

Exploring the Path of Digital Finance Empowering Green Transformation of Energy Enterprises under the Dual-Carbon Goals

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Abstract. Under the dual carbon targets, China's energy companies are speeding up their green transformation, but they usually encounter some common obstacles including lack of capital, weak technical assistance and an incomplete risk control system. The combination of digital technology and financial services provides new approaches to solve these problems. According to the specific characteristics of the transformation of energy enterprises, this research examines the mechanisms of digital finance from two aspects – financing enhancement and technological enhancement. It is found that methods such as digital green loans, bonds and equity financing can efficiently relieve the financial pressure of enterprises, while technologies like big data, blockchain and artificial intelligence can greatly improve the accuracy of emission reduction and the efficiency of energy operation. Furthermore, the enhancing effects have regional differences and threshold characteristics. Thus, countermeasures are put forward from four fields: improving service provision, deepening technological integration, setting up a risk management system and improving policy regulation, which offer guidance for the actual transformation of energy enterprises and the development of relevant policies.

Keywords: Digital finance, energy companies, green transformation, dual carbon targets

1. Introduction

After the proposal of the dual carbon target, the green and low-carbon transformation of China's energy industry has become one of the core tasks for high-quality economic and social development, and policy guidance is gradually transitioning from the previous government subsidy model to market-oriented regulatory tools [1, 2].

At present, traditional energy enterprises generally undertake the rigid task of energy conservation and carbon reduction transformation, and some leading enterprises' emission indicators have approached the international advanced level. However, the scale of the photovoltaic and wind power industries in the new energy field continues to expand, and the speed of technological iteration is constantly accelerating. Both types of enterprises are facing prominent development bottlenecks: transformation projects generally have the characteristics of large investment and long return cycles, and traditional financial services have problems such as high thresholds and lengthy

approval processes, leading to the dilemma of insufficient funding supply for enterprises; Long low-carbon R&D cycles and uncertain technological routes increase innovation risks for enterprises. Top new energy enterprises have sufficient digital layout, while a large number of small and medium-sized traditional energy enterprises have limited funds and a significant gap in digital investment. The driving force for green R&D is continuously suppressed; At the same time, most enterprises have not yet established a risk management system that adapts to the characteristics of transformation, resulting in insufficient precision in transformation decisions and low efficiency in resource allocation [3].

In recent years, the deep integration of digital technology and financial services has provided new possibilities for solving the above bottlenecks. The overall development of digital finance in China is on the rise, and a market system covering multiple service scenarios has been formed. The landing and application of technologies such as artificial intelligence and blockchain provide feasible paths for accurately identifying green projects, reducing transaction costs, and expanding financing channels. In this context, this article focuses on the mechanism and implementation path of digital finance in assisting energy enterprises in green transformation, in order to provide reference for relevant policy optimization and enterprise practice.

2. The current situation, challenges, and logic of digital finance in the green transformation of energy enterprises

2.1. The current characteristics of green transformation in energy enterprises

Against the backdrop of the gradual implementation of the dual carbon strategy, China's green transformation in the energy sector has shown multidimensional promotion characteristics. The policy has gone through three stages: subsidy led, electricity price subsidy, and market-oriented transformation, providing clear institutional guidance for energy enterprises to transform.

The change in energy saving and emission reduction in traditional energy enterprises is progressing rapidly. Large coal-fired power plants and oil and gas companies have made their emission indicators, like carbon emission per unit production and coal consumption for electricity generation, almost reach the advanced international standards. Some enterprises have successfully eliminated the emissions from coal-fired units by improving their techniques, which offers a feasible way for the traditional energy industry to develop in a low-carbon manner [1, 4]. In the new energy sector, the photovoltaic and wind power industries are expanding, and their supply chains are the best in the world. Technological progress is also speeding up. The commercialization period of important technologies such as PERC solar cells and large capacity wind turbines is becoming shorter. The listed new energy companies on the A-share market are obtaining more and more green patents every year, greatly increasing their self-sufficiency and controlling the core technologies [5]. The combination of digital technology with the energy sector is becoming more obvious. Provinces near the sea lead in researching digital low-carbon transformation plans for offshore wind power and marine oil and gas exploration. By using real-time data monitoring and intelligent dispatching systems, the efficiency of utilizing ocean energy is improved and the carbon intensity is reduced. Some areas have already established replicable experiences in the low-carbon transformation of marine industries. According to previous studies, green finance has already played a positive role in the sustainable development of energy, thus providing a strong basis for the further integration of digital finance in the energy transformation process.

The information shown in Figure 1 quantitatively evaluates the progress of China's energy green transformation from five aspects: the degree of policy model perfection, the low-carbon state of

traditional energy, the development trend of new energy industry, the level of information and energy integration, and the support of green finance. It can offer a clearer insight into the whole system and the non-equilibrium changes during the transformation process. It can be observed that progress has been made in all five dimensions to a certain extent, and they have jointly established a transformation framework, which includes "policies playing a leading and escort role, physical industries achieving landing and development, digital technology providing assistance and support, and financial services providing bottom line guarantees". However, there are significant differences in the maturity of each dimension, presenting a pattern of "institutional and industrial leading positions, and relatively lagging financial support dimensions".

Dimensional from a conceptual point of view: The policy model completeness and traditional energy decarbonization dimensions were at very high levels, they being the "ballast" of the transition. High maturity in policy dimension reflects China's success in phased, progressive institutional design, and the benefits of top-down institutional supply in transforming. Ongoing iterations of stage-specific incentive and constraint mechanisms provide stable institutional expectations and clear action paths for micro-level energy enterprises' transformation decisions –the backbone institutional framework for China to remain strategic and avoid short term shift in energy transition. The breakthrough for traditional energy decarbonization highlights China's pragmatic transformation logic of "prioritizing the current capacity and accelerating incremental substitution." As new energy sources cannot yet ensure energy security, deep decarbonisation upgrades of traditional coal-fired plants and oil-gas plants protect the baseline of energy security (which is a natural choice due to China's resourceowment of abundant coal but limited oil and gas) and as a reference path for other countries with large large coal-supply.

Second, the development of new energy industry and the degree of digital-energy integration are two major engines leading to the gain of energy transition in terms of the new energy sector. The high score in new energy-industry dimension is the result of a positive feedback between technology iteration and scale effect. Large industrial scale increases R&D costs, rapid growth of green patents increases global competitiveness across supply chain and the "technological breakthroughs-capacity expansion-cost reduction-market penetration". The increased level of digital energy integration will be a prerequisite for China going deeper in global value chain growth. Good performance in digital-integrated technologies presents a new paradigm of energy transformation. Digital technologies have gone from merely efficient efficiency tools for energy transition; they have been developed as main production factors for low-carbon transition. Replicable experience from coastal regions show that digitalization benefits accurate carbon emission control and smart energy system dispatching; a region-based transition transmission mechanism is developed based on "pilot scenarios followed by experience diffusion" for inland energy provinces pursuing low-caribration transition.

Third, green finance support dimension ranked relatively low among the five dimensions, and it is clear that financial support for energy shift is still at an early stage of developing. While the positive impact of green finance has been shown to be beneficial, there is still a gap between financial resources and actual resources.

From a system coordination perspective, these five dimensions are not independent of each other, but interdependent coupled transmission. Policy guidelines are defined within institutional regimes and incentive directions for industrial development and financial innovation are given. Technological developments in industry provide application scenarios and physical foundation for digital-energy integration and green finance. Digital energy is the means by which carbon emission measure and trace can be measured and traced, which can support green financial product innovation and risk management. The resource allocation function of green finance drives industrial

technology upgrades and digital conversion. This multidimensional, holistic evolution logic forms the system-based basis for China's energy green transition and, hence, future efforts can not only focus on breakthroughs in individual dimensions but also on strengthening inter-dimensional links and improving transform efficiency by addressing weaknesses and reinforcing vulnerable areas.

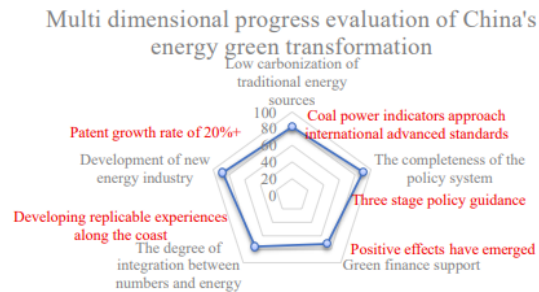


Figure 1. Schematic diagram of multidimensional progress in China's energy green transformation

Picture credit: Original

2.2. Common challenges faced by energy enterprises in green transformation

From the perspective of funding, green transformation projects of energy enterprises generally have the characteristics of large initial investment, long return cycle, and high uncertainty of returns. However, traditional financial service systems have problems such as high entry barriers, lengthy approval processes, and strict collateral requirements for such projects. Small and medium-sized new energy enterprises with light asset attributes find it difficult to meet traditional credit conditions and generally face prominent financing constraints [6].

From a technical perspective, low-carbon technology research and development also has risks such as uncertain technology paths and long achievement transformation periods. Most energy companies do not have enough digital investment, cannot analyze energy consumption information during production, or support transformation requirements such as carbon footprint determination and multi energy source collaborative scheduling, which significantly restricts the green innovation quality of enterprises.

From the management perspective, most energy companies have not yet developed the risk management system, adapting to green transformation characteristics. Most Energy Companies do not realize and evaluate the potential risks, risks at the market, and policy risk during transformation, which cause the transformation decisions to be inaccurate and slow in resource allocation. Some traditional high energy consuming enterprises may even be operating risks as they blind layout transformation projects.

This dilemma has wide range of enterprises, from regions to ownership. Digital green credit and carbon trading platforms in eastern coastal regions are very well-designed, while the total amount of traditional financial resources of resource-based energy firms in central and western regions are extremely low. The problem of unfair allocation of regional green finance resources is prominent [7].

2.3. The logic of the role of digital finance

The supporting role of digital finance in the green transformation of energy enterprises is based on the underlying logic of deep integration of digital technology and financial services. Its core is to

reduce information asymmetry, transaction costs, and entry barriers of financial services through technological means, and provide systematic support for the green innovation activities of energy enterprises. Existing empirical research on A-share listed new energy enterprises shows that the improvement of the breadth and depth of digital finance coverage has a significant positive effect on the number of green patent authorizations and green total factor productivity of enterprises. For every unit increase in the development level of digital finance, the average green innovation output of new energy enterprises increases by 12.3%. This effect is more prominent in small and medium-sized new energy enterprises with light assets and shorter establishment time [8, 9].

From the perspective of regional heterogeneity, in regions with higher levels of digital finance development, the incentive effect of green finance pilot policies on energy enterprise transformation is more significant. Local governments relying on digital finance platforms can achieve precise identification and direct subsidies for green projects, avoiding the problems of "free riding" and resource mismatch in the process of traditional policy implementation. Relevant research has confirmed that after the level of digital finance development exceeds the critical threshold, the rate of regional energy structure optimization increases by about 40% [10].

In the transmission path of this functional logic, the improvement of green total factor productivity plays an important intermediary role. Digital finance, on the one hand, alleviates financing constraints to enhance enterprises' willingness to invest in low-carbon technology research and development, and on the other hand, empowers enterprises to optimize production processes and reduce energy intensity through technological tools, ultimately achieving the dual goals of improving production efficiency and reducing carbon emissions. Compared to traditional financial services, digital finance can adapt to the long-term and high investment characteristics of energy transformation projects. Through mechanisms such as dynamic risk assessment and fund allocation tracing, it reduces the information gap between financial institutions and transformation enterprises, improves the efficiency of financial resource allocation, and provides data support and implementation carriers for the precise implementation of subsequent policy tools.

3. The core mechanism of digital finance empowering energy enterprises for green transformation

3.1. Financing empowerment path

Digital green credit for financing, a first step towards the empowerment of modern financial services, can circumvent the constraints of offline submission and multi-level review, it can fully automate the credit due to multi-dimensional information such as enterprise energy consumption data, ESG performance and project emission reduction benefits, provide service gaps, shorten financing docking times, and adapt to the dynamic funding needs of transformation projects. Experimental work shows that green credit policies can lead funds to switch towards low-carbon projects by resource allocation, which significantly increases the transformation willingness of high energy consumers [6, 11]. While traditional green bonds only indicate the purpose of funds in annual reports, digital green bonds take advantage of blockchain technology to provide real time project emission reductions and fund disbursement data, achieve dynamic traceability through the entire cycle, avoid fund misappropriation and greenwashing, increase direct financing channels for energy investors, and save financing costs for long-term transformation projects, as a result, digital finance can effectively reduce financial mismatches, increase issuance efficiency, and market awareness of green bonds.

For small and medium-sized new energy investors with light assets and no collateral, digital equity financing platforms can use a digital enterprise value evaluation system to index investment targets based on indicators such as the enterprise technology patent reserves, market opportunities and policy support, and provides docking channels for multiple businesses like venture capital, industry and the economy. Through the study of the enterprise level, it is demonstrated that digital finance may reduce financing constraints of new energy firms and increase their innovation investment strength.

The financing empowerment effect exhibits significant nonlinear characteristics. When the level of regional green finance development exceeds a specific threshold, the synergistic empowerment effect of digital financial instruments will show a nonlinear increase. This is because a sound green finance market system can provide supporting policy support, risk mitigation mechanisms, and transaction circulation markets for digital green credit, bond, and equity financing instruments, further amplifying the intermediary role of financing constraint relief, and enabling enterprises to more efficiently convert the financing support they receive into green innovation investment and the landing of transformation projects. This threshold effect is particularly prominent in regions where traditional financial supply is insufficient in the central and western regions. As digital financial infrastructure and supporting policies gradually improve, the financing accessibility of local energy enterprises is significantly higher than that of developed financial regions in the east, verifying the important role of financing empowerment in filling the gaps in traditional financial services.

3.2. Technological empowerment path

The core value of big data technology lies in breaking down the data silos in the production process of energy enterprises. By integrating multidimensional data such as equipment operation, material consumption, and emission monitoring, the energy consumption characteristics of the entire chain are quantitatively analyzed, and high energy consumption production nodes and potential emission reduction spaces are accurately identified. This provides data support for enterprises to develop differentiated carbon reduction transformation plans. Relevant research has confirmed that energy optimization plans based on big data can help traditional energy enterprises reduce energy consumption per unit output value by 15% to 22%, while improving the accuracy of investment in green technology innovation [9, 12]. Blockchain technology achieves full process traceability of green electricity trading and carbon asset circulation through distributed accounting and tamper proof technical features. It can automatically detect funds and emission reduction performance of green projects, avoid "greenwashing" and "greedy", and help enterprises to accurately predict their entire lifetime carbon footprint as data basis for carbon quota trading and carbon emission reduction project declaration. Recently, some domestic carbon trading pilot projects have used this technology to instantaneous transfer of carbon assets and reduce transaction cost by more than 40% compared to traditional systems [13].

Artificial intelligence can only benefit from demand forecasting and resource scheduling. Coupling past energy consumption data, weather patterns, industrial operation trends and other factors, it predicts short, medium, and long term fluctuations in regional electricity demand and optimizes the cooperative scheduling strategy of multiple types, including wind power, photovoltaic power, thermal power, and energy storage, smoothing the intermittency and volatility of new generation and increasing clean energy demand. Experimental results show that after applying AI multi energy cooperative scheduling platform to large-scale wind and solar power bases in Northwest China, average wind and photovoltaic abandonment rate is reduced 6-9% and the clean energy consumption capacity is improved by about 18%. The overall operating efficiency of the

energy system is improved in an inter-facility manner with a common approach. The joint adoption of three types of technologies can help energy enterprises reduce the trial and error costs of technology research and development and operating management during the transformation, provide a reliable basis for financial institutions to assess project emission reduction efficiency and dynamic credit change, further leveraging the empowering effect of digital finance.

4. Optimization strategies for digital finance to assist energy enterprises in green transformation

At the service supply level, it is necessary to develop differentiated layout strategies based on the heterogeneity characteristics of regions and enterprises. Offline digital carbon financial service centers should be established in resource-based prefecture level cities in the central and western regions where traditional financial resources are insufficient. Counties should rely on mini programs and online credit ports to lay out lightweight digital financial outlets and provide green financing services. At the same time, digital financial products that are adapted to the operational characteristics of small and medium-sized energy enterprises should be customized to match their light asset and unsecured financing needs with the long-term funding needs of traditional energy enterprises for emission reduction and transformation [2, 4]. On this basis, people can deepen the integration logic of digital technology and financial products, and rely on the existing ESG linked debt tool design experience to dynamically embed enterprise emission reduction indicators and ESG scores into credit approval and interest rate pricing rules. People can set differentiated credit conditions for traditional energy enterprise energy-saving and carbon reduction transformation projects and new energy enterprise technology research and development projects, appropriately relax the profitability assessment requirements for research and development projects, and guide funds to tilt towards projects with high emission reduction benefits [7].

The optimization of risk management and control system can refer to the decarbonization financing audit experience of multinational enterprises in the energy and technology fields, improve the risk return matching mechanism of digital financial products, dynamically collect multi-dimensional data such as enterprise production and operation, carbon emissions, technology iteration, etc., enhance the accuracy of risk identification, and strengthen the adaptability of digital financial services to the full cycle needs of energy enterprise transformation. At the policy level, it is necessary to further expand the digital financing channels for small and medium-sized energy enterprises, establish a unified digital green bond issuance platform and digital equity financing service port, reduce the entry threshold and issuance cost of direct financing, gradually improve the regulatory framework for digital finance to support green transformation, clarify the information disclosure standards and funding traceability requirements for digital green financial instruments, prevent moral risks such as "greenwashing" and "greenwashing", and build a stable institutional environment for digital finance to empower energy enterprises' green transformation.

5. Conclusion

Existing research has shown that digital finance can have a significant positive effect on the green transformation of energy enterprises through a dual path of financing empowerment and technology empowerment. Diversified tools such as digital green credit, digital green bonds, and digital equity financing can target the transformation capital needs of different types of energy enterprises, effectively alleviating financing constraints under traditional financial services. The integration of digital technologies such as big data, blockchain, and artificial intelligence can improve the accuracy

of enterprise emission reduction node identification, carbon footprint accounting, and energy scheduling, further strengthening the carbon reduction efficiency of operational processes. From a viewpoint of regional differences, areas with advanced digital finance have greater green innovation investments and lower emissions from energy enterprises, showing a close relationship between the promoting role of digital finance and the establishment of regional digital facilities and policy assistance. This also offers a realistic foundation for the spatial adjustment of the subsequent resource distribution.

There is still room for expansion in the current collaborative research on digital finance and energy transformation. In the future, the theoretical framework for the mechanism of their interaction can be further deepened, and the interactive relationship between digital finance development, policy incentives, and corporate behavior can be clarified by combining the analytical paradigm of social technological system transformation. At the same time, targeted research can be conducted on the heterogeneous transformation needs of traditional energy enterprises, new energy enterprises, and small and medium-sized energy enterprises, exploring the adaptability boundaries of different types of digital financial tools, and forming implementable differentiated empowerment strategies. Subsequently, the potential of big language models and privacy computing technologies in carbon data verification and intelligent green credit scenarios can be studied, and empirical evidence related to digital financial risk prevention and control mechanisms can be improved.

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