths to carbon neutrality and set goals for planning in agreement with carbon neutrality. Thanks to the construction and digital profiling of a process-wide digital chain, carbon emission reduction can be coupled with the core business in an organization and plans accurately can be matched to actions in favor of shift toward low-carbon and technological innovation, thus providing a direct reference for formulating measures to adapt and optimize the action plans for emission reduction. In manufacturing, for instance, digital twins are used to dynamically track and trace the full cycle of production in real time, to comprehensively analyze the key factors (including man, machine, material, method, environment, and measurement) in manufacturing, and to discover hidden sources to improve during carbon emissions and their solutions. ③ Digital twin technology plays a role in pinpointing the sources of, analyzing the data of, regulating,

predicting, and alerting on carbon emissions. It enables real-time panoramic simulation of energy production, supply, trading, and consumption, during which it will monitor the whole process of carbon emissions from the supply end to the consumption end, bolster the regulatory agencies in constructing a complete monitoring system for carbon emissions, and enable lean, online, and intelligent production of energy.

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