# Digital Pathways and Strategies for Pollution and Carbon Reduction in Power Enterprises: A Postprint

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**Date:** 2024-03-27T00:00:00+00:00

## Abstract

With the widespread application and innovation of digital technologies in the energy sector, the importance of digital technologies for the power industry to achieve pollution and carbon reduction goals has become increasingly prominent, and how digital technologies can empower power enterprises to achieve these goals has attracted considerable attention. This article first reviews and analyzes the progress of digital technology applications in pollution and carbon reduction by power enterprises; then reveals the problems existing in the current application of digital technologies for pollution and carbon reduction in the power industry; and finally explores the methodological pathways and corresponding implementation strategies for emerging digital technologies such as the Internet of Things, big data, artificial intelligence, blockchain, and digital twins to empower power enterprises in pollution and carbon reduction.

## Full Text

## Path and Strategy of Pollution and Carbon Reduction by Digitization in Electric Power Enterprises

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## Abstract

With the extensive application and innovation of digital technology in the energy sector, digital technology has become increasingly crucial for the power industry to achieve pollution and carbon reduction goals. How digital technology enables electric power enterprises to realize these objectives has attracted widespread attention. This study first systematically analyzes the progress of digital technology applications in pollution and carbon reduction within electric power enterprises. It then identifies existing problems in the current application of digital technology for pollution and carbon reduction in the power industry. Finally, it explores the potential pathways and implementation strategies through which emerging digital technologies—including the Internet of Things, big data, artificial intelligence, blockchain, and digital twins—can empower electric power enterprises to reduce pollution and carbon emissions.

**Keywords:** digitization, pollution reduction, carbon reduction, power industry, pathways, strategies

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## Introduction

With the proposal of the “dual carbon”goals (carbon peak and carbon neutrality), pollution and carbon reduction has become a global focus. In 2022, nearly 90% of China’s greenhouse gas emissions originated from the energy system, with the power industry serving as the largest single source of carbon dioxide emissions (48%) [1]. This has made the power industry a primary target for reform under the dual carbon objectives. China is currently in a critical phase of ecological civilization construction during its 14th Five-Year Plan period, with the main strategic direction being to prioritize carbon emission reduction, promote coordinated pollution and carbon reduction, and facilitate a comprehensive green transformation of economic and social development [2].

The traditional power industry faces enormous pressure to reduce pollution and carbon emissions across all segments of the “source-grid-load-storage”chain. Conventional power generation enterprises rely heavily on high-carbon fuels such as coal and natural gas, resulting in substantial greenhouse gas emissions and environmental pollutant releases. The transmission side primarily involves grid construction and operation, where the manufacturing of transmission equipment and civil engineering projects—particularly ultra-high voltage projects—generate considerable carbon emissions. The consumption side directly or indirectly affects the effectiveness of pollution and carbon reduction through energy choices, energy efficiency, load management, and equipment selection. The storage side confronts multiple challenges, including low energy density and high costs of storage materials, waste pollution and resource pressure, dependence on non-renewable materials, difficulties in commercializing and scaling emerging technologies, and complexity in matching storage systems with the power grid.

As digital technology becomes widely applied and innovated in the energy sector, its role in helping power enterprises achieve pollution and carbon reduction goals has become increasingly prominent. Through deep integration of digital technology, power enterprises can: achieve precise monitoring and measurement of carbon and pollution footprints; utilize intelligent sensing and big data to accurately assess carbon and pollution emissions across various segments, enabling targeted reduction measures; implement real-time data monitoring and feedback mechanisms for efficient energy dispatch; promote transformation of energy consumption concepts and reconstruct energy business models; and employ reliable data support and intelligent decision-making systems to facilitate precise carbon neutrality planning and implementation. Given that power generation, transmission/distribution, and consumption remain relatively independent in China' s energy system, a mature systematic solution has not yet been formed. However, with the advancement of energy internet construction and power market reform, transmission and distribution grid development will further tap the potential of virtual power plant technology [3]. By reducing the dispatching difficulties brought by distributed energy growth, it is expected to ensure safe, reliable, high-quality, and efficient power supply to meet the diverse electricity demands of economic and social development [4].

In summary, digital empowerment represents an important means for power enterprises to reduce pollution and carbon emissions. However, the digitalization of pollution and carbon reduction in power enterprises also faces numerous challenges, including uneven development of digital technology applications, significant data security risks, lack of unified technical standards, and mismatched costs and benefits of digital technology investments. These issues constrain the use of digital technology to advance pollution and carbon reduction in power enterprises. Therefore, this study addresses this problem by systematically analyzing the current status and challenges of digital technology application in power enterprise pollution and carbon reduction, proposing pathways and implementation strategies for emerging digital technologies—including IoT and big data, artificial intelligence, digital twins, and blockchain—to empower power enterprises in pollution and carbon reduction. The aim is to provide scientific theoretical references for pollution/carbon reduction and digital transformation development in the energy and power industry under the guidance of national dual carbon goals.

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## 1. Application Progress of Digital Technology in Power Enterprise Pollution and Carbon Reduction

Digital technology plays a crucial role in promoting pollution and carbon reduction in power enterprises, providing networked, digitalized, and intelligent technical means for green development, empowering enterprise transformation, upgrading, and institutional optimization, and improving resource allocation and management decision-making [5]. The following sections briefly describe the current application progress of digital technologies such as big data, artificial intelligence, blockchain, and cloud computing in power enterprise pollution and carbon reduction (Figure 1 [Figure 1: see original paper]).

### 1.1 Big Data Applications

In the era of digital economy, power enterprises are experiencing explosive growth in information volume. How to leverage big data for pollution and carbon reduction has become a common industry concern. Big data applications in pollution and carbon reduction for power enterprises at home and abroad mainly focus on two aspects:

First, big data technology can collect and analyze energy data from power enterprises to achieve effective energy management and optimization, improving generation efficiency and thereby reducing carbon emissions [6]. Currently, domestic thermal power equipment and technical potential are limited, and the comprehensive retrofitting process for China' s thermal power units is slow. Based on digital management technologies such as data mining and artificial intelligence algorithms, optimization decision models can be constructed to guide flexible and deep retrofitting of thermal power units, improving generation efficiency by 2% and achieving direct carbon emission reductions of 250 million tons [7].

Second, big data technology can monitor power equipment operation status and energy consumption in real time. Through data analysis and algorithmic models, it can convert data into visual charts and estimate future energy consumption to provide energy-saving recommendations and control strategies for power enterprise managers [8]. For example, State Grid Hunan Electric Power Company Limited, in collaboration with Baidu Intelligent Cloud, has built a smart energy new infrastructure. By fully utilizing Baidu Map big data and integrating multi-dimensional data including power user data, line data, and equipment data, they have formed a "unified grid map" to improve electricity utilization efficiency and reduce power resource losses.

### 1.2 Artificial Intelligence Technology Applications

Artificial intelligence technology is a key means to address complex system control and decision-making problems [9]. It is widely applied in production, consumption, transmission, operation, management, and trading during the digital transformation of power enterprises. To eliminate outdated traditional production processes and innovate a new generation of integrated energy interfaces dominated by renewable energy, AI helps reduce the total amount of "three wastes" (waste gas, waste water, and solid waste) and increase the proportion of green energy in power enterprises. AI technology assists power enterprises in pollution and carbon reduction mainly through three aspects: "prediction-mining," "scheduling-optimization," and "management-efficiency improvement."

First, applying AI for efficient and precise prediction. Power enterprises have large-scale and complex energy consumption structures, urgently requiring precise prediction and efficient management of multi-dimensional data for pollution and carbon reduction measures. For example, energy equipment image recognition, energy network damage prediction under extreme weather, user-side load prediction for enterprise energy consumption behavior, and energy system stability prediction can guide enterprises to build circular energy consumption paradigms and improve the overall carbon emission quality of energy systems.

Second, applying AI for flexible scheduling. The development of AI technology enables diversified and coordinated flexible scheduling for power enterprise energy consumption, achieving intelligent decision-making for pollution and carbon reduction through precise predictive data analysis. For instance, with AI prediction and optimization technology, enterprises can conduct comprehensive energy efficiency analysis and multi-link coordinated optimization management of energy systems under scenarios with coupled multi-energy supplies, thereby achieving the cleanest energy consumption in the most efficient manner [10]. Establishing a "fuel intelligent blending" system based on big data platforms can guide the selection of coal types for furnace combustion, and preset reasonable coal types before deep peak shaving of units to ensure boiler safety and economy.

Third, applying AI for autonomous learning management. Autonomous learning management utilizes AI technology to achieve adaptive control and self-perception of internal comprehensive energy systems. Based on machine learning or reinforcement learning algorithms, multi-physical, multi-scale, and multi-probability digital twin environments can be constructed according to collected or predicted data, with adaptive updates to model parameters [11]. For example, thermal power plants under the State Energy Group and State Power Investment Corporation have formed a "coal quality online monitoring—three-dimensional intelligent monitoring—intelligent operation optimization" smart decision-making system through autonomous learning in twin scenarios and AI optimization scheduling, achieving autonomous optimization of production processes to implement pollution and carbon reduction decisions.

### 1.3 Blockchain Technology Applications

Currently, the low-carbon transformation process of power enterprises is gradually developing toward multi-energy heterogeneous normalization, integrated production and consumption, and market-oriented electricity and carbon emission trading. Blockchain technology provides strong support for low-carbon transformation and pollution/carbon reduction in power enterprises.

First, blockchain technology empowers power enterprise transformation by optimizing production processes and promoting carbon emission reduction to enhance energy efficiency. By combining the energy supply chain with blockchain technology, power enterprises can achieve efficient management of energy production, storage, transmission, distribution, and consumption [12]. For example, the decentralized nature of blockchain can enable peer-to-peer interconnection of multiple entities in smart energy systems, and smart contracts can facilitate extensive interaction of various types of information among relevant parties, helping improve power enterprise system operation quality and pollution/carbon reduction effectiveness.

Second, blockchain technology empowers power enterprises to achieve carbon monitoring and management, providing quantitative decision-making basis and management measures for low-carbon development. For instance, Chint IoT Park has built a blockchain-based carbon emission monitoring platform that aggregates carbon emission data throughout the entire production line manufacturing process. Through smart contracts, it can monitor carbon emissions in real time and accurately, automatically complete various data declarations, close the carbon trading loop, and build a new regulatory model to help enterprises achieve carbon neutrality.

### 1.4 Cloud Computing Applications

Building cloud computing platforms is a key supporting technology for addressing computing power and algorithms in traditional sectors such as the energy industry. In the pollution and carbon reduction process of power enterprises, cloud computing platforms utilize technological breakthroughs to promote the sustainable development of computing and other information technology resources, enabling environmental advantages to match various pollution and carbon reduction demand scenarios in power enterprise operations.

First, cloud computing assists power enterprises in pooling data resources vertically and horizontally to support emission reduction. Through large-scale deployment of edge and end devices in power enterprise production and supply processes, combined with big data technology applications, data collection and analysis can be achieved for broader data exchange and collaboration. For example, State Grid Jiangsu Electric Power Company Limited uses a Platform as a Service (PaaS) to achieve unified management of various resources and applications. This platform can more effectively manage and analyze power consumption, generation efficiency, and other data to support carbon reduction decision-making and optimize power supply management.

Second, cloud computing platforms enable decoupling of enterprise software and hardware to meet power enterprise grid energy consumption supervision needs. Cloud computing can provide powerful computing capabilities for power system simulation and modeling [13]. By conducting power system simulation and optimization in the cloud, it can help power enterprises analyze and optimize grid operation modes. For example, State Grid Zhejiang Electric Power Company Limited uses Alibaba Cloud to obtain second-level fault cause analysis and intelligent processing information, accelerating fault location and improving repair efficiency.

## 2. Key Challenges of Digital Technology in Power Enterprise Pollution and Carbon Reduction

Big data, artificial intelligence, blockchain, and other digital technologies provide significant opportunities for digital transformation and coordinated pollution/carbon reduction in power enterprises. However, power enterprises still face numerous challenges in using digital technology for pollution and carbon reduction synergy, which greatly constrain the pace of low-carbon transformation.

### 2.1 Weak Application Links of Digital Technology in Power Enterprise Pollution and Carbon Reduction

Weaknesses in digital technology application for power enterprise pollution and carbon reduction are mainly reflected in two dimensions: First, from the perspective of the entire power industry chain, although generation enterprises, grid enterprises, storage enterprises, and integrated energy service enterprises have achieved some results using digital technology for pollution and carbon reduction, they could further leverage the important role of digital technology. For example, in monitoring and managing generation equipment, more efficient AI algorithms are urgently needed to intelligently analyze and optimize key parameters of various operational links, identify optimal equipment operating parameters under different loads, and maximize energy optimization. In power transmission processes of grid enterprises, coordination and deployment of technologies such as 5G communication, AI, digital twins, and smart microgrids to achieve "source-grid-load-storage" coordination and balance need to be strengthened. Second, from the process dimension of power enterprise pollution and carbon reduction, achieving the dual carbon goals places higher demands on carbon emission monitoring, precise carbon emission calculation, prediction of pollution/carbon reduction progress, formulation of reduction plans, and intelligent management and effect evaluation of implementation. Traditional carbon emission monitoring technologies cannot achieve extensive monitoring of numerous emission sources in the short term, and the emission factor method adopted by power enterprises cannot accurately calculate carbon emissions. Digital technologies such as IoT, big data, cloud computing, AI, and blockchain play important roles in carbon emission monitoring and calculation. However, due to the scattered and widespread sources of power big data, energy consumption big data, and production capacity big data, and multiple data ownership departments, the efficient utilization of digital technology is hindered, making it impossible to timely grasp real-time dynamics of carbon emissions during production and operation processes. Moreover, in the transformation and upgrading of power enterprise management models and production methods, it is difficult to find effective scenarios to promote deep integration and innovation between green technologies (represented by energy technology, pollution control technology, and environmental monitoring technology) and digital technology, resulting in inefficient utilization of digital technology for pollution and carbon reduction in power enterprises.

### 2.2 Data Security Protection Requires Further Strengthening

Power data mainly comes from generation, transmission, transformation, distribution, consumption, and dispatching links, characterized by diverse types, huge volume, and rapid growth. With the open sharing of power data and digital transformation of power enterprises, they face issues such as lack of data security supervision and weak data circulation security protection. Power enterprises have vast and diverse data types, including power production data, enterprise emission data, and user consumption data. Once leaked, key core businesses and user privacy of power enterprises will face potential exposure risks on networks [14]. Moreover, these data concern national and resource-sensitive information, imposing higher requirements on power network security and making the construction of a secure power data protection system critical.

### 2.3 Lack of Unified Technical Standards for Digital Technology in Power Enterprise Pollution and Carbon Reduction

Power data covers the entire chain of "generation, transmission, distribution, and sales" as well as enterprise management, characterized by large scale, diverse types, and high value. Power data protection focuses on the entire lifecycle including data collection, transmission, storage, and use. However, currently, each power enterprise formulates its own data security classification methods, and there are no unified management methods for classification, security protection, etc., resulting in a lack of unified standards for power data sharing, disclosure, and security protection.

Meanwhile, digital technologies such as big data, AI, IoT, and digital twins have gradually begun preliminary applications in carbon emission monitoring and smart grid management of power enterprises. Since applications of digital technology in power enterprise pollution and carbon reduction are still in the initial stage, there is a lack of capabilities in data collection, processing workflows, power data mining, intelligent analysis, and continuous algorithm iteration, making it difficult to form standards for data collection, analysis, and processing.

### 2.4 Difficulty in Efficiently Matching Digital Technology Investment Costs and Benefits

In achieving dual carbon goals, power enterprises are regarded as main drivers and leaders due to their crucial position in building a new power system dominated by new energy. Building a new power system aims to meet the growing demand for clean energy. However, this goal must rely on advanced electronic materials and equipment technology support. The development of high-end semiconductor materials will provide strong hardware support for the digital transformation of energy and power systems to achieve efficient integration of clean energy. The application of high-performance power chips will provide key guarantees for real-time, precise perception and efficient control of energy and power system equipment. The development of digitalized and intelligent power equipment will effectively promote safe and efficient operation of energy and power systems [15]. Additionally, digital technologies including 5G communication, big data, cloud computing, IoT, AI, and digital twins are profoundly affecting various links in power systems, playing a vital technical support role in the sustained and healthy development of power enterprises [16]. Moreover, the construction of new power systems with multi-flexibility, high reliability, and strong resilience imposes stricter requirements on information security. Robust operation of new power systems requires efficient access control, data encryption, and other technologies to provide comprehensive security assurance. However, investment in these digital technologies for power enterprise digital transformation requires substantial financial support, and the investment may not yield immediate results for pollution and carbon reduction. Therefore, power enterprises need to comprehensively consider the costs and benefits of digital technology investment, which is another key issue in the application of digital technology for pollution and carbon reduction.

### 2.5 Unbalanced Coordinated Development of Electricity and Carbon

In pollution and carbon reduction, power enterprises must both promote the construction of new power systems and fully utilize the advantages of power big data to assist carbon emission reduction. However, several issues currently exist in the coordinated development of electricity and carbon: First, carbon reduction strategies lack deeper integration with power development planning. Low-carbon power generation, efficient grid operation, and energy storage planning of power enterprises lack more efficient organic coordination with carbon reduction needs. Second, some electricity and carbon data have not been integrated, and a comprehensive electricity-carbon database has not been established. Power big data can be collected at high frequency every minute, while carbon emission data collection frequency is lower, making it difficult to deeply integrate the two types of data due to temporal differences. Moreover, due to insufficient high-frequency collection of emission data from major carbon emission regions and key industries, a high-frequency electricity-carbon database covering key regions and high-energy-consuming enterprises has not yet been formed. Third, electricity-carbon coordinated optimization scheduling technology is still immature. Carbon emission and optimization of generation equipment is an important link in power enterprise pollution and carbon reduction, requiring not only real-time monitoring of equipment carbon emissions but also comprehensive consideration of equipment operation status and parameters. There is an urgent need to develop dispatching-side electricity-carbon coordinated optimization technology that can accurately grasp dynamic carbon emission intensity of units and reasonably optimize generation unit combinations. Due to the difficulty in accurately calculating carbon market prices and dynamically measuring carbon emission intensity, coordinated optimization technology that comprehensively considers carbon emission intensity and carbon market prices is still lacking.

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## 3. Methods of Digital Technology Enabling Pollution and Carbon Reduction in Power Enterprises

Based on the aforementioned research, this section focuses on the pain points and difficulties faced by power enterprises in pollution and carbon reduction, targeting clean energy investment by generation enterprises, data monitoring of enterprise power consumption, and precise measurement of carbon emissions across the entire power system chain. It explores pathways for implementing intelligent management of pollution and carbon reduction and timely policy optimization to achieve source-side carbon reduction for generation enterprises, terminal-side decarbonization for consumption enterprises, and corresponding policy optimization. The study investigates how cutting-edge digital technologies such as IoT, big data, AI, digital twins, and blockchain can help power enterprises achieve the overall goal of pollution and carbon reduction (Figure 2 [Figure 2: see original paper]).

### 3.1 Digital Technology Enabling Clean Energy Generation for Source-Side Carbon Reduction

According to the "China' s Energy Development in the New Era" report, since 2005, China has implemented a series of energy conservation and emission reduction measures to promote non-fossil energy development and reduce power supply energy consumption and line loss rates, achieving major innovations in energy production and utilization modes. In this process, clean energy accounted for 23.4% of total energy consumption, and China' s carbon emission intensity in 2019 had decreased by 48.1% compared to 2005, demonstrating the vital role of green energy development in reducing China' s carbon emission intensity. Although the proportion of coal power installed capacity and thermal power generation continues to decline, coal power remains the main source of China' s electricity and power for the current and future period, resulting in a massive high-carbon structure in the power system.

During the 14th Five-Year Plan period, China will commit to developing and adopting more efficient and low-carbon energy production technologies to improve energy resource utilization efficiency. Simultaneously, it will increase investment in and use of clean energy to raise the proportion of clean energy in total energy consumption and drive the energy industry toward a more environmentally friendly and sustainable direction. By 2030, China' s clean energy consumption proportion is expected to reach approximately 25% [17]. Therefore, achieving dual carbon goals requires fundamentally reducing fossil energy consumption while substantially increasing non-fossil energy consumption. Clean energy generation technology must be used to reduce carbon pollution from source-side power generation and transform the generation structure of power supply enterprises.

First, big data technology enables efficient utilization of clean energy. For power supply enterprises, clean energy generation technology plays an important role in directly reducing carbon emissions at the source. However, clean energy utilization faces issues such as low utilization rates and instability. Big data technology can achieve precise prediction of generation power, enabling breakthroughs in low-cost, high-efficiency clean energy generation. For wind power, big data can collect and analyze meteorological data, wind speed, direction, and other parameters to predict future wind energy resources. By analyzing historical and real-time data, precise wind energy prediction models can be established to make generation plans and dispatching arrangements in advance, thereby improving wind power generation efficiency. For photovoltaic power generation, big data can monitor and analyze factors such as light intensity, temperature, and cloud cover in real time to predict photovoltaic generation potential and efficiency. Simultaneously, big data can monitor and manage PV cell components to improve the operational efficiency and reliability of photovoltaic power generation systems. By leveraging big data technology, photovoltaic system design and operation can be optimized to achieve breakthroughs in low cost and high efficiency.

Second, digital energy storage technology assists stable storage of clean energy. Clean energy management is a top priority in power industry development, with stable storage of clean energy being particularly critical. This faces three challenges: clean energy (such as solar and wind) has intermittent and uncontrollable characteristics, depending on weather conditions and natural resource availability, leading to supply-demand imbalances; currently widely used energy storage technologies such as battery energy storage systems (e.g., lithium-ion and sodium-ion batteries) and new storage technologies (e.g., hydrogen energy, compressed air storage) are relatively expensive, resulting in excessive enterprise investment costs; and energy transmission losses pose another challenge, as long-distance transmission of clean energy may cause energy losses that require effective transmission and distribution systems. The emergence and development of digital technology provide new opportunities for solving clean energy storage problems in the power industry, enabling intelligent storage management so that storage equipment can intelligently perceive and respond to energy needs in real time. By monitoring clean energy output and grid load in real time, intelligent energy storage systems can optimize energy storage and release to balance energy supply and demand. Additionally, big data predictive analysis can be used to plan storage behavior in advance, ensuring storage when clean energy is abundant and release during peak consumption periods, thereby achieving stable energy supply.

### 3.2 IoT and Big Data Technologies for Precise Carbon Measurement Across All Segments

A precise carbon emission measurement system is the cornerstone for achieving pollution and carbon reduction in power enterprises and plays a key policy guidance role. Carbon emission sources from power enterprises can be mainly divided into direct carbon emissions from generation enterprises and indirect carbon emissions caused by different behaviors of electricity consumption enterprises. Accurate carbon emission measurement involves multiple links, and full-chain carbon measurement is a complex engineering task [18]. Therefore, to achieve precise carbon measurement across all segments and allocate carbon responsibilities among enterprises, power enterprises can introduce IoT and big data technologies to solve problems of low accuracy and weak real-time capability in carbon measurement.

First, IoT technology enables real-time monitoring of power consumption in enterprises. To fully explore characteristics of enterprise power consumption, monitor electricity usage behavior, and transform enterprise electricity strategies to reduce consumption, power enterprises can use IoT technology to connect sensors and smart devices to various equipment for accurate power data monitoring. Sensors can collect key parameter data such as current, voltage, and power, and transmit the data via IoT networks to big data centers or cloud computing platforms. Through real-time monitoring and data collection, statistics on enterprise electricity usage habits can be analyzed to understand details and patterns of power usage, supporting power management and optimization decisions.

Second, big data technology enables carbon measurement for multiple types of power sources in generation enterprises. Based on the IPCC' s "measurability, reportability, and verifiability" principles, carbon emission measurement methods for multiple generation sources in power enterprises need to be studied [19]. Currently, generation sources in power enterprises are mainly divided into conventional fossil energy and renewable energy (e.g., wind, solar). For conventional fossil energy, the combustion emission factor method can be used , where direct carbon emissions can be calculated based on fuel consumption and corresponding emission factors [20]. For renewable energy, carbon emissions from backup and auxiliary services such as frequency regulation required for accommodation need to be considered, which can be modeled through big data technology for equivalent carbon emissions to achieve carbon measurement for renewable energy [19]. Some power enterprises may also use new energy sources such as hydrogen energy, which can be simulated and calculated through modeling to achieve carbon measurement for multiple types of power sources.

Third, big data technology enables real-time and precise carbon measurement for electricity consumption enterprises. When calculating carbon emission levels of various departments in electricity consumption enterprises, precise carbon measurement methods for electricity consumption behavior need to be studied

[21]. Big data technology can be used to establish an "electricity-carbon" model to analyze and process large amounts of power consumption data. Combined with carbon emission factors from the "electricity-carbon" model, precise calculation of power carbon emissions can be achieved. By applying the "electricity-carbon" model to analyze enterprise electricity consumption behavior patterns, high-energy-consuming equipment and peak consumption periods can be identified. The results of power carbon emissions can then be presented through big data visualization, enabling intuitive understanding of carbon emission situations. This provides data-based energy management decision support to help enterprises achieve carbon reduction targets. Through real-time and precise carbon measurement, enterprises can accurately allocate carbon emissions among different departments, promoting internal energy management and emission reduction measures.

### 3.3 Artificial Intelligence for Efficient Electricity Utilization

Artificial intelligence technology is an effective measure for solving complex system control and decision-making problems. Its in-depth application in the energy industry helps promote clean energy production and reduce carbon emissions [8]. Therefore, applying AI technology to achieve efficient electricity dispatching and utilization has become an important practical measure for carbon emission reduction in China' s power enterprises.

First, AI enables load forecasting and dispatching optimization. AI technology can analyze historical load data, weather, temperature, and other information to establish deep learning models that predict changes in electricity demand and formulate optimal load dispatching strategies. AI can monitor power system operation status in real time and perform intelligent dispatching according to demand and supply conditions to maximize the utilization of renewable energy and optimize the use of traditional energy, thereby improving electricity utilization efficiency.

Second, AI enables intelligent management of enterprise power systems. AI technology can combine with IoT technology to achieve intelligent management of power equipment and energy systems. By connecting sensors and smart devices, power enterprises can use AI technology to monitor energy consumption, equipment status, and environmental parameters in real time. Through machine learning and data analysis technologies, energy system operation and control strategies can be optimized to achieve efficient energy utilization and energy conservation.

### 3.4 Blockchain Technology for Incentivizing Low-Carbon Behavior in Power Enterprises

First, blockchain technology protects enterprise data privacy. In the digital empowerment of power enterprises, data privacy is an important consideration. When monitoring and recording key data such as energy consumption and carbon emissions, power enterprises need to ensure that this data is not tampered with or leaked. Blockchain technology, as a decentralized and tamper-proof distributed ledger technology, can provide secure data storage and transmission. By storing power enterprise data in encrypted form on the blockchain, data confidentiality and integrity can be ensured. Additionally, blockchain can provide data access permission control mechanisms, allowing only authorized parties to view and verify data, thereby protecting business privacy and sensitive information.

Second, blockchain technology incentivizes sustainable low-carbon behavior in power enterprises. Blockchain can not only protect data privacy but also incentivize power enterprises to adopt sustainable low-carbon behaviors through smart contract mechanisms. Smart contracts are automated contracts executed on the blockchain that set specific conditions and incentive mechanisms. By establishing contract rules, power enterprises can receive rewards or preferential policies to encourage low-carbon power generation, carbon emission reduction, and energy efficiency improvement. Blockchain ensures that smart contract execution results are recorded on the blockchain, achieving an open, transparent, and tamper-proof incentive mechanism that enhances power enterprise participation in low-carbon initiatives.

### 3.5 Digital Twin Technology for Carbon Reduction and Precise Planning

Digital twin technology refers to the interaction between digital models and real-world real-time data to achieve simulation and monitoring of physical entities. In power enterprises, digital twin technology can provide strong support for carbon reduction and precise planning (Figure 3 [Figure 3: see original paper]).

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## 4. Strategies for Digital Technology Enabling Pollution and Carbon Reduction in Power Enterprises

Based on the aforementioned pathways for digital technology to enable source-side carbon reduction, energy consumption monitoring, efficient energy utilization, low-carbon behavior incentives, and precise emission reduction planning, this study proposes implementation strategies for digital pollution and carbon reduction in power enterprises to ensure the effectiveness of these pathways and promote the intelligent, green, and low-carbon transformation of power enterprises.

### 4.1 Focus on Promoting Power Data Security Governance and Risk Prevention

While digital technology opens new avenues for the low-carbon and intelligent development of power enterprises, power data as a core enterprise asset faces stricter security challenges. Based on in-depth analysis of the current situation of power enterprises and the requirements of the big data era and industry development needs, the following approaches are proposed:

First, establish critical data security infrastructure and improve security management mechanisms. As critical infrastructure industries, energy and power enterprises require important data security management. Establishing a data security management organizational system with clear rights, responsibilities, and division of labor can help enterprises better protect data and effectively respond to potential security threats. Key steps include standardizing data classification and grading, promoting security management system construction, strengthening assessment and accountability, and establishing security responsibilities and rights. Additionally, establish a filing system for data that needs to be sent externally to ensure the security of outbound data. Build a flexible and efficient data security emergency response mechanism to timely address various security incidents and threats. Conduct regular security assessments of data processing, usage, and external distribution to identify potential risks and take corresponding improvement measures while strengthening accountability to enhance data security management levels and reduce the possibility of data leakage and risks. Continuously monitor the latest technologies and regulatory requirements in the data security field to continuously improve and enhance data security management.

Second, firmly establish legal red line awareness and bottom-line thinking, and promote security compliance mechanism construction. Keep pace with national laws and regulations, strengthen data security legal awareness promotion, deeply analyze data security cases, and implement personal information security protection requirements according to laws and regulations. Ensure enterprises comply with laws and regulations in data processing and management, prevent data security risks, improve organizational and individual awareness of data security legal requirements, and promote standardization and compliance of data security management. Effectively prevent data leakage and misuse risks, protect customer privacy and data security, and establish legal red line awareness in data business development. Implement personal information security protection requirements in accordance with laws and regulations, legally and compliantly obtain and use personal information, and promptly take corrective and punitive measures for violations of security compliance regulations to form strict systems and norms. Develop and promote data security and compliance policies applicable to enterprises, clarifying security requirements for all links including data collection, storage, processing, transmission, and sharing to avoid infringing on customer privacy or illegally obtaining customer information.

Third, enhance the professional capabilities of data security technical services and unify service processes and operational norms. Develop standards and norms applicable to data security technical services, clarifying various requirements and guidelines. Conduct regular reviews and assessments of data security technical services to identify problems and make timely improvements to maintain service quality and security levels. Accelerate the application of technologies such as data desensitization, watermark tracing, and big data situational awareness, and explore application scenarios for anonymization, data labeling, and multi-party secure computing. Strengthen the open invocation of security service capabilities, unified management of policies, and unified risk assessment. By enhancing data security monitoring and attack-defense verification capabilities, effectively reduce data leakage and security risks.

Fourth, commit to cultivating data security talent teams to consolidate security defense lines. Strengthen data security talent cultivation and build a solid data security protection architecture. For grid enterprises, there is an urgent need to accelerate the introduction of experts familiar with data security and focus on cultivating talents with professional skills in regulatory compliance and industrial attack-defense. Simultaneously, build professional data security teams, strengthen practitioners' duty performance capabilities and professional ethics, promote interaction and integration between data security management agencies and business departments, and collaboratively carry out data security work to ensure the implementation of data security responsibilities and cultivate professionals with solid business literacy and high security awareness. Additionally, strengthen exchanges and cooperation among enterprise departments in the data security field and establish normalized communication and collaboration mechanisms to create an excellent new ecosystem for data security professional talent cultivation, technological innovation, and industrial development [22].

### 4.3 Using Digital Technology to Address Adverse Impacts of EU Carbon Tax

Promote the integration of carbon emission data monitoring, reporting, and verification (MRV) with blockchain technology to ensure the authenticity of data monitoring and provide reliable support for enterprises to address potential carbon emission data disputes in the EU Carbon Border Adjustment Mechanism (CBAM). Power enterprises can use internationally recognized green power trading certificates to sell surplus carbon emission quotas in the carbon market and obtain additional economic benefits, which helps increase the number of participants in the carbon market and expand trading scale. Allow enterprises affected by CBAM to participate in both carbon and green certificate trading markets, and allow their purchased green certificates to be converted into Chinese Certified Emission Reductions (CCER) to offset carbon quotas, thereby reducing their indirect power consumption carbon emissions while leveraging the synergistic emission reduction effect of both markets.

Rely on digital carbon management platforms to carry out supply chain carbon footprint accounting and emission reduction implementation plan planning. Starting from the data source, use IoT services to collect data in real time, and use blockchain technology to solve problems of data traceability and tamper-proofing. This enables one-click compilation of full lifecycle carbon footprint reports for multiple scenarios/technology routes, supporting enterprises to proactively address green trade barriers such as CBAM and product carbon footprint disclosure requirements.

### 4.4 Establishing a Digital Standards System to Support Smart Power Systems

When establishing and improving intelligent power systems, a comprehensive indicator system should first be developed to provide a basis for daily AI inspections, thereby obtaining more accurate and reasonable data results. Currently, this standards system includes three types of technical standards:

First, on the generation side, it is necessary to coordinate technical standards for fossil energy (such as coal) and clean energy (such as water, wind, and solar) and multi-energy complementarity, conduct in-depth research and analysis on their data exchange methods and information transmission requirements, and understand application scenarios and influencing factors of various digital standards. Strengthen the construction of technical standards for traditional peak-shaving power sources, including coal power flexibility retrofitting, pumped storage, and gas power generation, to fully leverage their flexible regulation and coordinated operation capabilities and provide necessary support for continuous power system operation.

Second, on the grid side, it is necessary to improve the relevant standard system for transmission networks and transformation technology, accelerate the optimization and upgrading of distribution networks, and promote the construction of standards related to distributed power sources and microgrids to ensure efficient local consumption of distributed new energy and promote the deep development of microgrids. There are still shortcomings in the large-scale development of new energy, such as scarce flexible resources in power systems, weak new energy consumption capacity, declining system reliability, and increased difficulty in distribution network operation and maintenance management. Therefore, the new power system technical standards system still requires multi-faceted development and targeted improvement.

Third, on the storage side, it is necessary to continuously strengthen the construction of technical standard systems for various energy storage technologies and power system reserves. Refer to relevant industry standards such as communication interface standards and data format standards for energy storage equipment, understand existing digital standards in the industry, and make adaptive adjustments according to actual needs. Based on data exchange requirements on the storage side, define corresponding data models and interface specifications to ensure data consistency and interoperability, providing guarantees for safe and stable operation of power systems under special circumstances.

### 4.5 Helping Power Enterprises Improve Quality, Reduce Costs, and Increase Efficiency

The important content of cost reduction and efficiency improvement in power enterprises lies in energy and information exchange. Based on a full understanding of power industry digital transformation needs and combined with practical experience in digital transformation and serving power industry digitalization, provide "close accompanying" services for digital transformation to enterprises at different development stages and scales. Simultaneously, exert efforts from multiple aspects including computing power, network, platform, and security to comprehensively promote the construction of a new energy system featuring "extensive connectivity + intelligent efficiency + safety and reliability + green and low-carbon." Effectively integrate daily power asset management with digital management systems. On-site operators scan RFID tags to automatically obtain massive information data on equipment during planning and design, procurement and construction, acceptance and commissioning, operation and maintenance, and scrapping stages, thereby achieving real-time synchronization between physical information and system information. This enables physical management of grid assets such as transmission, transformation, and distribution production equipment, metering assets, office assets, information and communication assets, and tools, improving the efficiency of asset management business operations and the level of asset full lifecycle information traceability and management.

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Emission factor is the carbon emission coefficient per unit activity.

*Note: Figure translations are in progress. See original paper for figures.*