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Economic effects of the transformation and upgrading of energy-intensive industries in the context of carbon neutrality

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Abstract. Against the backdrop of global carbon neutrality governance and China's continued implementation of its carbon peaking and carbon neutrality strategy, energy-intensive industries, including iron and steel, chemicals, building materials, and non-ferrous metals, are major sources of industrial carbon emissions. Their transformation and upgrading are closely linked to the achievement of emission reduction targets and have significant economic implications for macroeconomic performance, industrial restructuring, and the economic efficiency of individual enterprises. Based on industrial economics and green growth theory, this study reviews the current state of transformation in China's energy-intensive industries and analyzes the series of positive and negative economic effects arising from their transformation and upgrading. It identifies three transmission mechanisms: technological innovation, factor allocation, and industrial restructuring—and examines practical challenges emerging during the transformation process, including cost pressures, technological constraints, and imbalanced regional development. The findings show that, driven by carbon neutrality goals, the transformation of energy-intensive industries can improve green total factor productivity, enhance their position in the industrial value chain, and foster new green business models. In the short term, however, it may also lead to higher transformation costs for enterprises, a decline in some traditional jobs, and economic adjustment pressures in certain regions. Accordingly, this study proposes optimization strategies from four perspectives: differentiated industrial policies, green finance, the development of a technological innovation system, and coordinated regional development. The aim is to reconcile carbon reduction constraints with high-quality economic growth and provide theoretical guidance and practical approaches for the smooth transition of energy-intensive industries.

Keywords: carbon neutrality, energy-intensive industries, industrial transformation and upgrading, economic effects, green total factor productivity

1. Introduction

Global warming has become a common externality problem confronting humanity, and carbon neutrality has gradually emerged as a shared goal of economic transformation among the world's major economies. Following China's announcement of its goals for carbon peaking and carbon neutrality, carbon reduction in the industrial sector has become a key area for implementing these strategic objectives. Given their large energy consumption base and high share of carbon emissions, energy-intensive industries have naturally become a major focus of the transformation process. Industries such as iron and steel, electrolytic aluminum, cement, and petrochemicals and chemicals provide essential support for China's industrialization and the development of the real economy and constitute indispensable foundations of the national economy. However, these industries are highly dependent on fossil fuels, and their existing production facilities are subject to strong carbon lock-in effects. Consequently, achieving deep decarbonization within a short period will inevitably involve complex economic trade-offs.

In recent years, domestic research has focused primarily on emission reduction technologies and environmental benefit assessments in energy-intensive industries, while providing insufficiently balanced analysis of the economic effects arising during the transformation process. On the one hand, some studies argue that stringent carbon constraints may reduce the output of traditional industries and increase the operating costs of the real economy, thereby affecting local industrial output. On the other hand, green growth theory suggests that environmental regulation can encourage enterprises to engage in technological innovation and enhance their long-term industrial competitiveness through the innovation compensation effect, thereby facilitating the shift from traditional to new growth drivers. In actual economic operations, the transformation brought about by carbon neutrality is neither an unequivocal benefit nor a purely negative shock. Rather, it is a process in which short-term adjustment pains coexist with long-term gains.

Against this backdrop, this study takes the transformation and upgrading of energy-intensive industries in the context of carbon neutrality as its research subject. It examines the economic impacts of such transformation at the macroeconomic, industrial, and micro-enterprise levels, analyzes the practical challenges involved, and proposes policy recommendations suited to China's national conditions. This study can not only enrich the empirical understanding of the relationship between environmental regulation and industrial upgrading but also provide a reference for the government in formulating differentiated industrial carbon reduction policies, thereby contributing to the coordinated advancement of environmental protection and economic development.

2. Conceptual definitions and theoretical foundations of the transformation and upgrading of energy-intensive industries and their economic effects in the context of carbon neutrality

2.1. Definition of core concepts: energy-intensive industries, transformation and upgrading, and economic effects of transformation

According to China's national statistical classification standards, energy-intensive industries are divided into six major categories: ferrous metal smelting, non-ferrous metal smelting, non-metallic mineral products, petroleum and chemical industries, chemical raw material manufacturing, and electricity and heat production and supply. These industries are characterized by high total energy consumption, high carbon emission intensity, large-scale capital investment, and pronounced capital-intensive features, making them the primary targets of industrial carbon reduction in China [1].

The transformation and upgrading of energy-intensive industries refers to a systematic and comprehensive restructuring of these industries in the context of carbon neutrality. It is not simply a matter of shutting down outdated production capacity, but rather a multidimensional and systemic transformation. Its scope includes adjusting production capacity structures, implementing low-carbon upgrades to production processes, shifting the energy consumption structure from fossil fuels toward green electricity and green hydrogen, extending industrial value chains through digitalization and intelligent transformation, and developing circular economy models. The ultimate goal is to transform these industries from extensive production characterized by high energy consumption and high emissions into modern production characterized by low carbon emissions and high efficiency.

The economic effects examined in this study refer to the various positive and negative economic impacts generated by the transformation of energy-intensive industries. At the macro level, these effects include the quality of economic growth and factor allocation efficiency; at the industrial level, they include changes in industrial structure and the position of industries within value chains and industrial chains; and at the micro level, they include enterprise profitability, R&D investment, and employment structure.

2.2. Theoretical foundations for analyzing the economic effects of the transformation of energy-intensive industries

The first is Porter's Hypothesis. Porter argues that appropriate and stringent environmental regulation does not necessarily undermine corporate competitiveness. When environmental policies create external pressure, enterprises are encouraged to undertake technological R&D and generate innovation compensation effects, which can offset the costs of compliance and transformation and thereby improve production efficiency and market competitiveness. However, the Porter effect is subject to certain preconditions and is influenced by factors such as firms' R&D capabilities, external financing conditions, and the appropriateness of policy design. In the short term, enterprises may have to bear relatively high investment costs associated with transformation [2].

The second is the theory of Green Total Factor Productivity (GTFP). Traditional total factor productivity focuses primarily on the efficiency of capital and labor in generating output, whereas green total factor productivity incorporates carbon emissions, pollutant emissions, and other undesirable outputs into the accounting framework. It is therefore used to measure the quality of economic development in terms of the coordination between economic output and environmental constraints. The fundamental purpose of transforming and upgrading energy-intensive industries is to improve green total factor productivity, thereby increasing the value of economic output while controlling carbon emissions.

The third is industrial structure optimization theory. Industrial structural upgrading refers to the reallocation of production factors from inefficient sectors to more efficient ones. Under the constraints imposed by carbon neutrality, factor price signals also change. Production factors such as capital and labor are gradually reallocated from outdated, high-carbon production capacity toward emerging fields such as low-carbon transformation, green new materials, and resource recycling, thereby driving structural renewal throughout the industrial system.

3. Current status of the transformation and upgrading of China's energy-intensive industries in the context of carbon neutrality

After years of policy guidance, China has made considerable progress in transforming its energy-intensive industries. The government has successively introduced a range of policy instruments, including dual control over total energy consumption and energy intensity, the national carbon emissions trading market, and initiatives to accelerate energy conservation and carbon reduction in key industries. These policies have promoted the phase-out of outdated production processes and equipment in sectors such as iron and steel, cement, and electrolytic aluminum, while continuously advancing energy-efficiency benchmarking and upgrading programs. The proportion of enterprises achieving benchmark energy efficiency has increased year by year. As the carbon market continues to operate, carbon allowance trading generates carbon price signals that alter the production costs of energy-intensive enterprises, thereby encouraging them to increase investment in energy conservation and carbon reduction.

From the perspective of the energy mix, some energy-intensive enterprises have begun to adopt measures such as direct access to green electricity, waste heat recovery, and the recycling of solid waste. Low-carbon technologies, including hydrogen metallurgy, Carbon Capture, Utilization and Storage (CCUS), and electric arc furnace-based short-process steelmaking, have also entered pilot and demonstration stages. Nevertheless, the transformation of these industries remains subject to numerous practical constraints. First, the existing stock of capital-intensive assets is substantial, and most production equipment has not yet reached the end of its depreciation period. A mandatory and rapid phase-out of such assets could therefore create significant risks of stranded assets. Second, the maturity of low-carbon technologies varies considerably. Some disruptive low-carbon technologies remain at the demonstration stage, and their costs are still too high for large-scale commercial deployment. Third, significant regional disparities exist. Resource-dependent provinces in central and western China rely heavily on energy-intensive industries as pillars of their local economies, with fiscal revenues and employment closely tied to traditional industries, placing them under greater pressure during the transition. By contrast, eastern coastal regions generally have stronger technological R&D capabilities and better access to green finance, allowing them to advance the transition more rapidly. In addition, small and medium-sized energy-intensive enterprises commonly face financing constraints. The substantial upfront investment and long payback periods associated with low-carbon retrofitting weaken their incentives to undertake upgrading and transformation independently [3].

4. The dual economic effects and transmission mechanisms of the transformation and upgrading of energy-intensive industries

Carbon neutrality has driven energy-intensive industries to undergo transformation and upgrading, generating both positive returns and short-term adverse effects. These effects operate at three levels—macroeconomic, industrial, and micro-enterprise—and are transmitted through three principal channels: technological innovation, factor reallocation, and industrial restructuring.

4.1. Positive economic effects

First, the incentive effect on technological innovation. The emission reduction pressures generated by carbon neutrality encourage enterprises to increase R&D investment, improve existing production processes, and introduce low-carbon equipment. Continuous technological innovation subsequently raises the overall technological level of the industry, while the number of green patents continues to grow. Technological upgrading also generates learning-curve effects, gradually reducing the production costs of low-carbon equipment and expanding the diffusion of advanced technologies. As a result, overall industrial production efficiency improves, accompanied by increases in green total factor productivity. Some enterprises have undertaken technological upgrading and developed low-carbon new materials and products, enabling them to secure important positions in domestic and international green markets and move toward the higher end of the value chain. With the implementation of global carbon border adjustment mechanisms, domestic energy-intensive enterprises that complete low-carbon transformation can reduce the burden of carbon-related tariffs on their exports and thereby maintain their competitive position in international trade [4].

Second, the effect of industrial structure optimization and the cultivation of new business models. Transformation and upgrading facilitate the orderly withdrawal of outdated production capacity, reduce inefficient supply, and alleviate persistent overcapacity in some industries. At the same time, they stimulate the development of green supporting industries along upstream and downstream value chains. Emerging markets for low-carbon equipment manufacturing, carbon-related consulting services, solid waste resource utilization, and energy storage systems are gaining new development opportunities, creating a range of new employment opportunities. Resources within industries are increasingly concentrated in leading enterprises characterized by high efficiency and low carbon emissions, resulting in a rational increase in industry concentration and creating favorable conditions for large-scale green investment.

Third, the long-term improvement in the quality of macroeconomic growth. The decarbonization and transformation of energy-intensive industries can help reduce public expenditures on environmental governance and mitigate economic losses caused by extreme weather events. Green transformation creates new sources of growth through green investment, guides social capital toward the low-carbon real economy, and helps the economy move away from carbon-intensive path dependence. It also supports the development of new quality productive forces, facilitating a shift in the model of economic development from extensive growth toward high-quality development.

4.2. Short-term negative economic effects

First, pressure from rising operating costs. Enterprises must make substantial capital expenditures on equipment replacement, process upgrades, and the purchase of carbon emission allowances. Small and medium-sized enterprises, in particular, face considerable pressure from large upfront investments, which can squeeze their profit margins during the initial stage of transformation. If carbon constraints are imposed too aggressively in the short term, enterprises with relatively weak financial and operational capabilities may face serious survival pressures.

Second, short-term adjustment pains for local economies and employment. In resource-dependent cities where iron and steel and chemical industries constitute major economic pillars, energy-intensive industries provide substantial support for local GDP, tax revenues, and employment. Capacity adjustments and business contraction may therefore lead to slower growth in local industrial output and a reduction in jobs in traditional industries. Although emerging green industries can create new employment opportunities, there is often a skills mismatch between new and existing jobs. Workers from traditional industries may find it difficult to transition directly into green jobs, thereby increasing the risk of structural unemployment.

Third, the risk of factor misallocation during the transformation process. If policies are implemented indiscriminately through a "one-size-fits-all" approach, requiring enterprises to suspend or reduce production regardless of their technological capabilities, high-quality production factors may be unnecessarily wasted, undermining the stability of industrial and supply chains. In some regions, excessive emphasis on project scale rather than actual effectiveness has also resulted in the indiscriminate launch of low-carbon demonstration projects, leading to inefficient investment.

4.3. Analysis of the transmission mechanisms

The transmission mechanism of technological innovation can be summarized as follows: Carbon constraints → greater pressure on enterprises to reduce emissions → increased corporate R&D investment → process innovation and efficiency improvements → enhanced corporate competitiveness.

The transmission mechanism of factor allocation operates through changes in the relative costs of production factors caused by carbon prices and environmental policies: Carbon prices and environmental policies alter the relative costs of production factors → capital and labor flow out of outdated production capacity → capital and labor flow toward enterprises undertaking low-carbon transformation and emerging green industries → improved allocation of industrial resources.

The transmission mechanism of industrial restructuring can be described as: Exit of outdated production capacity and commercialization of low-carbon technologies → restructuring of the industrial supply structure and emergence of new green business models → transformation of the macroeconomic structure.

5. Practical challenges constraining the full realization of the positive economic effects of the transformation of energy-intensive industries

5.1. The cost-sharing mechanism for transformation remains inadequate

Low-carbon transformation projects in energy-intensive industries typically require substantial upfront investment and have long payback periods. Large enterprises generally have strong financial capacity, whereas many small and medium-sized energy-intensive enterprises face severe financing constraints. Although the scale of green credit and green bonds continues to expand, a large proportion of these financial resources flows to large state-owned enterprises, making it difficult for small and medium-sized private enterprises to obtain low-cost green financing. When transformation costs are borne disproportionately by enterprises themselves, their incentives to undertake upgrading initiatives are weakened. Financial institutions, motivated by risk-control considerations, generally apply relatively stringent risk assessment criteria to low-carbon projects undertaken by small and medium-sized enterprises. Some transformation projects are unable to secure loans because they lack sufficient collateral. Meanwhile, government special-purpose subsidies have limited coverage and relatively high eligibility thresholds, leaving most small and medium-sized enterprises unable to obtain adequate fiscal support. Opportunities for private capital to participate in transformation projects also remain limited, while market-oriented cost-sharing mechanisms based on risk sharing have yet to become widespread. These factors further increase the financial burden on enterprises [5].

5.2. Shortcomings in the supply of core low-carbon technologies

Some key low-carbon technologies remain at the demonstration-project stage and have yet to achieve large-scale commercial application. Technologies such as Carbon Capture, Utilization and Storage (CCUS) and green hydrogen metallurgy remain relatively costly, while industry–university–research collaboration in translating technological achievements into practical applications is still inadequate. Technological diffusion within industries is also uneven. Leading enterprises generally possess stronger R&D capabilities, whereas small and medium-sized enterprises have limited access to advanced low-carbon processes, resulting in widening technological disparities within the industry. Technological achievements produced by research institutions are often based primarily on laboratory research and lack sufficient applicability to industrial production environments. Considerable engineering challenges remain in transferring technologies from prototype testing to industrial-scale production. At the same time, there is a substantial shortage of interdisciplinary professionals with expertise in low-carbon technologies. The supply of personnel capable of both operating industrial processes and applying low-carbon technologies remains insufficient. Furthermore, intellectual property protection in the low-carbon technology sector is not yet fully developed, which to some extent discourages enterprises from sharing technologies and promoting technological spillovers, thereby prolonging the process of disseminating and applying advanced low-carbon technologies across industries.

5.3. Insufficient implementation of regionally differentiated policies

China's regions differ substantially in terms of resource endowments and industrial foundations. Eastern regions generally have stronger industrial bases and greater fiscal capacity, whereas many cities in central and western China rely heavily on energy-intensive pillar industries for economic development. During policy implementation, however, some regions lack sufficiently tailored policy design. Uniform emission reduction requirements can therefore place excessive transformation pressure on resource-dependent regions, making it more difficult to balance carbon reduction objectives with local economic stability. In some cases, local governments have directly adopted carbon reduction schemes developed for more economically advanced regions in order to meet assessment targets, without adequately considering local conditions such as industrial structure and fiscal capacity. As a result, differentiated and phased implementation plans have not been effectively developed. Mechanisms for coordinating cross-regional interests have also developed relatively slowly. Regions from which energy-intensive industries relocate may experience tax revenue losses and declining employment, while regions receiving these industries must cope with additional carbon emissions. Effective channels for compensating the interests of the respective regions have yet to be established. Moreover, the cultivation of alternative industries in resource-dependent regions generally requires a relatively long period. Before new sources of economic growth have emerged, excessively rapid contraction of traditional industries may further increase pressure on local fiscal operations.

5.4. Market-supporting mechanisms remain to be improved

China's national carbon emissions trading market is still undergoing development and improvement. Considerable fluctuations in carbon prices make it difficult to establish stable long-term expectations regarding market prices. Meanwhile, incentives provided by green product certification systems and low-carbon product markets remain insufficient. Enterprises that incur additional costs to produce low-carbon products often find it difficult to obtain corresponding price premiums in consumer markets, which to some extent weakens the economic returns associated with transformation. Carbon trading products remain relatively limited, while carbon finance derivatives have developed slowly, leaving enterprises with insufficient tools to hedge against the operational risks arising from carbon price fluctuations. The range of low-carbon product certifications is also relatively narrow, and certification standards vary across institutions, making it difficult for the market to accurately distinguish low-carbon industrial products. In addition, downstream industrial customers have not yet widely incorporated low-carbon indicators into their procurement evaluation systems, resulting in relatively weak market demand for low-carbon products [6]. Consequently, enterprises often cannot recover the substantial costs of low-carbon transformation through product sales, preventing the endogenous incentives of the market from being fully activated.

6. Policy recommendations for unlocking the positive economic effects of transformation and upgrading

6.1. Develop differentiated and sector-specific industrial policies to avoid a one-size-fits-all approach

Transformation timetables should be formulated by industry and implemented in stages, taking into account the technological characteristics of sectors such as iron and steel, chemicals, and non-ferrous metals. Carbon reduction should not be pursued through campaign-style approaches. Enterprises should be differentiated according to their energy-efficiency levels: policy incentives should be provided to enterprises that achieve energy-efficiency benchmarks, while inefficient and outdated production capacity should be guided toward an orderly exit. The actual conditions of resource-dependent regions should also be fully considered, and cross-regional compensation mechanisms should be established. Fiscal transfers should be provided to regions with a high proportion of energy-intensive industries to mitigate the local economic shocks caused by transformation and safeguard the stability of industrial and supply chains.

6.2. Improve the green finance system and reasonably share the costs of transformation

Diversified green financing channels should be expanded to encourage a greater flow of green credit toward small and medium-sized energy-intensive enterprises, while special interest subsidies should be established for low-carbon transformation projects in energy-intensive industries. Innovation in green bonds and green insurance products for transformation projects should be supported to provide risk protection for low-carbon initiatives. The price-regulating function of the carbon market should be utilized appropriately, and the allocation mechanism for carbon allowances should be improved to establish stable and predictable carbon price signals. Market-based mechanisms should be used to guide enterprises' investment in emission reduction and reduce the economic shocks caused by excessive reliance on mandatory administrative measures [7].

6.3. Strengthen low-carbon technological innovation and industrial diffusion systems

Investment in the R&D of common low-carbon technologies should be increased, with industry–university–research institutions encouraged to conduct joint research to reduce the application costs of frontier technologies such as hydrogen metallurgy and CCUS. Public technology service platforms should be established to facilitate the dissemination of mature energy-saving and transformation technologies to small and medium-sized enterprises and narrow technological gaps between enterprises. Support for low-carbon technology demonstration projects should also be strengthened, and the replication and wider application of successful demonstration-project experience should be encouraged. Technological progress can thereby reduce the economic burden associated with transformation and amplify the innovation compensation effect.

6.4. Cultivate low-carbon product markets and improve supporting social security mechanisms

Green and low-carbon product labeling and certification systems should be improved, and government procurement should give greater preference to low-carbon industrial products. This would help create a market premium for low-carbon products and enable enterprises to obtain market returns on their transformation investments. Skills training should be provided to facilitate the transition of workers from traditional industries to new positions and address structural employment problems. The withdrawal of traditional industries and the development of emerging industries should be coordinated. Drawing on the existing industrial foundations of resource-dependent cities, efforts should be made to develop circular economy industries and green new materials, helping these cities cultivate alternative industries and achieve a smooth transition [8].

7. Conclusion

The carbon neutrality strategy is driving a profound industrial transformation in China's energy-intensive industries, and the resulting economic effects are dual in nature. In the long term, transformation can promote technological innovation, improve the allocation of industrial resources, foster new green industries, and enhance the quality of economic development, thereby contributing to the development of new quality productive forces. In the short term, however, unavoidable challenges remain, including higher enterprise transformation costs, disruptions to local economies, and changes in the employment structure.

At present, several factors constrain the full realization of the positive economic effects of transformation, including difficulties in sharing transformation costs, shortages in the supply of core technologies, insufficient coordination among regional policies, and weak links between production and market demand. To balance carbon neutrality objectives with stable economic growth, policymakers should not rely solely on mandatory constraints. Instead, differentiated policies should be adopted, with multiple instruments—including industrial policies, green finance, technological R&D, and market development—used in combination. The short-term adjustment costs of transformation should be appropriately shared, while the growth dividends generated by innovation compensation should be fully unlocked. In this way, energy-intensive industries can achieve a smooth transition toward low-carbon development and realize coordinated improvements in environmental and economic performance. The transformation and upgrading of energy-intensive industries is a long-term and systematic undertaking. As carbon market mechanisms continue to improve and low-carbon technologies undergo further development and replacement, future research can employ panel data from a broader range of subsectors to conduct empirical and econometric analyses and quantitatively evaluate the economic effects of different policy instruments, thereby providing more detailed empirical evidence for policy refinement.

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