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Driving Low-Carbon Transition in the Energy Sector through Digital Transformation: Opportunities, Challenges, and Strategic Responses

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Abstract: Under the twin forces of global carbon neutrality pledges and the rapid expansion of the digital economy, traditional energy industries are caught between the urgent need to decarbonize and the imperative to upgrade operations. In this paper, we systematically examine the main opportunities and obstacles brought by digital transformation to the energy sector, and propose concrete optimization measures. Our analysis reveals that digitalization can significantly improve production efficiency, enable better allocation of clean energy, and reduce market inefficiencies. However, challenges such as technological path dependency, high upfront costs, and data security risks remain critical bottlenecks. We aim to provide actionable insights for policymakers and industry practitioners who are advancing the low-carbon energy transition.

Keywords: Low-carbon transition; Digital transformation; Energy industry; Energy efficiency

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1. Introduction

1.1. Global low-carbon transition background

The global carbon neutrality goal is fundamentally reshaping the development direction of the energy industry. The sixth assessment report of the IPCC clearly points out that in order to limit global warming to within 1.5°C, carbon dioxide emissions in 2030 need to be reduced by 43% compared with 2019, and the energy sector contributes about 75% of greenhouse gases, which is naturally the top priority for emission reduction. At present, more than 130 economies have proposed the goal of achieving net zero emissions by the middle of this century, which means that energy decarbonization has become a core issue of global climate action. The European Union has promised to reduce emissions by 55% by 2030 and achieve carbon

neutrality by 2050. China and the United States have also announced a clear timetable for carbon peaking and carbon neutrality. The problem is that the traditional fossil energy system contributes more than 70% of the carbon emissions of human activity. Now it is facing unprecedented regulatory and market pressure, and the transformation is imminent.

1.2. Digital economy penetrates traditional energy industry

The widespread penetration of digital technology is becoming a key driving force for the restructuring of energy systems. According to data from the International Energy Agency (IEA), global digital energy investment has exceeded 70 billion US dollars in 2025, with an annual growth rate of more than 12%, which is one of the fastest-growing areas in the energy industry. Technologies such as big data, artificial intelligence, the Internet of Things, and cloud computing are deeply embedded in the production, transmission, distribution, and consumption of energy. This deep integration not only breaks the operational boundaries of the traditional energy industry, but also promotes the transformation of the industrial value chain from resource-driven to data-driven.

1.3. The dilemma of the traditional energy industry

Despite the urgency of the transition, traditional energy industries face entrenched structural dilemmas. Legacy production systems suffer from low operational efficiency and high carbon intensity: global average coal-fired power generation efficiency remains around 36%, while a large number of aging units have even lower efficiency levels. Inflexible allocation mechanisms lead to persistent renewable energy curtailment, with the global average curtailment rate of wind and solar power staying above 5% in most emerging economies. Meanwhile, information asymmetry in energy markets distorts price signals, increases transaction costs by 15%-20% compared with efficient digital markets, and slows low-carbon investment flows.

1.4. Research significance and structure

Systematically unpacking digitalization's role in the energy low-carbon transition holds strong practical value for policymakers and industrial practitioners. Theoretically, this paper constructs a systematic analytical framework of opportunities, challenges, and countermeasures, making up for the lack of a holistic industrial economic perspective in existing technical studies. Practically, the targeted countermeasures proposed can provide decision-making references for governments to formulate industrial policies and for energy enterprises to design transformation paths. The rest of the paper proceeds with literature review, opportunity analysis, challenge discussion, countermeasure proposal and conclusion sequentially.

2. Literature review

2.1. Research on low-carbon energy transition

In recent years, more and more studies have begun to pay attention to the driving factors and realization paths of low-carbon energy transformation, involving different countries and industry backgrounds. Most of the early studies analyzed the emission reduction effect of single policy tools and renewable energy technologies from the perspective of technology-policy. However, with the deepening of transformation practice, the academic community has gradually turned to structural factors, such as technological progress and industrial restructuring [1]. Interestingly, scholars are now more concerned about systemic change - how

energy restructuring, industrial chain restructuring and changes in the institutional environment affect each other. The existing empirical evidence consistently shows that improving energy efficiency and optimizing energy structure are the two core paths of carbon emission reduction in the energy sector.

2.2. Digitalization and industrial upgrading research

Research on the digital economy has generally confirmed that digital technology can improve the productivity of traditional industries. From the perspective of transaction cost theory, digitalization reduces the cost of information search and the friction of organizational coordination, thus improving the efficiency of resource allocation in the whole industrial chain. As Song (2025)[2] pointed out, digitalization reduces production costs, optimizes resource allocation and accelerates innovation by improving the efficiency of information transmission and reducing organizational friction. From the perspective of resource foundation, digital capabilities have become a core competitiveness of enterprises in the digital age, promoting continuous innovation of products and business models. Recent research has further explored the differences in the effect of digital transformation in different industries and enterprise scales. It is found that although capital-intensive industries such as energy have greater potential for efficiency improvement, they also face higher transformation obstacles.

2.3. Research progress of energy digital transformation

Research on energy digitalization has grown rapidly in recent years, mainly focusing on technology application and operation model innovation. It can be roughly divided into two categories: one focuses on power grid-side intelligence, such as smart grid and digital scheduling technology; the other focuses on demand-side management, such as smart meters and demand response systems. The research of Tang et al. (2026) [3] confirms that smart grid technology can effectively improve the consumption rate of renewable energy and enhance the stability of system operation. In addition, some scholars have explored the application of the Internet of Things and big data in device monitoring and demand-side response management. However, most of the existing studies are from the perspective of engineering technology, and not enough attention is paid to the economic effects of digital transformation at the industry level and the impact of industrial structure.

2.4. Research gaps

After combing, there are three obvious shortcomings in the existing research. First, most studies focus on the technical level, do not pay enough attention to the economic impact of energy digital transformation at the industry level, and rarely discuss the structural adjustment effect of digitalization on the entire energy industry. Second, a systematic analysis framework that takes into account both opportunities and challenges is still rare[4]. Most studies only discuss one aspect of digital transformation and fail to form a complete logical chain from cause to obstacle to solution. Third, there are few studies that put forward specific countermeasures to the actual difficulties of the traditional energy industry, and policy proposals are often too general and not easy to implement. This article tries to make up for these shortcomings: build a holistic analysis framework and put forward feasible coping strategies in combination with the actual characteristics of the traditional energy industry.

3. Opportunities brought by digital transformation

3.1. Digital improvement of production efficiency and operation level

Digital technology really improves the efficiency of energy production and transmission. For example, Internet of Things sensors can monitor the status of core equipment such as generators, transformers and pipelines in real time, and automatically identify abnormal situations through algorithms. Compared with traditional manual inspection, unplanned downtime can be reduced by 40 to 50%. Looking at the AI dispatching system, it can adjust the combustion parameters of the coal-fired unit in real time according to the changes in coal quality and load. In this way, the energy consumption of the unit is reduced by 2% to 5%, and the carbon emission intensity is also reduced. In addition, the digital operation and maintenance platform can also save two to three times the manual inspection costs. At the same time, because the risk of on-site operation is reduced, the overall level of safe production will also be improved.

3.2. Optimization path of clean energy allocation and consumption

The volatility and intermittent nature of renewable energy has always been a difficult problem, and digitalization has provided a pragmatic solution. The smart grid system can accurately predict the output of renewable energy based on meteorological data and real-time load information, and dynamically match supply and demand by optimizing the scheduling algorithm. The distributed energy management platform integrates rooftop photovoltaics, energy storage facilities and demand-side response resources to form a virtual power plant, which is equivalent to a flexible adjustable unit to participate in the grid scheduling, so as to realize the flexible configuration of clean energy. In addition, the demand response mechanism based on digital price signals can reduce the peak load by 10% to 15%, effectively alleviating the grid congestion during peak hours. These measures directly reduce the rate of wind and light abandonment, and also reduce the carbon intensity of the overall energy consumption.

3.3. Mitigation mechanism for asymmetry of market information

The digital energy trading platform breaks down the information barriers of the traditional market and makes transactions more efficient. The transparent digital transaction mechanism allows all participants to see price and supply and demand data in real time, and the search cost and transaction cost are greatly reduced. Compared with traditional offline transactions, digital platforms can reduce intermediate links, and comprehensive transaction costs can be reduced by 15% to 25%. Big data-driven price forecasting tools can also help market entities make more rational production and consumption decisions and optimize the allocation of energy resources across time, space, and regions. In addition, the digital credit system based on transaction data can reduce the moral risk in transactions, reduce the financing costs of small and medium-sized energy enterprises, and alleviate their capital pressure during the transformation process.

3.4. Digital drive of green innovation and industrial upgrading

Digital transformation can also accelerate the pace of green innovation and promote the structural upgrading of the energy industry. For example, digital twin technology can simulate and optimize the research and development process of low-carbon technologies such as carbon capture, energy storage and new energy materials, shorten the innovation cycle by 3 by 3 times, and greatly reduce the development cost. The integration of digital technology and the energy industry has also given rise to new business forms such as comprehensive energy services, energy management outsourcing, and integrated energy solutions,

extending the industrial value chain from simple energy supply to full-cycle energy services. In the long run, digitalization will promote the energy industry from fossil fuels to clean energy, and support the realization of low-carbon development goals through continuous technological innovation and business model innovation.

4. Core challenges of energy digital transformation

4.1. Industrial path dependence and structural rigidity

The heavy-asset nature of traditional energy industries creates strong technological and institutional path dependence. From a technical perspective, traditional energy equipment such as power plants and oil refineries has a service life of up to 30-40 years, and the huge stock of assets forms a strong technology lock-in effect. Decades of investment in fossil fuel infrastructure have formed a self-reinforcing production system, with supporting policies, standards and industrial chains all adapted to traditional operation modes. From an institutional perspective, the current energy regulatory system, industry standards and interest distribution patterns are all built around the traditional fossil fuel system. Digital transformation requires fundamental adjustments to existing technical systems and interest structures, which encounters significant structural resistance from entrenched incumbents.

4.2. High transformation cost and insufficient incentive

Energy digital transformation requires substantial upfront investment in hardware upgrading, software deployment and professional talent training. From the perspective of cost structure, hardware investment such as sensing terminals and edge computing equipment accounts for about 50%-60% of the total transformation cost, software and platform deployment accounts for 20%-30%, and talent training and later operation and maintenance accounts for 10%-20%. For most traditional energy enterprises, digital transformation costs are directly visible in short-term financial statements, while carbon reduction and efficiency benefits are often long-term and partially externalized. The payback period of most digital transformation projects is 5-8 years, which exceeds the short-term performance assessment cycle of many enterprises. The lack of targeted fiscal subsidies and incentive mechanisms further weakens enterprises' willingness to transform, especially for small and medium-sized players with limited capital reserves.

4.3. Data isolation and insufficient data sharing

The energy industry covers multiple links from production to end consumption, operated by diverse stakeholders with separate management systems. Fragmented data standards and incompatible interfaces have formed widespread data silos across generation, transmission, distribution and retail segments. On the power generation side, production data of power plants are mostly kept internally and not open to the public; on the grid side, power dispatch data are managed independently by grid enterprises with unified internal standards but poor external connectivity; on the user side, energy consumption data are scattered among grid companies, energy retailers and property management entities [5]. Cross-sectoral data sharing faces both technical barriers and institutional obstacles, preventing the full release of data element value across the industrial chain.

5. Optimization countermeasures

5.1. Strengthen technological innovation to break path dependence

Increase R&D investment in core digital energy technologies such as smart sensors, digital twin systems and intelligent scheduling algorithms. Support leading energy enterprises to cooperate with universities and research institutes to build joint innovation platforms, and carry out targeted research on key common technologies suitable for the transformation needs of traditional energy industries. Lay out next-generation energy digital infrastructure in a forward-looking manner, and gradually guide the upgrading of stock assets through technological iteration to weaken the lock-in effect of traditional fossil fuel paths. Encourage enterprises to implement digital transformation step by step, starting from non-core links such as operation and maintenance and scheduling with high cost-effectiveness, and gradually expand to the whole production process, so as to reduce transformation risks and sunk costs.

5.2. Build diversified cost subsidy mechanism

It is recommended to set up a special fund for energy digital transformation, and implement differentiated subsidy policies according to the scale and type of enterprises. Specifically, a combination incentive mechanism of basic subsidies and performance incentives can be adopted: on the one hand, a certain proportion of early subsidies can be provided for enterprises' digital transformation projects, and on the other hand, additional carbon emission reduction incentives can be given to those projects with significant energy-saving and carbon reduction effects. It can also explore the internalization of low-carbon benefits through carbon market linkage, allowing enterprises to convert the carbon emission reduction brought about by digital transformation into carbon quotas for trading. For small and medium-sized enterprises, they should innovate green financial products, such as launching special loans for digital transformation, carbon emission reduction support tools, etc., to broaden their financing channels and reduce the capital burden in the process of transformation.

5.3. Construct unified energy digital platform

First of all, it is necessary to unify the industry data standards and interface specifications of the entire energy chain, and formulate unified energy data element standards and data exchange protocols, so as to solve the technical obstacles to the interconnection between different systems. Build a public service platform for energy data sharing and interaction, and promote interconnection of data resources among generation, grid, retail, and end users. Establish a hierarchical and classified data sharing mechanism, clarify the sharing scope and access authority of public data, commercial data and sensitive data respectively, and fully activate the value of data as a production factor on the premise of ensuring data security.

6. Conclusion

This paper demonstrates that digital transformation serves as a core enabler for the low-carbon transition of traditional energy industries, bringing comprehensive improvements in production efficiency, clean energy allocation, market operation and green innovation. However, path dependence, high costs, data silos and security risks remain major bottlenecks restricting the deep development of energy digitalization. The targeted countermeasures proposed in this paper can provide practical references for policymakers and industrial practitioners.

For policymakers, it is necessary to improve top-level design, unify industry data standards, build diversified incentive mechanisms, and improve digital supervision systems, so as to create a sound institutional environment for energy digital transformation. For energy enterprises, they should formulate differentiated digital transformation paths according to their own development basis, promote step-by-step transformation from easy to difficult, and balance short-term costs and long-term benefits.

This study focuses on qualitative analysis and framework construction, and future research can carry out quantitative empirical testing based on micro-enterprise data to further measure the carbon reduction effect and economic benefits of energy digital transformation, and explore the heterogeneous transformation paths of different types of enterprises.

Disclosure statement

The author declares no conflict of interest.

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