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Research on Efficiency Evaluation and Path of Green Transformation in Energy-Intensive Industries Under the Dual Carbon Goals

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Abstract

Against the strategic background of peaking carbon dioxide emissions and achieving carbon neutrality, the green transformation of energy-intensive industries serves as a key measure to realize the dual carbon goals. Its transformation efficiency evaluation, influencing factors and transformation paths have become hot topics in academic research. Based on core literature, this paper systematically sorts out the research achievements in three major core directions, namely the efficiency evaluation of green transformation in energy-intensive industries, influencing factors and policy effects, as well as transformation paths. It critically analyzes the deficiencies of existing studies in the evaluation system, factor analysis and path design, identifies research gaps and future research prospects, provides theoretical reference and direction guidance for subsequent studies on the green transformation of energy-intensive industries, and highlights the theoretical and practical value of this research. Adopting the methods of literature review, comparative analysis and induction and deduction, this study ensures the rigor and comprehensiveness of the research. The research results show that existing studies have made certain achievements in the green transformation of energy-intensive industries, but there still exist shortcomings such as insufficient pertinence of evaluation systems, inadequate analysis of influencing factors, and poor operability of path design. By sorting out and analyzing core literature, this paper provides theoretical basis and practical reference for the green transformation of energy-intensive industries under the dual carbon goals.

Keywords

dual carbon goals, energy-intensive industries, green transformation, efficiency evaluation, transformation path

1. Introduction

Against the backdrop of global climate warming, carbon peaking and carbon neutrality have become a common goal for all countries to address climate change and promote sustainable development. China has also incorporated the dual carbon strategy into the overall layout of national development [1]. As major carriers of energy consumption and carbon emissions in China, energy-intensive industries such as iron and steel, chemical engineering, and electric power undertake green and low-carbon transformation. This transformation is not only an inevitable requirement for advancing high-quality industrial development and breaking resource

and environmental constraints, but also a key link to ensure the scheduled advancement of the dual carbon goals [2]. At present, the transformation of China's energy-intensive industries still faces practical dilemmas, including unreasonable energy structure, prominent bottlenecks in low-carbon technologies, and unclear transformation paths. It is urgent to conduct a systematic literature review to comprehensively summarize existing research findings, accurately identify research gaps, and provide solid theoretical support for the practice of industrial transformation [3].

2. Research Objectives

Against the above background, this paper defines the core research objectives as follows:

Research Objective 1: To systematically sort out the research context and theoretical foundation of the green transformation of energy-intensive industries under the dual carbon goals, and clarify the core logic and mechanism of efficient green transformation.

Research Objective 2: To critically analyze the existing efficiency evaluation system for the green transformation of energy-intensive industries, summarize the advantages and limitations of different evaluation methods, and clarify the optimization direction of the evaluation system.

Research Objective 3: To analyze the role and influence of policy instruments in the green transformation of energy-intensive industries, and sort out the practical effects and action paths of different types of policies.

Research Objective 4: To summarize the existing research achievements on the path design of green transformation for energy-intensive industries, identify shortcomings such as insufficient operability and lack of industry adaptability in path design, and put forward prospects for future research.

On this basis, this paper conducts a systematic literature review centering on the above research objectives, sorts out the research status, critically analyzes the existing deficiencies, clarifies future research directions, and lays a solid foundation for in-depth research on the green transformation of energy-intensive industries under the dual carbon goals.

3. Literature Review

3.1 Research Progress and Prospect on Efficiency Evaluation of Green Transformation in Energy-Intensive Industries

The scientific measurement of green transformation efficiency in energy-intensive industries serves as the foundation for relevant research. Existing studies mainly focus on two core aspects: the innovation of evaluation methods and the construction of indicator systems, yielding abundant research achievements. In terms of evaluation methods, early studies mostly adopted the single-index evaluation method, focusing on single dimensions such as energy utilization efficiency and carbon emission intensity, which failed to fully reflect the multi-dimensional value of green transformation. With the deepening of research, the total factor productivity evaluation method has gradually become mainstream. In China's Regional Environmental Efficiency and Environmental Total Factor Productivity Growth, environmental factors were incorporated into the measurement framework of total factor productivity, and an efficiency evaluation model containing undesirable outputs was constructed, providing an important methodological reference for the green efficiency evaluation of energy-intensive industries [4]. Breaking through the limitation of traditional efficiency evaluation that ignores environmental costs, this method can measure the actual effect of industrial green transformation more accurately. However, relevant research mainly focuses on the regional level and lacks pertinence to segmented energy-intensive industries.

In terms of industry-targeted research, Green total factor productivity of China's iron and steel industry under carbon emission constraints constructed a green total factor productivity evaluation model under carbon constraints specifically for the iron and steel industry, clarified the measurement methods and core dimensions of green transformation efficiency in the iron and steel industry, and offered practical references for the efficiency evaluation of individual energy-intensive industries. Nevertheless, this method is difficult to be extend to other energy-intensive industries such as chemical and power sectors, lacking universality [5].

In terms of indicator system construction, most existing studies adopt a two-dimensional framework of "economy-environment". In Environmental Regulation, Green Total Factor Productivity and the Transformation of China's Industrial Development Mode, energy consumption and pollutant emissions were selected as environmental indicators, and industrial added value as economic indicators, establishing an evaluation indicator system for industrial green total factor productivity, which provides a basis for the indicator design of efficiency evaluation in energy-intensive industries [3].

Nevertheless, in light of the requirements of the dual carbon goals, the existing indicator systems still have obvious shortcomings. Most studies fail to fully incorporate core indicators such as low-carbon technology investment and energy structure optimization, making it difficult to adapt to the low-carbon-oriented transformation demands under the dual carbon goals. Meanwhile, the indicator design in some studies is overly general, without differentiated consideration of various energy-intensive industries such as iron and steel and chemical industries. This leads to insufficient pertinence of evaluation results and cannot accurately reflect the actual shortcomings of industrial transformation.

In terms of future research prospects, combined with the deficiencies of existing studies and the requirements of the dual carbon goals, research should focus on two aspects. First, optimize evaluation methods, balance universality and industry pertinence, fully incorporate carbon constraints into the evaluation framework, and improve the measurement method of undesirable outputs. Second, construct a four-dimensional evaluation indicator system covering "economy-environment-technology-energy", add core indicators including low-carbon technology investment and the proportion of renewable energy, and design differentiated indicators according to the characteristics of different energy-intensive industries, so as to enhance the accuracy and adaptability of the evaluation system.

3.2 Influencing Factors and Policy Effects of Green Transformation in Energy-Intensive Industries.

The green transformation of energy-intensive industries is driven by the combined effect of multiple factors. Existing studies have conducted extensive discussions on core influencing factors such as technology, capital, policies and the market, clarified the basic mechanism of each factor, and evaluated relevant policy effects. Nevertheless, there still remain problems, including insufficient in-depth analysis of influencing factors and incomplete evaluation of policy effects. In terms of core influencing factors, technological progress is generally regarded as the core driving force for the green transformation of energy-intensive industries. In Green technology progress and low-carbon development of high-energy-consuming industries, empirical analysis verifies that green technological progress can significantly improve energy utilization efficiency and reduce carbon emission intensity of energy-intensive industries, among which investment in low-carbon technology research and development and the transformation efficiency of technological achievements serve as key supports. However, energy-intensive industries in China are currently faced with insufficient investment in green technology R&D and high external dependence on core technologies, which restrict the exertion of the technology-driven effect [7]. As for policy factors, carbon reduction policies and green transition in energy-intensive industries systematically analyzes the impacts of different carbon emission reduction policies on the green transformation of energy-intensive industries. It finds that command-and-control policies (such as environmental regulation and carbon emission quotas) exert short-term constraint effects and can quickly force enterprises to reduce emissions, while market-incentive policies (such as green finance and tax incentives) generate long-term guiding effects and stimulate the endogenous motivation of enterprises for transformation [8]. Nevertheless, existing policies adopt a one-size-fits-all approach, lack differentiated design for different industries and regions, and are insufficient in policy coordination. In terms of policy effect evaluation, relevant studies point out that as an important policy instrument, environmental regulation can promote the green transformation of energy-intensive industries by forcing enterprises to carry out technological innovation and optimize production modes. However, excessively stringent environmental regulation will increase the transformation cost of enterprises and even inhibit the transformation process, highlighting the importance of grasping the appropriate policy intensity [5]. In the context of China’s reality, the constraint effect of existing carbon emission reduction policies on energy-intensive industries has initially emerged. Yet in the process of policy implementation, issues such as inadequate policy implementation, excessive compliance costs for enterprises, and insufficient transformation motivation of small and medium-sized enterprises have prevented policy effects from being fully released. In addition, existing studies lack long-term follow-up analysis of

policy effects and in-depth discussion on policy optimization directions, making it difficult to provide accurate support for policy improvement. Overall, existing studies have clarified the basic action mechanism of each core factor, but fall short in analyzing the interactive effects among factors and pay insufficient attention to regional and industrial differences. In the evaluation of policy effects, systematic analysis is lacking, which constitutes the key area to be broken through in the subsequent research of this paper.

3.3 A Review of Research on Green Transformation Paths of Energy-Intensive Industries Under the Dual Carbon Background

Against the backdrop of the dual carbon goals, the optimal design of green transformation paths for energy-intensive industries is the key to breaking through transformation dilemmas and improving transformation efficiency. Existing studies have proposed various transformation paths centering on technological innovation, policy guidance, and industrial chain coordination. However, these paths still suffer from insufficient pertinence, poor operability and lack of systematicness, making it difficult to adapt to the actual transformation needs of energy-intensive industries in China.

In the research on transformation paths, the technology-driven path has been widely recognized. Studies indicate that increasing investment in low-carbon technology research and development, promoting the transformation of technological achievements, and introducing advanced low-carbon technologies constitute the core path for energy-intensive industries to realize green transformation. Especially for technology-intensive energy-intensive industries such as iron and steel and chemical industries, technological upgrading can effectively reduce energy consumption and carbon emissions [7].

The collaborative transformation path of industrial chains is also a research hotspot in current literature. Research on the iron and steel industry proposes constructing a circular industrial chain of "upstream raw materials – midstream production – downstream recycling" to realize the resource utilization of waste and cascaded utilization of energy, which can significantly improve the green transformation efficiency of the industry [6]. Nevertheless, the implementation of this path requires inter-enterprise collaboration and imposes high requirements on industrial chain integration capability. At present, the low level of collaborative development of China’s energy-intensive industrial chains restricts the popularization and application of this path.

Targeting the transformation practice of China’s energy-intensive industries, Research on the Green Transformation Path of China's Energy-Intensive Industries puts forward a multi-dimensional collaborative transformation path of "policy guidance + technological innovation + market driving", clarifying the role positioning of the government, enterprises and the market, and providing an important practical reference for the green transformation of China’s energy-intensive industries [9]. Even so, this path still has certain deficiencies. First, it lacks differentiated consideration of segmented energy-intensive industries and fails to design targeted paths combined with the transformation characteristics of iron and steel, chemical, electric power and other industries. Second, the path design is inclined to the macro level, lacking specific implementation procedures and guarantee measures, resulting in poor operability. Third, insufficient attention is paid to the transformation paths of small and medium-sized enterprises. As an important part of energy-intensive industries, small and medium-sized enterprises are faced with dilemmas such as insufficient transformation funds and low technical level, and existing paths can hardly meet their transformation needs.

In addition, some transformation paths in existing studies overemphasize short-term emission reduction effects while ignoring the balance between economic benefits and transformation costs, making it difficult for some paths to be implemented in the long run. Meanwhile, there is inadequate discussion on the integrated path of digitalization, intelligentization and green transformation. The supporting role of digital technology in efficiency improvement and carbon emission control has not been fully exerted, which also constitutes an important research gap in current studies.

4. Core Findings

Combined with the above literature review results and the actual situation of the green transformation of energy-intensive industries under the dual carbon goals, this section summarizes three core findings through

systematically sorting out the key literature, and clarifies the core conclusions and academic value of this research.

4.1 Research on Efficiency Evaluation

The methodological system is well-established, while its adaptability remains to be optimized. Existing studies have formed a sound theoretical and methodological system for the efficiency evaluation of green transformation in energy-intensive industries. Based on Green Total Factor Productivity (GTFP), the core theory incorporates energy consumption and carbon emissions into the evaluation framework as undesirable outputs. Mainstream methods include SBM-DEA, super-efficiency DEA, and the Luenberger productivity index, which can comprehensively measure the level of industrial green development and provide solid methodological support for efficiency assessment. Based on literature review, this paper puts forward the core viewpoint: the key to optimizing the efficiency evaluation system lies in balancing universality and industry pertinence, and deeply integrating the dual carbon goals into the evaluation framework. Existing studies have verified the effectiveness of efficiency evaluation methods, yet distinct differences exist in the applicable scenarios of different models, laying a foundation for the subsequent construction of an evaluation system adapted to segmented energy-intensive industries.

4.2 Research on Influencing Factors and Policy Effects

Core driving factors have been clarified, while their interactive mechanisms remain to be further explored. Existing studies have systematically analyzed the key influencing factors of green transformation in energy-intensive industries from multiple dimensions, including technology, policy, market and industrial structure, forming a clear academic consensus. Technological progress serves as the core driving force for promoting green transformation, and factors such as energy structure optimization, environmental regulation policies and digital transformation all exert significant impacts on transformation efficiency. The effects of different types of policies present heterogeneity: command-and-control policies perform prominently in short-term emission reduction, while market-incentive policies are more conducive to fostering long-term transformation momentum.

On this basis, this paper puts forward the core viewpoint: the green transformation of energy-intensive industries results from the synergistic effect of multiple factors, and the exertion of policy effects is constrained by regional economy, industrial characteristics and other multiple conditions. Existing studies have identified the core influencing factors, providing a theoretical basis for further analyzing multi-factor interaction and optimizing policy portfolios in subsequent research.

4.3 Research on Transformation Paths Diverse

Transformation paths have been formed, yet their practical implementation remains to be improved. Based on efficiency evaluation and influencing factor analysis, existing studies have proposed diversified green transformation paths for energy-intensive industries, mainly including the technology innovation-driven path, the guided path of combined policy instruments, and the industrial chain collaborative upgrading path, which provide abundant theoretical references for industrial transformation in different industries and regions. On this basis, this paper puts forward the core viewpoint: the optimization of transformation paths should focus on differentiation and operability, integrate digital technologies in combination with the characteristics of segmented industries and enterprises, and enhance the practical application value of the paths. The transformation path framework constructed by existing studies offers directional guidance for the subsequent design of implementable and highly adaptable transformation schemes.

5. Discussion

Based on the above core analytical findings, this section conducts a focused discussion on the limitations of existing studies and identifies research gaps as well as future optimization directions. Firstly, in terms of efficiency evaluation, although a mature methodological system has been established in current research, there are prominent deficiencies in adaptability and pertinence. The evaluation model constructed by Wang Bing, Wu Yanrui and Yan Pengfei (2010) is applicable to regional-level research yet lacks targeted design for segmented energy-intensive industries [3]. The model proposed by Chen Y et al. (2020) is only suitable for

the iron and steel industry and lacks universality [6]. The indicator system developed by Zhang Ke and Dou Jianmin (2013) fails to fully take into account the requirements of the dual carbon goals on low-carbon technologies and energy structure, leading to evaluation results that cannot comprehensively reflect the green transformation level of energy-intensive industries [5]. Therefore, the key to optimizing the efficiency evaluation system lies in balancing universality and industry pertinence, and deeply integrating the dual carbon goals into the evaluation framework.

Secondly, regarding influencing factors and policy effects, existing studies have clarified core influencing factors such as technological progress and environmental regulation, but remain insufficient in analytical depth and comprehensiveness. Wang Z et al. (2021) only focused on the impact of green technological progress without analyzing the interactive relationship between technological progress and other factors, including policy support and market environment [7]. Zhang Q et al. (2022) explored the impacts of different types of policies but lacked systematic analysis of policy coordination and regional heterogeneity [8]. In practice, the green transformation of energy-intensive industries is driven by the combined effect of multiple factors, and policy effects are also affected by regional economic development level and industrial characteristics. The analytical depth of existing studies is inadequate to meet the practical demands of policy optimization. It is necessary to further analyze the interaction among various factors as well as the regional and industrial differences of policy effects, so as to provide more targeted support for policy optimization.

Finally, in terms of transformation paths, the existing paths proposed by scholars such as Wang Z et al. (2021), Lin Boqiang and Tan Ruipeng (2022) possess certain guiding significance but suffer from inadequate pertinence and poor operability. The technology-driven path put forward by Wang Z et al. (2021) fails to consider the differences in technological foundation and transformation capacity among enterprises. The multi-dimensional collaborative path proposed by Lin Boqiang and Tan Ruipeng (2022) is overly macro and lacks specific implementation measures, making it difficult for practical application [9]. In addition, existing paths do not fully incorporate the integration of digitalization and green transformation, which is inconsistent with the development trend of industrial upgrading. Accordingly, the optimization of transformation paths should focus on differentiation and operability, incorporate digital technologies in light of the characteristics of different segmented industries and enterprises, and enhance the practicality of such paths.

In summary, existing studies have laid a solid theoretical foundation for the green transformation of energy-intensive industries, yet obvious research gaps still exist in efficiency evaluation, influencing factors and transformation paths. By systematically sorting out core literature and summarizing key analytical findings, this paper clarifies the strengths and deficiencies of current research, and provides theoretical basis and practical reference for subsequent research and practical advancement of the green transformation of energy-intensive industries under the dual carbon goals.

6. Conclusion

In conclusion, existing research on the green transformation of energy-intensive industries has achieved phased results in three core fields: efficiency evaluation, influencing factors and policy effects, and transformation paths. In terms of efficiency evaluation, a variety of methods and indicator systems have been formed. However, there still exist problems such as insufficient pertinence, poor adaptability to the dual carbon goals, and a lack of balance between universality and industry specificity. Evaluation methods and indicator systems need to be further optimized to adapt to the actual demands of industrial transformation. In terms of influencing factors, studies have clarified the combined effect and basic mechanism of multiple factors including technological progress, environmental regulation and market environment on green transformation. Nevertheless, the analysis of interactive relationships among various factors is not in-depth enough, and insufficient attention has been paid to the regional and industrial differences of policy effects, resulting in limited targeted guidance of research findings for practical application. Although certain instructive schemes have been proposed regarding transformation paths, they are hampered by deficiencies including inadequate pertinence, weak operability, and failure to integrate digital technologies. Such paths can hardly meet the differentiated needs of various segmented industries and enterprises, and it is necessary to design differentiated and operable transformation paths in combination with practical conditions.

Through literature review and analytical discussion, this paper identifies research gaps and optimization directions, enriches the theoretical research on the green transformation of energy-intensive industries under

the dual carbon goals, and provides practical references for the government to formulate differentiated policies and for enterprises to carry out green transformation. Future research can further expand the scope of literature and conduct empirical studies to verify the rationality of evaluation systems and transformation paths, so as to better promote the green transformation of energy-intensive industries and facilitate the smooth achievement of the dual carbon goals.

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Conflicts of Interest

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