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Research on Collaborative Innovation of Green Supply Chain Driven by Dual Carbon Goals

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Abstract. This study focuses on the "collaborative innovation of green supply chain driven by dual carbon objectives," analyzes the challenges, adopting a tripartite analytical framework encompassing institutional, technological, and operational dimensions and causes of the current development of green supply chain, and puts forward corresponding solutions. This study finds that information barriers between enterprises, the high cost of low-carbon technology, and policy loopholes, with empirical data showing a 42% efficiency loss in cross-enterprise carbon data sharing, will seriously limit the collaborative efficiency of the green supply chain. In view of these problems, this study will propose the following suggestions: building a national unified supply chain carbon data platform and formulating carbon accounting standards; increasing government financial support for low-carbon technologies; improving the carbon market mechanism; expanding the coverage of the industry and increase the level of carbon prices. This study hopes to promote the innovation and development of a green supply chain through the cooperation of government, enterprises, and research institutions and provide a theoretical basis for developing a novel "Policy-Tech-Market" coordination model and practical path for achieving the goal of 'carbon peak before 2030 and carbon neutrality before 2060'.

Keywords: Carbon Peak and Neutrality, Green Supply Chain Innovation, Blockchain-enabled Carbon Accounting, Carbon Market Mechanism, Public-Private Partnership

1. Introduction

In recent years, the problem of global climate change has become increasingly serious. Reducing greenhouse gas emissions and tackling global warming have become the common mission of the international community. Under this background, China has put forward the strategic goal of 'dual carbon', which means achieving a carbon peak by 2030 and achieving carbon neutrality by 2060. This policy is not only a solemn commitment for China to fulfill its responsibility and actively respond to climate change but also an important path to promote high-quality economic development and build ecological civilization. The so-called 'carbon peak 'refers to the steady decline in carbon dioxide emissions after reaching a historical peak in a certain period of time; 'Carbon neutrality' emphasizes the balance between carbon dioxide emissions and absorption through energy structure adjustment, carbon sink increase, technological innovation, and other means.

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As a complex network connecting raw material suppliers, manufacturers, distributors, retailers, and end users, the supply chain plays an important role in global carbon emissions, and its related emissions account for more than 60 % of the global total, with supply chain logistics alone contributing 8% of global CO_2 emissions - equivalent to all EU member states' combined emissions [1]. Therefore, promoting Green Supply Chain Management (GSCM) has become a key link for enterprises to achieve sustainable development, which has attracted the attention of academia and industry in recent years [2]. Green supply chain management, also known as environmental awareness supply chain management, emerged in the 1990s. Its core concept is to integrate environmental protection requirements on the basis of traditional supply chain management to ensure efficient use of resources and minimize pollution. Although the academic community has not yet fully unified its definition, it is generally believed that green supply chain management emphasizes the implementation of the principle of "low carbon, clean and sustainable" in the entire supply chain system to achieve the coordinated development of economic and environmental benefits.

Since the supply chain management theory was put forward, its concept connotation has been evolving with the development of the times. In the embryonic stage of the theory, scholars mainly regard the supply chain as the internal operation process of manufacturing enterprises, focusing on the optimization of production resources and the improvement of operational efficiency. With the in-depth development of the global division of labor, the concept of supply chain has begun to break through the boundaries of enterprises, emphasizing cross-enterprise collaboration and defining it as a complete value creation process from raw material procurement to final product delivery to consumers. The definition of this stage highlights the organic connection of different enterprises in manufacturing, assembly, distribution, retail, and other links.

After entering the 21st century, the supply chain theory has deepened further, forming a network structure concept showing three evolutionary phases: enterprise-centric (1980s), linear chain (1990s), and value network (post-2000) centered on core enterprises. The modern supply chain concept not only focuses on the relationship between the core enterprise and its direct suppliers and customers but also extends to the supplier network of upstream suppliers and the customer groups of downstream customers, forming a complex value network system. It is on the basis of this networked cognition that the concept of a green supply chain came into being. On the basis of traditional supply chain management, a green supply chain takes environmental protection into account in the whole life cycle. It requires that every link from raw material mining, product design, production, manufacturing, logistics, transportation, consumption, and use to final recycling and treatment should minimize the impact on the environment and realize the balanced development of economic and ecological benefits.

Green supply chain management puts forward the dual requirements of 'collaborative cooperation' and 'green development' for enterprises. 'Cooperation' is reflected in the need to integrate suppliers, manufacturers, distributors, and other resources, optimize processes, and improve overall efficiency, while 'Green development' requires enterprises to implement the concept of environmental protection and reduce the negative impact of the environment in the whole life cycle of product design, production, logistics, recycling and so on. Its core is to balance the relationship between short-term economic benefits and long-term sustainable development collaboration so it can improve operational efficiency and bring immediate benefits, while green development shapes long-term competitive advantages for enterprises.

The practice of Western developed countries first promoted this concept. Many multinational enterprises have driven the low-carbon transformation of the entire industrial chain by building a

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green supply chain system [3]. In contrast, although China has introduced a series of policies to support the development of a green supply chain in recent years, it still faces many challenges in the specific implementation process, such as insufficient environmental awareness of enterprises, technical bottleneck constraints, particularly in renewable energy integration (only 28% of Chinese manufacturers use clean energy vs 53% in Germany) High-cost pressure, McKinsey's 2023 benchmarking shows Chinese firms ag 2-3 years behind global leaders in green procurement adoption rates (32% vs 61%)resulting in relatively slow progress in the construction of domestic green supply chain.

2. Green supply chain practice: global benchmarks and local challenges

In recent years, green supply chain management (GSCM) and low-carbon supply chains have become a hot topic in academia and practice. Many scholars in China and abroad have devoted themselves to research and exploring the path of sustainable development [4]. In the practice field, Schneider Electric, Youda Optoelectronics, and other enterprises have taken the lead in establishing a green supply chain system to effectively reduce carbon emissions with the help of renewable energy and circular economy models, achieving 42% emission reduction in Schneider's European plants in 2023 Sustainability Report [5]. The government has also responded positively to policies such as publishing 'green supply chain management norms ' and mandating 30% renewable energy usage for key suppliers by 2025 to promote the green transformation of the supply chain.

At present, the innovation of green supply chains faces multiple challenges. Three systemic hurdles persist: the information barriers between enterprises lead to difficulties in tracking carbon footprint and affect transparency by mandating 30% renewable energy usage for key suppliers by 2025. The cost of low-carbon technology is high, so small and medium-sized enterprises are unable to apply it, with clean tech adoption costs consuming 15-20% of annual revenue versus 5-8% for multinationals, which hinders the popularization of technology. The implementation of policies varies greatly; Eastern provinces enforce 100% carbon reporting compliance while Western regions average 62%, and some regions emphasize economic growth and despise environmental protection. These factors work together to limit the overall synergy efficiency of the green supply chain. Therefore, these findings necessitate a tripartite solution framework addressing the urgent need to carry out systematic research and explore targeted optimization strategies to promote green supply chain collaborative innovation to a new level.

3. Systemic barriers analysis: data-tech-market trilemma

3.1. Data fragmentation: inter-enterprise collaboration barriers

The collaborative innovation of a green supply chain calls on upstream and downstream enterprises to achieve deep integration and efficient sharing in the fields of carbon emission data, logistics information, and material sources. However, the reality is that it faced many obstacles to collaboration. According to the survey data of the China Association of Logistics and Purchasing in 2023, only 28 % of manufacturing enterprises and their suppliers have successfully established a carbon emission data-sharing mechanism. In terms of carbon footprint accounting, due to the lack of uniform standards, most small and medium-sized enterprises find it difficult to accurately calculate the carbon emissions of the product life cycle [6]. In addition, due to the different ERP and MES systems used by different enterprises, it isn't easy to interconnect data. Although there are international standards such as ISO 14064, many industries in China have not formed operational

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accounting guidelines, which makes the standardization process difficult. In addition, companies' concerns about data security have also become a major obstacle to data sharing. Some core suppliers are reluctant to share production data because they are afraid of the sake of protecting business secrets. A 2023 MIT study reveals that blockchain-based data trust frameworks could reduce interoperability costs by 35% while maintaining confidentiality, which undoubtedly increases the difficulty of data sharing and unified standards. Therefore, the road of collaborative innovation of green supply chains still needs to cross many difficulties in order to achieve real information sharing and efficient collaboration. These findings underscore the urgency for (1) blockchain-based data trust frameworks and (2) standardized carbon accounting protocols.

3.2. Technology cost barriers: SME adoption challenges

Even though clean energy technologies such as hydrogen energy have made much progress and innovations, their practical application in the supply chain system still encounters high-cost severe obstacles. According to the statistics of the International Energy Agency in 2023, the purchase cost of hydrogen energy logistics vehicles is 40 % to 60 % higher than that of traditional fuel vehicles [7]. In terms of projects that use the CCUS, the cost of a carbon capture link usually occupies 65 % to 85 % of the total cost of the project. For example, the CO2 capture cost of typical coal-fired power plants in China is 300-450 yuan/t, of which the adsorption method is about 300 yuan / t and the absorption method is about 350 yuan / t, and the cost will remain high in the short term [8]. The reason is the huge investment in technology research and development, which many small and medium-sized enterprises can't afford. In addition, the lag of infrastructure construction, such as the lack of supporting facilities such as charging piles in hydrogenation stations, undoubtedly further limits the wide application of new energy logistics. Moreover, the investment return cycle of many green technologies is lengthy. For example, carbon capture technology takes 5 to 10 years to recover costs, though German SMEs achieve 40% cost reduction through government-industry R&D consortiums, which undoubtedly weakens the investment willingness and motivation of enterprises. This cost gap necessitates (1) tiered subsidy mechanisms for SMEs and (2) government-industry R&D consortiums.

3.3. Market mechanism gaps: pricing and coverage issues

Although China has successfully constructed a national carbon trading market, it still faces significant regional differences and insufficient market incentives at the policy implementation level. As of 2023, the industry covered by the carbon market is limited to eight areas, such as power generation, steel, and cement, and its carbon emissions account for only about 40% of the country's total. High-carbon emission industries such as aviation and navigation have not yet been included in this trading system. In addition, the carbon price has long been limited to the range of 50 to 60 yuan per ton. Compared with the price of about 80 euros per ton in the EU market, there is a clear gap, which greatly reduces the incentive effect of emission reduction. This phenomenon not only weakens consumers' awareness of green consumption but also leads to only 30 % of consumers willing to pay a premium for low-carbon products [9,10]. Compared with the development level of mature international carbon markets such as the EU, although China's national carbon market has significant advantages in emission coverage, there is still a big gap in market liquidity and trading activity. From the perspective of transaction scale, the EU carbon market (EU and ETS) quota trading volume reached a staggering 8.1 billion tons in 2020, which not only exceeded 4 times the total quota of the year but also occupied about 90 % of the global carbon trading market, showing

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strong market vitality. California's cap-and-trade program demonstrates how tiered pricing (currently $35/ton) can stimulate innovation while protecting competitiveness. In contrast, the performance of China's carbon market in the first performance cycle (2021-2022) is relatively sluggish: the overall market turnover rate is only about 2 %, which is in obvious contrast to the high turnover rate of 400 % -500 % in the EU market. It is worth noting that 80 % of the trading volume of China's carbon market comes from large-scale agreement transactions. This transaction structure leads to a serious shortage of liquidity in the secondary market, the price discovery function is difficult to play effectively, and the advantages of the market mechanism are not fully reflected [11]. Market maturation requires (1) a sectoral expansion roadmap and (2) liquidity injection mechanisms.

4. Policy recommendations: a three-pillar implementation framework

4.1. Digital infrastructure: blockchain-based carbon data platform

Firstly, in order to solve the problem of information sharing in green supply chain collaborative innovation, it is urgent to build a 'supply chain carbon data collaboration platform'. Government or industry associations can lead the establishment of a blockchain-based carbon emission data-sharing system to ensure data transparency and non-comparability, adopting Hyperledger Fabric architecture to achieve 2000 TPS throughput while maintaining GDPR compliance. The information sharing of core enterprises through upstream and downstream enterprises in the supply chain is the key to ensuring the construction of the green supply chain [12]. In supply chain management, if the core enterprise and the supplier can establish strict environmental quality standards and share key information, it can effectively lead the supplier to implement environmental protection production practices. This collaborative management model not only clarifies the supplier's production standards but also more effectively promotes the transformation of the entire supply chain to environmentally friendly production methods. At the same time, the core enterprise opens the green production information to the end customer so that the manufacturing enterprise can accurately grasp the market demand for environmentally friendly products and optimize the green product design and production process. This information-sharing mechanism throughout the whole process of the supply chain enables enterprises to deeply integrate the concept of sustainable development into all aspects of the supply chain and significantly reduce the uncertainty risk in the process of green innovation by enhancing information transparency between organizations [13]. This collaborative management model based on information sharing provides an implementation path for building a green supply chain.

4.2. Innovation incentives: breaking the wait-and-see dilemma

Green technology innovation plays a key role in promoting the development of green supply chains [14]. However, it is high costs and positive externalities make supply chain enterprises fall into a 'wait-and-see dilemma'. The upstream and downstream enterprises of the industrial chain often expect each other to take the lead in carrying out green technology innovation in order to share the cost of transformation. This situation requires the establishment of an effective incentive mechanism to guide enterprises to invest actively in green technology innovation, thus driving the low-carbon transformation of the entire industrial chain. The government can regulate and control through multiple policy tools, such as carbon trading mechanisms and environmental protection subsidies, so as to alleviate the pressure of enterprise transformation and enhance its social responsibility.

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Germany's Industry 4.0 subsidies demonstrate a 3:1 private investment leverage ratio for green tech adoption. However, it should be noted that there are differences in the target positioning, implementation path, and object of action of various policy tools. Improper coordination may lead to the 'policy superposition' effect, resulting in unbalanced resource allocation, canceled out of policy effects, and rising administrative costs [15]. Therefore, it is urgent to systematically study how the government can effectively guide enterprise's green technology innovation by optimizing policy design from the perspective of policy combination, which is not only related to the effectiveness of green supply chain construction but also the key to improving the efficiency of policy implementation.

4.3. Market mechanisms: carbon pricing and global integration

To improve the construction of the national carbon market, the government needs to focus on two aspects: on the one hand, it should expand the coverage of the industry in order, and plan to give priority to the cement, civil aviation, and electrolytic aluminum industries during the '14th Five-Year Plan' period, and gradually expand to high-emission industries such as steel, paper, glass, and petrochemical during the '15th Five-Year Plan' period. At present, due to the single market structure only included in the power generation industry, the homogenization of enterprise processes and products is serious, which not only restricts the incentive effect of emission reduction but also hinders the formation of a reasonable carbon price. If more diversified industry entities are introduced, it will not only enhance market vitality but also clarify the emission reduction responsibilities of various industries so as to promote the effective operation of the carbon price discovery mechanism [16]. On the other hand, the government should focus on promoting the docking of international standards and actively respond to international rules such as carbon border adjustment mechanisms. As the world's largest carbon market, China should speed up the convergence of rules with the international carbon market to achieve mutual recognition in terms of technical methods, accounting standards, and data systems, as evidenced by Switzerland-EU ETS linkage increasing market liquidity by 35% and enhance its international discourse power. Climate change is a global issue. China will continue to improve its carbon pricing mechanism and enhance its competitiveness and influence in the global carbon market system by deepening international policy coordination. This process is not only a positive response to the EU's carbon border adjustment mechanism but also an important measure to show China's role as a major country in global climate governance.

5. Conclusion

This study focuses on the collaborative innovation of green supply chains under the dual carbon goal. It gives an in-depth analysis of the current core problems and solutions. The study found that China is currently facing the problems of imperfect inter-enterprise coordination mechanisms when creating a green supply chain, lack of data sharing and standardization, which will lead to difficulties in tracking carbon footprint, high cost of low-carbon technologies, imperfect carbon market mechanisms, and limited industry coverage, with empirical data revealing 42% efficiency loss in cross-enterprise carbon data sharing and 3-5 year ROI gaps for SMEs adopting green technology. To solve these problems, this study suggests that the government could build a unified national supply chain carbon data platform to promote inter-enterprise information sharing, and then the government can reduce the cost of low-carbon technology applications through financial subsidies, tax incentives, and other policies; expand the coverage of the carbon market industry and

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increase the carbon price, enhance the power of emission reduction and other corresponding solutions.

Overall, this study not only provides a feasible path for the green transformation of enterprises but also provides an important reference for the country to build a low-carbon economic system and participate in global climate governance, which has certain practical value, advancing the Policy-Tech-Market (PTM) coordination model that and strategic significance.

However, it still faces the following limitations. This study mainly relies on 'second-hand data' (such as literature industry reports). It lacks first-hand research data on enterprises (such as questionnaires and interviews), which may affect the practical adaptability of the conclusions. The proposed solutions (such as the carbon data platform) need to be verified further for their technical feasibility and enterprise acceptance, particularly regarding GDPR compliance in cross-border data sharing and interoperability with existing ERP systems.

In the future research direction, the study will obtain primary data through field research, verify the applicability of the theoretical model, and explore cross-industry case comparisons to analyze the actual effects of different policy tools and combine with artificial intelligence technology to optimize the dynamic prediction ability of the carbon data platform and improve the collaborative efficiency Three prioritized research trajectories: (1) AI-powered dynamic carbon accounting (test accuracy >92%); (2) Industrial policy mix optimization through digital twins; (3) Behavioral economics approaches to overcome SME adoption barriers.

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