The Pathways for the Integrated Development of the "Four Chains" under the Low-Carbon Economy

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Abstract: *Against the backdrop of the low-carbon economy becoming a global development trend, the coordinated integration of the industrial chain, talent chain, innovation chain, and capital chain is regarded as a key factor for achieving green transformation and sustainable growth. Based on the theory of "four-chain" coordination, this study explores the integration logic and pathways within the low-carbon economy, highlighting the complementarity and synergy of the four chains in resource flow, technology diffusion, and value transformation, with their relationships exhibiting circular feedback and dynamic evolution characteristics. The study proposes three main pathways: constructing a resource-oriented coordination mechanism, integrating the support of the capital chain and talent chain, and promoting the linkage and upgrading of the innovation chain and industrial chain, while emphasizing the enabling role of digital platforms, multidimensional data, and digital twin technologies in inter-chain coordination. The study concludes that four-chain coordination can significantly enhance the efficiency of low-carbon technology diffusion and resource allocation, offering substantial value for building a sustainable low-carbon economic system.*

Keywords: *low-carbon economy; four-chain integration; resource coordination; digital empowerment; chain evolution*

Introduction

As the global economy undergoes a deep transformation toward greening and low carbon, establishing a new economic system centered on efficient resource utilization and carbon emission control has become a critical development direction. The low-carbon economy not only relies on green technological innovation and industrial structure optimization but also requires a systematic support framework through multi-chain coordination to ensure the synchronized advancement of technological breakthroughs, talent supply, and capital allocation. In this process, the industrial chain, talent chain, innovation chain, and capital chain, as the core driving forces of the low-carbon economy, have their degree of integration directly determining the breadth and depth of green transformation. Traditional development models often face issues such as fragmented chains, resource misallocation, and slow innovation diffusion, making it difficult to meet the low-carbon economy's demands for dynamic adaptation and coordinated evolution. Therefore, investigating the pathways for the integrated development of the "four chains" under the low-carbon economy, and systematically exploring their interaction logic, integration mechanisms, and digital empowerment methods, holds significant theoretical value and practical necessity for achieving green transformation goals and enhancing the sustainable competitiveness of the economic system.

1. The Coordination Foundation of the "Four Chains" in Low-Carbon Economic Transformation

1.1 Connotation and Functional Positioning of the "Four Chains"

Within the development framework of the low-carbon economy, the industrial chain, talent chain, innovation chain, and capital chain constitute the core driving system for green transformation. The industrial chain achieves a green upgrade across resource acquisition, product design, and distribution processes through systematic integration of production factors and process optimization, with its level of carbon reduction directly affecting overall economic carbon emissions and resource utilization efficiency. The talent chain, grounded in knowledge accumulation and capability development, continuously supplies critical intellectual support and management capacity to the innovation chain and

industrial chain through the concentration of high-level talent, optimization of professional structures, and reinforcement of cross-domain collaboration, thereby generating endogenous momentum for green technological breakthroughs and industrial upgrading. The innovation chain plays a key role in green technology research and development, results incubation, and application diffusion, functioning not only to drive the emergence of new technologies but also to facilitate the effective embedding of knowledge into the industrial chain and the transformation of such knowledge into value. The capital chain provides essential financial support for innovation R&D and industrial expansion through capital provision, risk control, and return optimization, with its flow efficiency and resource allocation capacity determining the speed and depth of technology diffusion and industrial upgrading.

The value of these four chains in the low-carbon economy lies not only in their functional independence but also in their complementarity and synergy. The green demand from the industrial chain guides the R&D direction of the innovation chain, while the outcomes of the innovation chain reciprocally drive technological upgrading and structural optimization in the industrial chain. The talent chain, through a continuous supply of interdisciplinary talent and compound skills, offers dynamic support to the innovation and industrial chains, whereas the capital chain's flow of funds serves as a critical linkage among the four chains, with its investment orientation and risk preferences influencing the effective allocation of talent and innovation resources. Efficient coordination among the four chains can break the traditional linear development model, forming a multi-directional interactive and cyclically evolving low-carbon economic system, thereby enhancing the sustainability and structural stability of green transformation [1].

1.2 Interaction Logic of the "Four Chains" Driven by Low-Carbon Transformation

The core objective of the low-carbon economy is to achieve a dual balance between carbon emission control and economic growth, and its operational logic necessitates the formation of a dynamic interaction mechanism among the "four chains" based on the flow of resources, information, and value. The green upgrade demands of the industrial chain provide clear guidance for technological R&D within the innovation chain, ensuring that innovation activities are highly targeted and adaptable. The large-scale application of innovation outcomes, in turn, drives the industrial chain to undergo process reengineering and structural reorganization, forming an innovation-driven green industrial system. The talent chain, serving as an intermediary linking innovation and industry, ensures the alignment between technological R&D and industrial demands through the mobility of high-level talent and cross-domain collaboration, while enhancing the system's adaptability and iteration speed through knowledge renewal and skill redevelopment. The capital chain plays a central role in resource allocation and flow regulation, with investment decisions determining the continuity of innovation R&D and the pace of industrial upgrading, and the flexibility of capital structure directly affecting the stability of inter-chain coordination.

This interaction is not a simple linear transmission but a systemic evolution characterized by circular feedback and dynamic adjustment. The level of industrial chain greening and the scale of capital inflow influence the R&D intensity of the innovation chain, while the diffusion of technological breakthroughs attracts further capital into the capital chain, thereby accelerating technology transfer and industrial upgrading. The professional composition and mobility direction of the talent chain dynamically adjust according to changes in industry and innovation, forming a demand-oriented rapid response mechanism across chains. Through this multidimensional interaction, the four chains gradually establish an efficient positive feedback loop, enhancing the agility of resource allocation and the self-adaptiveness of system evolution, thereby enabling the low-carbon economy to maintain strong resilience and sustainable growth capacity under uncertain conditions.

1.3 Structural Bottlenecks and Optimization Directions in Coordinated Evolution

Although the integration of the "four chains" theoretically offers significant synergy advantages, multiple structural bottlenecks remain in the process of low-carbon economic transformation. The green level of the industrial chain varies significantly across regions and industries, resulting in gaps in technological coordination and resource flows between upstream and downstream segments; the innovation chain faces low efficiency in the linkage between basic research and industrialization, making it difficult for new technologies to be rapidly embedded into the industrial chain for large-scale application; the talent chain suffers from a mismatch between professional structure and the demands of green industries, hindering precise support for the innovation and industrial chains and creating a structural imbalance between talent supply and demand; the capital chain, due to the long return cycles

of low-carbon industries and an underdeveloped risk assessment system, lacks continuity and stability in capital inflows, thereby restricting the coordinated advancement of innovation and industrial upgrading [2].

To address these issues, optimization should focus on the systemic reconstruction of inter-chain relationships. The industrial chain needs to achieve orderly and efficient resource flows through the enhancement of green process standards and the establishment of upstream–downstream linkage mechanisms; the innovation chain should shorten the time from basic research to industrialization by constructing technology incubation platforms and rapid transformation mechanisms; the talent chain must achieve breakthroughs in interdisciplinary training and compound skill development to ensure precise alignment with innovation and industrial demands; the capital chain should attract long-term investment into the low-carbon sector by improving risk diversification mechanisms and return prediction models, thereby generating a linkage effect among capital, technology, and industry. Through these multidimensional optimizations, the four chains can achieve dynamic matching and positive feedback, forming a sustainable and scalable model for coordinated evolution in the low-carbon economy.

2. Design of the "Four-Chain" Integration Path Based on Coordination and Integration

2.1 Resource-Oriented Coordination Mechanism under Strategic Planning

The systemic evolution of the low-carbon economy requires the "four chains" to achieve efficient and stable coordination in resource allocation, and the core value of strategic planning lies in precisely guiding resource flows and optimizing the combination of factors through holistic design. By establishing a resource-oriented coordination mechanism centered on system coupling, different chains can form dynamic adaptive relationships based on functional complementarity and value maximization. The green upgrading of the industrial chain depends not only on the internal optimization of a single chain but also on the coordinated injection of capital, talent, and technology, with resource allocation scientifically guided by low-carbon value output and green performance. In this process, the talent chain assumes the role of efficiently supplying knowledge and capabilities, with the deployment of high-level talent following principles of hierarchical aggregation and cross-chain mobility to ensure precise embedding in key R&D nodes of the innovation chain and green manufacturing segments of the industrial chain. The capital chain should adopt phased and sector-specific investment strategies, concentrating limited resources on the core nodes of the innovation and industrial chains, thereby generating inter-chain linkage and value-added effects.

The effective operation of a resource-oriented coordination mechanism depends on the high integration and efficient interaction of information flows and value flows. A transparent information-sharing system not only facilitates real-time understanding of demand changes and resource status across chains but also enables dynamic resource scheduling through predictive analysis and feedback adjustment, reducing redundancy and structural mismatches caused by chain fragmentation. The dynamic adjustment of value flows provides scientific incentive signals for resource allocation, ensuring that capital, talent, and technology maintain agile circulation across chains through green value assessment and carbon reduction performance measurement, thereby forming positive feedback. Coupling design based on strategic planning not only optimizes the spatial and temporal distribution of resources but also provides stable momentum for the continuous iteration of the low-carbon economic system, transforming the "four-chain" integration from static coordination to dynamic synergy [3].

2.2 Integrated Support Structure of the Capital Chain and Talent Chain

The degree of integration between the capital chain and the talent chain determines the collaborative efficiency of the innovation chain and industrial chain in the low-carbon economy and constitutes a key element in building a systematic integration model. The capital chain provides material support to the talent chain through capital supply, risk diversification, and return optimization, while the talent chain generates potential growth value for the capital chain through knowledge innovation and technological R&D capabilities embodied in high-level human capital. An integrated support structure requires functional complementarity and dynamic matching as its foundation, with capital investment concentrated in technology fields with high innovation potential and long-term green returns, and talent cultivation and recruitment closely aligned with capital needs and technological

evolution trends. The concentrated deployment of capital and precise supply of talent generate a mutually reinforcing effect, where capital creates research and innovation conditions for the talent chain, and talent enhances capital returns through technological breakthroughs, thereby forming a closed-loop collaborative relationship.

The construction of this integrated support relies on the comprehensive application of cross-chain coordination platforms and data-driven mechanisms. By integrating and analyzing multidimensional data, capital flows and talent flows can achieve dynamic and precise coupling, avoiding resource idling or misallocation caused by information asymmetry between supply and demand. In long-term investment, the capital chain should maintain stable input through scientific risk diversification and return forecasting models, adjusting investment structure based on performance feedback; the talent chain can enhance responsiveness through interdisciplinary training systems, flexible capability iteration mechanisms, and cross-chain talent mobility frameworks to meet the dynamic needs of the industrial and innovation chains for green technology R&D and application. Their efficient integration not only significantly enhances the efficiency of the innovation chain in R&D, incubation, and results transformation, but also drives green upgrading of the industrial chain through rapid technological iteration, thereby constructing an integrated support system with sustained driving capability in the context of the low-carbon economy.

2.3 Linkage and Upgrading Path of the Innovation Chain and Industrial Chain

The linkage and upgrading of the innovation chain and industrial chain constitute the core pathway for low-carbon technological breakthroughs and green diffusion, with the key lying in the rapid connection between technology supply and industrial application. The innovation chain provides a technological reserve through basic research, applied R&D, and results incubation, while the industrial chain amplifies the value of innovation outcomes through production organization optimization, green manufacturing upgrades, and market diffusion. The linkage and upgrading path should focus on value chain embedding and technology diffusion efficiency, with innovation outcomes completing the transition from laboratory to industrialization in the shortest possible time to achieve large-scale application of green technologies. By establishing multi-level technology transfer channels, application verification systems, and results evaluation mechanisms, the innovation chain and industrial chain can achieve efficient coupling of knowledge, technology, and market, forming a technology-driven production system guided by green value creation [4].

Sustained advancement of linkage and upgrading requires the industrial chain to possess agile feedback capabilities and the innovation chain to maintain dynamic iteration capacity. The industrial chain provides the innovation chain with precise directions for R&D optimization through real-time feedback on market demand, carbon reduction effectiveness, and green performance, making technological development more targeted and adaptable. The innovation chain, in turn, continuously adjusts R&D pathways based on the industrial chain’s practical production and market diffusion needs, using big data and simulation analysis to create a dynamic cycle that combines demand orientation with technology-driven innovation. Through this interactive mechanism, the innovation chain and industrial chain can not only achieve synchronized upgrading in coordination but also significantly enhance the depth of green technology application and the breadth of its promotion, providing sustained innovation momentum and industrial structure optimization support for the low-carbon economy.

3. Reshaping the "Four-Chain" Integration Mechanism Driven by Digitalization

3.1 Structural Empowerment of Inter-Chain Coordination by Digital Platforms

Digital platforms play a role in the coordination of the "four chains" through structural empowerment and process reengineering, achieving systematic optimization of inter-chain collaboration by integrating information flows, value flows, and knowledge flows. Based on a unified data infrastructure, information exchange among the industrial chain, talent chain, innovation chain, and capital chain becomes highly transparent and real-time, helping to overcome resource misallocation caused by traditional information silos between chains. Platform-based structural design supports multidimensional interaction patterns across chains, using algorithmic models to dynamically predict and match demand and supply, enabling adaptive resource flows among the chains and forming a data-driven coordination system.

This structural empowerment not only optimizes resource flows but also redefines inter-chain

relationships. Digital platforms establish standardized interfaces and modular functions, allowing different chains to couple within the same system framework and form cross-chain dynamic feedback loops. For example, in the R&D and application of low-carbon technologies, the progress of the innovation chain can directly link to the production demands of the industrial chain through the platform, while the capability reserves of the talent chain and the investment intentions of the capital chain can be adjusted in real time to match the latest technological and market dynamics. Through this structural empowerment, the coordination of the four chains transforms from linear transmission to networked interaction, significantly enhancing the overall system's responsiveness and iteration capacity [5].

3.2 Element Precision Matching Mechanism Supported by Multidimensional Data

The integration and intelligent analysis of multidimensional data provide critical support for the precise matching of elements across the "four chains." By collecting and integrating multi-source data on industrial demand, talent capabilities, technological outcomes, and capital flows, the system can achieve dynamic perception and correlation analysis of inter-chain elements at a higher dimensional level. Intelligent algorithms based on machine learning and knowledge graphs can uncover potential relationships, predict future resource demand trends, and accordingly optimize capital allocation structures, talent development directions, and innovation R&D priorities, ensuring that element allocation aligns more closely with the systemic goals of the low-carbon economy.

The core of the precision matching mechanism lies in forming a closed-loop dynamic adjustment system. Through data-driven feedback loops, capital flows in the capital chain can be flexibly adjusted according to the real-time needs of the innovation chain and industrial chain, while the talent supply within the talent chain can be rapidly updated by analyzing changes in market and technological demand. Efficient utilization of multidimensional data enhances the agility and predictability of resource flows, avoiding allocation imbalances caused by information lags in traditional chain coordination. Through this precision matching, the four chains can establish highly efficient collaboration based on data logic, promoting the rapid diffusion and value transformation of low-carbon technologies on a broader scale.

3.3 Chain Evolution Model Driven by Digital Twin Technology

Digital twin technology provides a new technical pathway for the evolution of the "four-chain" integration by constructing a dynamic simulation system that maps virtual and real environments, enabling global perception and predictive optimization of chain operations. The digital twin model can simulate in real time the interactions among the industrial chain, innovation chain, talent chain, and capital chain, dynamically calculating and scenario-simulating resource flows, technology diffusion, and market responses, thereby providing decision-making support for inter-chain coupling. Through experimentation and adjustments in the virtual environment, uncertainty in the transformation process from the innovation chain to the industrial chain can be reduced, and the precision of capital and talent allocation can be enhanced [6].

The application of digital twin technology is not only a representation of inter-chain interaction but also a tool for driving evolution. Through continuous data updates and model iteration, the virtual environment can simulate the dynamic evolution paths of chain coordination under different strategies, identifying potential bottlenecks and optimization opportunities. Based on this evolution model, the four chains can achieve pre-optimization and rapid iteration within the virtual space, forming more forward-looking resource allocation and coordination strategies. The introduction of digital twin technology endows the low-carbon economic system with self-learning and self-optimization capabilities, providing both technical support and theoretical innovation for the continuous upgrading of the "four-chain" integration.

Conclusion

This study systematically explored the internal mechanisms and implementation pathways of the "four-chain" integration under the low-carbon economy, proposing that resource-oriented coordination can be achieved through strategic planning, innovation capacity and technology diffusion efficiency can be strengthened through the integrated support of the capital chain and talent chain, and the value transformation of green technologies can be accelerated through the linkage and upgrading of the

innovation chain and industrial chain. Additionally, digital platforms, multidimensional data, and digital twin technology were introduced to achieve structural reshaping and dynamic optimization of inter-chain relationships. The study demonstrates that the coordination of the four chains can not only overcome the limitations of traditional linear development models and form a networked cyclic interaction structure, but also significantly enhance the diffusion speed of low-carbon technologies and the agility of resource allocation, providing core driving forces for the greening and sustainable development of economic systems. Future research can further deepen the application of digital twin technology and intelligent algorithms in inter-chain dynamic evolution, construct predictable and self-optimizing chain evolution models, and explore the heterogeneous characteristics and cross-regional linkage patterns of four-chain coordination across different industrial sectors, offering more precise theoretical guidance and technical support for the systematic development of the low-carbon economy.

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