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Synergistic Transformation of Digitalization and Greenization: International Research Frontiers, Theoretical Framework and Practical Implications

Jiang Zhao[1,*] & Meng-yin Xu[2]
[1]Shaoxing University, China

Abstract: Against the dual backdrop of increasingly stringent global climate governance and the accelerated iteration of digital technologies, the synergistic transformation of digitalization and greenization (hereinafter referred to as "dual synergy") has become a core pathway for countries to reconcile the contradiction between development and environmental protection and drive the high-quality upgrading of industries, as well as a cutting-edge research topic in the international management field. Taking the relevant literatures on dual synergy published in foreign core journals from 1976 to 2026 as the research object, this paper adopts the systematic literature review method to comprehensively sort out the conceptual connotation and multi-scenario evolutionary characteristics of dual synergy, and deeply analyze the bidirectional interaction mechanism of "digitalization empowering greenization and greenization guiding digitalization". It systematically identifies the core obstacles faced by the dual synergetic transformation worldwide from the technical, organizational and market dimensions, and thoroughly dissects the impact effects and heterogeneous characteristics of dual synergy on enterprises' environmental, economic and social performance. Based on foreign policy practices and typical enterprise cases, a three-dimensional collaborative path system of "policy governance - multi-stakeholder ecological governance - internal corporate governance" is constructed. The study finds that foreign research on dual synergy has formed a complete research framework of "concept definition - mechanism analysis - challenge identification - performance test - path construction", with the core consensus focusing on the effectiveness of the bidirectional empowerment mechanism, yet there remain research gaps in terms of endogenous technological integration, cross-stakeholder collaboration logic and scenario-adaptive paths. The policy practices and enterprise transformation experiences of economies such as the European Union, the United States, Japan and South Korea provide important references for China to break through the bottlenecks of dual synergy. The research value of this paper lies in clarifying the theoretical context and frontier trends of international research on dual synergy, filling the gap in the systematic review of existing foreign literatures, and providing a theoretical framework for China's academic research to dialogue with international frontiers. Meanwhile, it offers targeted international experience references for Chinese enterprises to formulate dual synergetic transformation strategies and for the government to improve relevant policy design, thus promoting the dual synergy to evolve from a policy-initiated initiative to an endogenously driven systemic reform.

Keywords: digital transformation, green transformation, dual synergy

1. Introduction

With the growing prominence of global environmental issues and the accelerated evolution of a new round of scientific and technological revolution and industrial transformation, digitalization and greenization have become two core pillars for the world's major economies to achieve sustainable development. These two are not isolated and fragmented transformation processes, but present the characteristics of synergistic evolution featuring "bidirectional empowerment and integrated symbiosis", namely the dual synergetic

Corresponding Author: Jiang Zhao
Shaoxing University, China

From the perspective of international practice, the European Union (EU) incorporated dual synergy into its top-level strategic layout as early as 2019, explicitly proposing the parallel advancement of the *Digital Europe Programme* and the *European Green Deal*. It emphasized addressing climate change through digital technologies and guiding the innovation direction of digital technologies by virtue of green development, thus constructing a dual synergy system of "technological integration - policy coordination - ecological support". The United States promoted the in-depth integration of digital technologies and green industries through the coordinated implementation of the *Digital Infrastructure Act* and the *Inflation Reduction Act*, focusing on collaborative innovation in fields such as new energy and artificial intelligence. East Asian economies including Japan and South Korea, based on their manufacturing advantages, drove the in-depth integration of digital technologies with green production and the circular economy, forming distinctive dual synergetic transformation models. These international practices indicate that dual synergy has become a core strategic choice for countries to cope with environmental pressures and enhance industrial competitiveness, and has also spawned a large number of research results on dual synergy in the international management field.

From the perspective of international academic research, existing literatures have conducted in-depth discussions on digital transformation and green transformation respectively, accumulating rich theoretical and empirical achievements. However, with the continuous deepening of dual synergy practices, scholars have gradually realized that single-dimensional transformation research can hardly explain complex transformation practices. Core issues such as the internal mechanism, dynamic laws and governance paths of dual synergy have become research hotspots in the fields of international management, environmental economics and industrial economics in recent years. At present, foreign scholars have carried out extensive research on the concept definition, interaction mechanism, transformation challenges and performance impact of dual synergy, yet obvious deficiencies remain in existing studies: first, a unified definition of the conceptual connotation of dual synergy has not been formed, and scholars have different cognitions of the core boundaries and characteristic attributes of dual synergy based on the practices of different economies such as the EU and the United States, which affects the consistency and comparability of research; second, research on the bidirectional interaction mechanism of dual synergy mostly focuses on the empowerment effect of a single dimension, with insufficient discussion on their interaction, regulatory factors and heterogeneous characteristics, and no systematic theoretical framework has been formed; third, most existing studies focus on case or empirical analysis of a single country or a single industry, with insufficient comparative research on the differences of dual synergy among enterprises of different economies and scales, making it difficult to reveal the universal laws and scenario-based characteristics of dual synergy; fourth, research on the governance paths of dual synergetic transformation mostly focuses on a single subject (government or enterprise), with in-depth discussion on the logic and mechanism of multi-stakeholder collaborative governance lacking, and no operable systematic path design available.

Taking the relevant literatures on dual synergy published in foreign core journals as the research object, this paper adopts the systematic literature review method to comprehensively sort out the frontier trends of international research on dual synergy, clarify the research context, and put forward targeted implications combined with international practical experience and typical cases. The research objectives of this paper are as follows: first, to systematically sort out the conceptual connotation and evolutionary characteristics of foreign dual synergy, and clarify the core differences of dual synergy in different economies and scenarios; second, to deeply analyze the bidirectional interaction mechanism of dual synergy and summarize the core empirical evidence of mechanism testing in the international academic community; third, to systematically identify the core technical, organizational and market barriers faced by dual synergetic transformation and reveal the formation mechanism of different barriers; fourth, to comprehensively dissect the impact effects and heterogeneous characteristics of dual synergy on enterprise performance and sort out the research controversies in the international academic community; fifth, to construct a governance path system for dual synergetic transformation based on foreign policy practices and enterprise experience,

providing international references for China.

2. Concept Definition and Characteristic Evolution of Dual Synergetic Transformation

The concept definition of dual synergetic transformation by foreign scholars has been gradually deepened with the development of practice, focusing on the three core characteristics of "integration", "bidirectionality" and "systematicness". The conceptual connotation under different economies and research perspectives presents differentiated characteristics, but an evolutionary context of "from technological superposition to systematic integration" has been formed on the whole. Combining foreign core literatures, this paper systematically sorts out the concept definition and characteristic evolution of foreign dual synergy from three dimensions: conceptual connotation, multi-scenario characteristics and regional differences.

2.1 Evolution and core definition of conceptual connotation

The concept definition of dual synergy abroad has roughly gone through three stages: the first stage (before 2016) is the **technological superposition perspective**, where scholars mostly understood dual synergy as a simple combination of digital and green technologies, holding that its core is to improve green production efficiency through digital technologies, without realizing the bidirectional empowerment relationship between the two (Adner & Kapoor, 2016). Research in this stage mostly focused on the application of a single technology, such as the digital monitoring of industrial energy consumption and the energy-saving transformation of data centers by green technologies, with insufficient systematic cognition of dual synergy.

The second stage (2017-2022) is the **bidirectional empowerment perspective**, where scholars gradually realized the mutual supporting role of digitalization and greenization, and explicitly proposed that dual synergy is a bidirectional interaction process of "digitalization empowering greenization and greenization guiding digitalization" (Fouquet & Hippe, 2022). The concept definition in this stage corely emphasizes the complementarity of the two: as an efficient tool, digital technology provides precise support for green transformation; guided by rigid demands, green development drives the upgrading of digital technology towards sustainability, and the two jointly realize the synergy of economic and environmental values (Luo et al., 2023). Meanwhile, scholars began to pay attention to the organizational and institutional dimensions of dual synergy, holding that dual synergy is not a simple technological integration, but a systematic project involving organizational change and institutional design (Montresor & Vezzani, 2023).

The third stage (2023 to present) is the **systematic integration perspective**, where foreign scholars further expanded the conceptual boundary of dual synergy, defining it as "a systemic transformation involving multiple dimensions such as technology, organization, market and policy, whose core is to reconstruct industrial models, organizational forms and governance systems through the in-depth integration of digital resources and green production factors, so as to realize the three-dimensional balance of economy-environment-society" (Baumgartner et al., 2025; Schallmo & Jehle, 2025). Research in this stage emphasizes the endogenous driving nature of dual synergy, holding that it is not a mere result of policy promotion, but a product of the joint action of multiple factors such as technological innovation, market demand and organizational change, with the core lying in constructing a complete system of "technological integration - organizational adaptation - ecological support" (Tabares et al., 2025).

Synthesizing the definitions of foreign core literatures, this paper defines dual synergetic transformation (based on foreign research consensus) as follows: under the guidance of global sustainable development goals, multiple subjects including enterprises, governments and universities make joint efforts to drive the collaborative innovation of digital and green technologies, the systemic reform of organizational forms and governance models, and the bidirectional adaptation of market demand and policy orientation through the in-depth integration of digital resources and green production factors, forming a bidirectional interaction mechanism of "digitalization empowering greenization and greenization guiding digitalization", and ultimately realizing a systemic transformation process of dynamic balance among economic growth, environmental protection and social inclusion.

2.2 International research consensus on multi-scenario characteristics

Based on research in different scenarios, foreign

scholars have summarized the multi-scenario characteristics of dual synergetic transformation, which mainly focus on the industrial, enterprise and regional levels, with obvious differences in the collaboration logic and focus under different scenarios, which is also one of the key research directions in the international academic community in recent years.

At the **industrial level**, foreign research generally holds that dual synergy is reflected in the in-depth integration of digital and green technologies in the entire chain of production, logistics and supply chain (Gkypali et al., 2025). Among them, manufacturing, as the core application scenario of dual synergy, is defined by foreign scholars as "the synchronous advancement process of the transformation of manufacturing from linear production to circular production and digital transformation", whose core is to optimize production processes and improve resource utilization efficiency through digital technologies, while driving the transformation of production models towards low-carbon and circularity by virtue of green technologies (van Erp & Rytter, 2023). In fields such as logistics and service industry, dual synergy focuses on the integration of digital technologies and green services, such as intelligent logistics and green e-commerce, improving service efficiency and reducing environmental load through digital technologies (Hustad & Olsen, 2021).

At the **enterprise level**, foreign research emphasizes that dual synergy is "two parallel and mutually reinforcing transformation paths", whose core is to enhance the sustainable competitiveness of enterprises through bidirectional empowerment (Tabares et al., 2025). There are obvious differences in the dual synergy characteristics of enterprises of different scales: large enterprises, relying on resource and technological advantages, tend to construct an ecological system of dual synergy to drive technological innovation and model reconstruction; small and medium-sized enterprises (SMEs) focus on the collaborative optimization of core links and break through resource and capacity constraints by virtue of external ecological support (Abilakimova et al., 2025; Ogrean & Herciu, 2021). In addition, foreign scholars have found that dual synergy in high-reliability organizations such as aerospace and nuclear power pays more attention to resilience construction and risk prevention and control, forming a unique characteristic of "technological collaboration - capacity improvement - risk management and control" (Kleinschmidt et al., 2025).

At the **regional level**, dual synergy is manifested in the adaptive adjustment and coordinated implementation of national green and digital policies by local governments, whose core is to construct differentiated collaborative transformation models combined with regional resource endowments and industrial characteristics (Brueck et al., 2025; Faggian et al., 2025). Foreign research has found that economically developed regions such as Western Europe and the U.S. West Coast have a higher level of dual synergy and pay more attention to technological innovation and ecological construction; underdeveloped regions focus more on basic capacity building and gradually promote dual synergetic transformation relying on policy support and external assistance (Bianchini et al., 2023).

2.3 Conceptual differences and practical orientations of different economies

Due to differences in industrial foundation, policy environment and market demand of different economies, the concept definition and practical orientation of dual synergy by foreign scholars also present obvious regional differences, among which the research of the three major economies of the EU, the United States, Japan and South Korea is the most concentrated, forming representative research perspectives.

In the **EU context**, dual synergy is essentially a governance innovation to cope with environmental crises and technological changes, with the core orientation of "sustainable development first". It emphasizes building a transformation system of "policy coordination - technological integration - ecological support" through the combination of digital technologies and green goals (Quintavalla & Yalnazov, 2025). EU scholars' research mostly focuses on policy coordination mechanisms, dual synergy of SMEs and regional collaborative transformation, emphasizing the overall leading role of the government in dual synergy (Ben Youssef, 2025; Gerlitz & Meyer, 2021).

American scholars' research on dual synergy focuses more on "market-driven and technological innovation", with the core orientation of "enhancing industrial competitiveness". It emphasizes fostering new economic growth points through the

collaborative innovation of digital technologies and green industries (Veugelers et al., 2023). The research focuses on the green transformation of digital infrastructure, the integration of new energy and digital technologies, and the performance evaluation of enterprise dual synergy, highlighting the core role of market mechanisms in resource allocation (Timmermans et al., 2023).

Based on their national manufacturing advantages, **Japanese and South Korean scholars'** research takes the core orientation of "dual improvement of production efficiency and environmental performance", emphasizing the scenario-based application of dual synergy in manufacturing, such as the integration of digital twins, intelligent production and green production, and the combination of circular economy and digital technologies (Choi & Kim, 2025). The research focuses on the internal collaborative paths of enterprises and the specific models of technological integration, paying attention to practical orientation and operability.

3. Bidirectional Interaction Mechanism of Dual Synergetic Transformation (Systematic Analysis Based on Foreign Literatures)

Foreign scholars' research on the interaction mechanism of dual synergy mainly focuses on the two main lines of "digitalization empowering greenization" and "greenization guiding digitalization", forming rich theoretical and empirical achievements, and clarifying the specific paths, influencing factors and empirical evidence of bidirectional empowerment. Based on foreign core literatures, this paper systematically analyzes the bidirectional interaction mechanism of dual synergy, sorts out the theoretical support and empirical findings of different mechanisms, and clarifies the research consensus in the international academic community.

3.1 Empowering mechanism of digitalization on greenization: a three-dimensional path of technology, efficiency and management

Foreign research generally holds that the empowering effect of digitalization on greenization is mainly carried out through three dimensions: technological innovation, efficiency improvement and management optimization, which support and cooperate with each other to jointly promote the implementation of green transformation, and this empowering effect has been empirically verified in different industries and enterprises of different scales.

At the level of **technological innovation**, digital technology provides precise support for the R&D and application of green technology, reducing the cost and risk of green innovation (Montresor & Vezzani, 2023). Digital technologies such as big data, artificial intelligence and the Internet of Things (IoT) can help enterprises more accurately identify green innovation demands, optimize green production processes, and improve the R&D efficiency and application effect of green technologies. For example, German chemical giant BASF applies AI and big data to optimize the R&D process of biodegradable materials, shortening the R&D cycle by 40% and reducing the R&D energy consumption by 35% (Dal Mas et al., 2024). Meanwhile, the collaboration between industry leaders, entrepreneurs and academic researchers in the digital entrepreneurial ecosystem can promote the integrated innovation of green and digital technologies and cultivate benchmark enterprises for dual synergetic transformation. In addition, foreign scholars have found that compound talents with dual backgrounds in digital and green technologies can effectively reduce the cost of technology integration in the transformation process, improve the efficiency of technological fusion, and strengthen the empowering effect of digitalization on greenization (Kleinschmidt et al., 2025).

At the level of **efficiency improvement**, digital transformation effectively reduces the environmental load of enterprises by optimizing resource allocation and reducing energy consumption (Shang et al., 2023). Foreign empirical studies have shown that enterprise digital transformation can significantly reduce carbon emission intensity by improving technological innovation capacity, internal control capacity and environmental information disclosure capacity. For the high energy consumption of digital infrastructure itself, foreign scholars proposed that the green upgrading of digital infrastructure can be realized through new energy access and energy-saving technological transformation. Google has completed the green transformation of all its global data centers, with 100% of electricity consumption coming from renewable energy, reducing the carbon emission intensity of data centers by 85% compared with the industry average (Hustad & Olsen, 2021; Wang et al., 2023). In addition, the application of digital technologies in

resource recycling, low-carbon supply chain management and other fields helps to improve the efficiency of the whole-chain resource management, driving the industrial transformation to the circular economy, and is an important channel for enterprises to achieve sustainable development goals (Husain et al., 2022).

At the level of **management optimization**, digital tools can improve the accuracy and effectiveness of environmental governance and promote the implementation of green management concepts (Veit et al., 2024). On the one hand, digital technology can indirectly promote employees' green behavior by cultivating their psychological sense of belonging and perceived organizational environmental support, driving green transformation from within the enterprise; on the other hand, some foreign scholars combined stakeholder theory with artificial intelligence technology and found that platform-based enterprises such as Walmart can effectively promote their green transformation and strengthen the empowering effect of digitalization by balancing the demands of multiple stakeholders such as consumers, suppliers and regulatory authorities through AI technology (Ma & Zhu, 2022). In addition, digital technologies can improve the transparency and timeliness of environmental information disclosure, strengthen the constraint of external supervision on enterprises' green behavior, and further promote enterprises' green transformation.

3.2 Reverse guiding mechanism of greenization on digitalization: a three-dimensional path of demand, policy and technology

Compared with the one-way empowerment of digitalization on greenization, foreign scholars have gradually paid attention to the reverse guiding role of greenization on digitalization in recent years, holding that green development is not only an important goal of digital transformation, but also a core driving force to promote the optimization and upgrading of digital transformation. This guiding role is mainly carried out through three dimensions: demand driving, policy constraint and technical support, and presents obvious phased characteristics.

In terms of **demand driving**, with the improvement of global environmental awareness and the rise of the green consumer market, the market demand for green products and services has been growing continuously. This demand forces enterprises to further explore the green empowerment value of digitalization and drive the optimization and upgrading of digital transformation towards greenization (Fouquet & Hippe, 2022). Foreign research has found that the improvement of consumers' green consumption awareness will prompt enterprises to increase the application of digital technologies in green production, green marketing and other fields. For example, Swedish home furnishing brand IKEA uses big data to analyze consumers' green consumption demand, and combines digital design technology to develop low-carbon furniture products, whose green product line sales account for more than 60% of the total sales (Wu et al., 2023). Meanwhile, public environmental attention will also indirectly promote the application of digital technologies and drive the coordinated advancement of digitalization and greenization. In the agri-food field, platform-based enterprises realize green supply chain management through AI technology, which not only meets consumers' green demands, but also promotes the in-depth application of digital technologies (Ma & Zhu, 2022).

In terms of **policy constraint**, as a comprehensive environmental regulation tool, low-carbon policies guide the optimization of digital technologies towards greenization through dual mechanisms of incentives and constraints (Xu et al., 2022). Foreign research has shown that the government can encourage enterprises to research, develop and apply green digital technologies through incentive policies such as financial subsidies and tax reductions and exemptions, reducing the cost of enterprises' dual synergetic transformation; at the same time, it forces enterprises to improve their low-carbon management capacity with the help of digital technologies through constraint indicators such as carbon emission quotas and environmental protection standards. The EU, through the Carbon Border Adjustment Mechanism (CBAM), forces enterprises to increase the application of digital technologies in carbon emission management, promoting the in-depth integration of digitalization and greenization (Ortega-Gras et al., 2021). For example, French steel giant ArcelorMittal has built a digital carbon monitoring system under the constraints of EU carbon policies, realizing real-time monitoring and precise control of carbon emissions in the production process, with carbon emissions per

ton of steel reduced by 28%.

In terms of **technical support**, green technology provides a low-carbon foundation for digital transformation, and also puts forward new requirements for the application of digital technologies, driving the optimization and upgrading of digital technologies (Céline et al., 2023). Foreign research has found that while requiring enterprises to carry out low-carbon, energy-saving and environment-friendly production activities, green transformation is also promoting the in-depth development of digital technology application, and enterprises' energy-saving and low-carbon technologies can provide green technical support for the low-carbon transformation of digital infrastructure (Wang et al., 2023). However, it should be noted that foreign scholars have also found that when dual synergy enters the middle and late stages, the excessive use of digital technologies will have an adverse impact on the environment, producing a "rebound effect" (Timmermans et al., 2023). Therefore, green development requires enterprises to consider the environmental costs brought by the development of digital technologies, advocate moderate digitalization, guide the precise matching of digital technology application with green goals, and avoid the environmental burden caused by technology abuse (Céline et al., 2023). For example, Dutch technology company Philips has optimized its digital office system by reducing redundant data computing and storage, cutting the energy consumption of the digital system by 30% on the premise of ensuring business operation.

3.3 Regulatory factors and heterogeneous characteristics of the bidirectional interaction mechanism

Latest foreign research shows that the bidirectional interaction mechanism of dual synergy is not an absolute linear relationship, but is regulated by a variety of factors and presents obvious heterogeneous characteristics, which is also one of the frontier directions of international research in recent years. In terms of **regulatory factors**, they mainly include enterprise scale, industry attributes, property rights nature and policy environment (Tabares et al., 2025). For example, the digital empowerment effect of SMEs is weaker than that of large enterprises, mainly due to resource and capacity constraints; the bidirectional empowerment effect of emerging industries such as new energy and digital economy is stronger than that of traditional industries because emerging industries have a faster technological iteration speed and smaller transformation resistance; the more perfect the policy environment, the more significant the bidirectional empowerment effect, which can effectively reduce transformation costs and resolve transformation risks (Abilakimova et al., 2025).

In terms of **heterogeneous characteristics**, there are obvious differences in the bidirectional interaction mechanism of different economies and industries. The bidirectional empowerment of EU economies relies more on policy coordination, that of the United States more on market driving, and that of Japan and South Korea more on technological integration in manufacturing scenarios (Choi & Kim, 2025; Veugelers et al., 2023); the bidirectional empowerment of manufacturing mainly focuses on technological integration in the production link, while that of the service industry focuses on the optimization and upgrading of service processes (Gkypali et al., 2025; van Erp & Rytter, 2023). In addition, foreign scholars have found that the bidirectional empowerment mechanism has phased differences: in the early stage of transformation, the empowering effect of digitalization on greenization is more significant; in the middle and late stages of transformation, the guiding effect of greenization on digitalization is more prominent, and the two present the characteristics of "dynamic balance and synergistic evolution" (Fouquet & Hippe, 2022). For example, in the early stage of transformation, Chinese manufacturing enterprises mainly use digital technology to transform green production processes, while in the middle and late stages, they develop green digital technologies such as low-carbon industrial software according to green development demands.

4. Core Challenges Faced by Dual Synergetic Transformation (Systematic Sorting Based on Foreign Literatures)

Although dual synergetic transformation has a significant positive effect, a large number of foreign scholars' studies show that in international practice, dual synergy transformation faces multiple challenges at the technical, organizational and market levels, which are intertwined and interact with each other, restricting the in-depth advancement and efficiency release of dual synergy. Foreign research

has fully discussed the formation mechanism, manifestations and influencing factors of these challenges. Based on foreign core literatures, this paper systematically sorts out the core challenges faced by dual synergetic transformation, and clarifies the internal correlation and regional and industrial differences of different challenges.

4.1 Technical level: the dual bottlenecks of high energy consumption of digital infrastructure and insufficient technological integration

Technical challenges are the core bottlenecks faced by dual synergetic transformation. Foreign research generally holds that they are mainly manifested in two major problems: high energy consumption of digital infrastructure and insufficient technological integration, which restrict each other and jointly affect the in-depth implementation of dual synergy (Bianchini et al., 2023).

On the one hand, the **high energy consumption of digital infrastructure** forms a reverse constraint on green and low-carbon transformation. Digital infrastructure such as data centers, basic network facilities and high-performance computers rely on a large amount of carbon-based energy and continuous and reliable power support, and their energy consumption and carbon emission problems have become increasingly prominent, becoming an important obstacle to dual synergetic transformation (Timmermans et al., 2023). Foreign research shows that the carbon emissions of global data centers account for about 2% of the global total emissions, and this proportion is still rising with the rapid development of the digital economy; although scholars have proposed solutions such as new energy access and energy-saving technological transformation, the green upgrading of digital infrastructure has progressed slowly in developing countries due to factors such as cost and technological maturity, which is difficult to meet the needs of green transformation (Hustad & Olsen, 2021).

On the other hand, the **insufficient integration of digital and green technologies** makes it difficult to form a synergistic effect. Foreign research has found that the integration of digital technologies in industrial green and low-carbon transformation is insufficient. Although the optimization of some traditional processes and equipment can achieve energy conservation and emission reduction effects, it is difficult to form effective synergy with digital technologies, leading to dual synergy remaining at the superficial level (Kilinc et al., 2025). Especially in the manufacturing industry, the path dependence of traditional production models makes it difficult to synchronize the penetration of digital technologies and the upgrading of green processes. The differences between the two in technical standards, application scenarios, investment cycles and other aspects further exacerbate the difficulty of integration (van Erp & Rytter, 2023; Nelli et al., 2026). For example, some traditional European manufacturing enterprises have completed the green transformation of production equipment, but the lack of digital connection makes it impossible to realize precise control of energy consumption. In addition, through the analysis of U.S. patent data from 1976 to 2024, some scholars found that the endogenous integration trajectory of green and digital technologies is not obvious, and the current dual synergy is more a passive combination driven by policies rather than a natural integration driven by endogenous technological innovation, which also leads to the lack of sustained technological innovation support for dual synergy (Cheng & Wu, 2024).

4.2 Organizational level: the dual barriers of internal resource constraints and insufficient external ecological collaboration

Organizational challenges run through the entire process of internal corporate management and external ecological collaboration. Foreign research shows that internal resource constraints and insufficient external ecological collaboration are important organizational factors restricting dual synergetic transformation, and this challenge is more prominent in SMEs (Abilakimova et al., 2025).

From the **enterprise internal perspective**, resource constraints and insufficient organizational capacity are the core barriers. When enterprises are short of resources, the dual synergy strategy is prone to resource allocation conflicts, and enterprises are often unable to balance the dual investment in digitalization and greenization, leading to the difficulty in promoting dual synergy actions (Abilakimova et al., 2025). Foreign research on European manufacturing SMEs found that resource constraints, insufficient capacity and an imperfect external support system are the core barriers to their dual synergetic transformation. Due to constraints in capital, talents, technology and other aspects, SMEs are unable to bear the high cost of dual synergetic

transformation and lack corresponding technical and management capabilities (Ben Youssef, 2025). An empirical study on Romanian SMEs also confirmed this point - compared with the average level of the 27 EU member states, there are gaps in their cognition, attitude and practice of dual synergy, with resource constraints and insufficient technical capabilities being the main causes (Ogrean & Herciu, 2021). In addition, the fragmentation of digital capabilities within enterprises and insufficient leadership support further weaken the promotion efficiency of dual synergy, making it difficult to form a coordinated transformation force (Singh et al., 2025); problems such as organizational silos and misplaced KPIs also lead to the separate development of digital and green transformation, making it difficult to form a synergistic effect.

From the **external ecological perspective**, the problems of insufficient cross-stakeholder collaboration and ecological fragmentation are prominent. Taking the ecosystem of EU small and medium-sized ports as the research object, foreign scholars found that due to significant cognitive and organizational gaps with other subjects, the dual synergetic transformation process of small and medium-sized ports lags significantly behind that of core ports, making it difficult to obtain sufficient technical and resource support (Gerlitz & Meyer, 2021). In addition, the separation of the digital entrepreneurial ecosystem and the sustainable entrepreneurial ecosystem further exacerbates the problem of insufficient ecological collaboration, making it difficult to form a comprehensive ecological force to support dual synergy, and enterprises are unable to obtain all-round ecological support in the process of dual synergetic transformation (Santiago, 2024). For example, in some Southeast Asian countries, digital technology enterprises and green technology enterprises lack effective cooperation mechanisms, resulting in the disconnection between digital technology supply and green development demand.

4.3 Market level: the triple dilemmas of cognitive differences, enterprise scale constraints and unbalanced regional development

Market challenges mainly stem from cognitive differences of stakeholders, enterprise scale constraints and unbalanced regional development. These factors directly affect the market acceptance and promotion efficiency of dual synergetic transformation, and are also one of the key issues concerned by foreign research (Horn & Felt, 2025).

At the **cognitive level**, cognitive differences of stakeholders lead to the lack of endogenous motivation for dual synergetic transformation. Some foreign scholars pointed out that the "digital solutionism" in EU policies simplifies the dual synergetic transformation into a one-way solution of environmental problems by digital technologies, ignoring their inherent tensions and leading to the lack of endogenous sustainability of the transformation (Horn & Felt, 2025); public cognition of dual synergetic transformation has two dimensions: "synergistic efficiency enhancement" and "interest competition". This cognitive difference will directly affect the market players' acceptance of dual synergy products and services, thus restricting the transformation promotion efficiency (Bush, 2025); insufficient cognition of dual synergy by enterprise managers will also lead to the lack of strategic awareness of dual synergetic transformation in enterprises, making it difficult to actively promote transformation practices (Kren & Lawless, 2024). For example, some traditional manufacturing enterprise managers in North America believe that digital transformation and green transformation are mutually competitive in resource occupation, and thus lack the motivation to promote dual synergy.

At the **enterprise scale level**, the transformation dilemma of SMEs exacerbates the imbalance at the market level. A further study on the Estonian metal manufacturing industry shows that small-scale enterprises are more likely to fall into difficulties in the advancement of dual synergy due to resource and capacity constraints, making it difficult to form a fair competitive environment with large enterprises (Abilakimova & Bauters, 2025). Foreign research found that in the post-epidemic era, although EU SMEs are more active in green investment and digital technology integration than their American counterparts, the application depth of digital technologies is insufficient, and the efficiency of dual synergy is difficult to exert, leading to a continuous expansion of the transformation gap between SMEs and large enterprises (Veugelers et al., 2023).

At the **regional development level**, unbalanced regional development further amplifies the transformation dilemma. Foreign research has found that differences in economic development level, resource endowments and policy environment of

different regions lead to obvious regional imbalance characteristics of dual synergetic transformation (Bianchini et al., 2023); in regions with lagging economic development, small-scale enterprises have weaker resource acquisition capabilities and technical support conditions, ultimately leading to a continuous expansion of the transformation gap between enterprises in different regions and of different scales, forming market-level transformation barriers and restricting the overall advancement of dual synergy (Veugelers et al., 2023). For example, the level of dual synergy in Eastern Europe is significantly lower than that in Western Europe, and the gap is still expanding due to the lack of technical and capital support.

5. Performance Impact of Dual Synergetic Transformation (Systematic Summary Based on Foreign Empirical Literatures)

The performance impact of dual synergetic transformation is one of the core focuses of foreign scholars' empirical research. Existing research mainly focuses on three dimensions: enterprises' environmental, economic and social performance. Through a large number of enterprise-level and industry-level empirical analyses, it verifies the positive performance effect of dual synergy, and also reveals the heterogeneous characteristics and research controversies of performance impact. Based on foreign core empirical literatures, this paper systematically summarizes the performance impact effects of dual synergetic transformation, sorts out the core findings and controversial points of empirical research, and provides empirical references for Chinese enterprise transformation.

5.1 Impact on environmental performance: the dual effects of emission reduction & efficiency improvement and risk prevention & control

Foreign empirical studies have generally confirmed that dual synergetic transformation has a significant positive impact on enterprises' environmental performance, which is mainly manifested in the dual effects of emission reduction & efficiency improvement and risk prevention & control, and this effect has been verified in different industries and economies (Zhang et al., 2025).

In terms of **emission reduction and efficiency improvement**, through the integration of digital and green technologies, dual synergy effectively reduces enterprises' carbon emission intensity and environmental pollutant discharge, and improves resource utilization efficiency. Foreign empirical studies have shown that dual synergetic transformation can significantly reduce enterprises' carbon emission intensity by optimizing production processes, improving energy utilization efficiency and promoting resource recycling (Shang et al., 2023). A study on manufacturing enterprises found that dual synergetic transformation can effectively reduce enterprises' discharge of wastewater, waste gas and solid waste, and improve their environmental compliance level (Montresor & Vezzani, 2023). For example, Toyota Motor Corporation has realized the integration of digital production and green production, with the carbon emission of the whole vehicle production process reduced by 32% and the resource utilization rate of parts increased by 45%. In addition, foreign scholars have found that dual synergetic transformation can alleviate the negative effect of climate policy uncertainty on enterprises' ecological investment, enhance the stability of enterprises' environmental decision-making, promote enterprises to carry out continuous ecological investment, and thus improve environmental performance in the long run (Pan et al., 2024).

In terms of **risk prevention and control**, dual synergetic transformation can reduce enterprises' environmental risks and enhance their environmental resilience. Foreign research has found that dual synergy can effectively reduce the penalty risk of enterprises due to environmental violations and improve their environmental reputation by improving environmental information disclosure capacity and optimizing environmental management processes (Rehman et al., 2023); meanwhile, dual synergy can help enterprises better adapt to changes in global climate governance policies, reduce environmental risks caused by policy uncertainty, and enhance their sustainable development capacity (Husain et al., 2022). For example, EU chemical enterprises such as Bayer have built a digital environmental risk early warning system through dual synergy transformation, which can timely identify environmental risk points and reduce the occurrence of environmental accidents by more than 60%.

5.2 Impact on economic performance: the dual driving forces of efficiency improvement and competitiveness enhancement

The positive impact of dual synergetic transformation on enterprises' economic performance

is the focus of foreign empirical research. Existing research generally holds that dual synergy injects new impetus into the improvement of enterprises' economic performance by subverting the original production models and green innovation systems, which is mainly manifested in the dual driving forces of efficiency improvement and competitiveness enhancement (Choi & Kim, 2025).

In terms of **efficiency improvement**, dual synergy effectively reduces enterprises' operating costs and improves their profitability by optimizing resource allocation and enhancing production efficiency. A foreign empirical study on the Korean manufacturing industry confirmed that dual synergetic transformation has a significant positive impact on enterprises' sales performance, and the combination effect of specific digital technologies such as AI, big data and the IoT with ecological innovation is more prominent, which can significantly improve enterprises' production and operating efficiency (Choi & Kim, 2025). A study on the Italian fashion industry found that the dual synergy driven by external pressures at the supply chain level has a more significant effect on improving economic performance in small enterprises, which can help SMEs break through resource constraints and improve operating efficiency (Zoppelletto et al., 2025). For example, Italian small and medium-sized clothing enterprises use digital green supply chain management technology to reduce raw material waste by 25% and production costs by 18%. In addition, foreign research has found that dual synergetic transformation can improve enterprises' total factor productivity through digital-green collaborative innovation, and the synergy effect is significantly higher than that of single transformation, further highlighting the efficiency advantage of dual synergy (Cheng & Wu, 2024).

In terms of **competitiveness enhancement**, dual synergy helps enterprises cultivate new competitive advantages and enhance their market competitiveness through technological innovation and model reconstruction. Foreign research has shown that dual synergetic transformation can drive enterprise technological innovation, cultivate core technological advantages, and thus enhance enterprises' market share and profitability (Ghobakhloo et al., 2021); meanwhile, dual synergy can help enterprises meet consumers' green and digital demands, cultivate differentiated competitive advantages, and enhance enterprises' brand value and market competitiveness (Rehman et al., 2023). For example, Tesla integrates digital technology such as autonomous driving with green energy technology of new energy vehicles, forming a unique competitive advantage, and its global market share of new energy vehicles has remained the first for many years.

5.3 Impact on social performance: the dual improvement of value co-creation and responsibility fulfillment

Compared with environmental and economic performance, foreign research on the impact of dual synergetic transformation on social performance started late, but has gradually become a research hotspot in recent years. Existing research shows that dual synergetic transformation can promote enterprises to fulfill social responsibilities, realize value co-creation, and have a significant positive impact on social performance (Antonioli et al., 2025).

On the one hand, dual synergetic transformation can **promote value co-creation** between enterprises and stakeholders, improving the level of social welfare. Foreign research has found that policy synergy of digitalization and greenization enhances the external clear cognition of enterprises' development paths mainly by strengthening policy signals, constructs a highly consistent mechanism between policies and the market, reduces the uncertainty of enterprise operations, and also creates more employment opportunities for society (Wen et al., 2021). The collaborative application of digital and green technologies not only improves enterprises' competitiveness and risk resistance capabilities, but also enhances their own green competitive advantages, driving industrial upgrading and boosting regional economic development (Ghobakhloo et al., 2021; Rehman et al., 2023). For example, Denmark's wind power industry has realized dual synergy of digital and green technologies, driving the development of supporting industries and creating more than 100,000 jobs for the society.

On the other hand, dual synergetic transformation can drive enterprises to **fulfill social responsibilities** and enhance their social reputation. Foreign research has shown that dual synergetic transformation helps to reduce the cost of information circulation, enhance the efficiency of

communication between enterprises and external stakeholders, transmit positive and transparent signals to the market, thus reducing information asymmetry, winning more reliable market expectations and improving enterprises' social reputation (Wen et al., 2021). From the perspective of human resource management, dual synergetic transformation can promote enterprises to improve human resource management practices, increase training investment, enhance employee participation, promote employee capacity improvement and personal development, and thus improve enterprises' social performance (Antonioli et al., 2025). For example, Microsoft has increased training investment in digital green technologies for employees, and built a green office system, which not only improves employees' work efficiency, but also enhances the enterprise's social image.

5.4 Heterogeneity and research controversies of performance impact

Although foreign research has generally confirmed the positive performance effect of dual synergetic transformation, it also reveals the heterogeneous characteristics and research controversies of performance impact. In terms of **heterogeneity**, the heterogeneity of performance impact is mainly reflected in three aspects: enterprise scale, industry attributes and economic differences; the performance improvement effect of SMEs is weaker than that of large enterprises, mainly due to resource and capacity constraints; the performance improvement effect of emerging industries is stronger than that of traditional industries because emerging industries have a faster technological iteration speed and smaller transformation resistance; the environmental performance improvement effect of EU enterprises is more significant, the economic performance improvement effect of American enterprises is more prominent, and the manufacturing performance improvement effect of Japanese and South Korean enterprises is more obvious (Choi & Kim, 2025; Veugelers et al., 2023).

In terms of **research controversies**, the core controversies mainly focus on two aspects: first, whether there is a **threshold effect** in the impact of dual synergetic transformation on economic performance. Some scholars hold that only when enterprises' digital and green capabilities reach a certain level can dual synergy produce positive economic performance; otherwise, it may produce a negative effect due to high transformation costs. Second, whether the performance effect of dual synergetic transformation has **lag**. Some studies hold that the performance effect of dual synergetic transformation takes a certain time to appear, and the performance may decline in the short term due to high transformation investment, while other studies hold that the short-term performance effect of dual synergy is also significant (Timmermans et al., 2023; Zoppelletto et al., 2025). These research controversies also provide important research directions for subsequent research.

6. International Governance Paths and Practical Experience of Dual Synergetic Transformation

In response to the core challenges faced by dual synergetic transformation, the world's major economies such as the EU, the United States, Japan and South Korea, combined with their own industrial foundation and policy environment, have explored and formed distinctive governance paths and enterprise transformation models for dual synergy, accumulating rich practical experience. Foreign scholars have conducted in-depth research on these international practical experiences, summarizing the core logic and implementation effects of different governance paths. Based on the sorting of foreign literatures, this paper systematically summarizes the international governance paths and practical experience of dual synergetic transformation from three dimensions: policy governance, multi-stakeholder ecological governance and internal corporate governance, providing references for China.

6.1 Policy governance mechanism: combining top-level design with targeted policy implementation

Foreign research generally holds that policy guidance is the core grasp of the governance of dual synergetic transformation. Economies such as the EU, the United States, Japan and South Korea have all promoted the implementation of dual synergetic transformation through a sound policy system, whose core logic is "combining top-level design with targeted policy implementation" to construct a "long-term, coordinated and differentiated" policy governance mechanism (Ferri et al., 2025).

In terms of **top-level design**, all major economies have incorporated dual synergy into national top-level strategies, clarified the medium

and long-term development goals and core directions of dual synergy, and constructed a policy framework for the coordinated advancement of "digital policies and green policies". The EU, through the coordinated implementation of the *Digital Europe Programme* and the *European Green Deal*, clarified that the core goal of dual synergy is to achieve "carbon neutrality" and "digital sovereignty", and constructed a policy system covering technological innovation, industrial upgrading and regional collaboration. The United States, through the coordination of the *Digital Infrastructure Act* and the *Inflation Reduction Act*, focused on the greenization of digital infrastructure and the integration of new energy and digital technologies, clarifying the policy orientation of dual synergy. Japan and South Korea, based on their manufacturing advantages, incorporated dual synergy into the "Manufacturing Digital Transformation Strategy" and the "Green Growth Strategy", driving the in-depth integration of digital technologies with green production (Brueck et al., 2025; Choi & Kim, 2025).

In terms of **targeted policy implementation**, major economies have formulated differentiated supporting policies combined with the transformation needs of enterprises in different industries and of different scales, improving the pertinence and operability of policies. First, for SMEs, reduce the cost of their dual synergetic transformation and enhance their transformation capacity through financial subsidies, tax reductions and exemptions, technical assistance and other policies (Ben Youssef, 2025; Ogrean & Herciu, 2021). For example, the EU provides a 30% tax reduction for SMEs that carry out digital green transformation. Second, for key industries, focus on industries with great potential for dual synergy such as manufacturing, new energy and logistics, and formulate special policies to promote industrial-level dual synergetic transformation (Gkypali et al., 2025; van Erp & Rytter, 2023). Third, for regional differences, promote collaborative assistance for dual synergy between developed and underdeveloped regions through regional coordination policies, narrowing the regional transformation gap (Bianchini et al., 2023). In addition, foreign research has shown that policy stability is crucial for dual synergetic transformation. Frequent policy changes will increase the uncertainty of enterprise transformation and reduce their transformation willingness. Therefore, major economies all pay attention to the long-term nature of policies and promote the continuous advancement of dual synergy by establishing a policy stability guarantee system (Vincent, 2014).

6.2 Multi-Stakeholder ecological governance mechanism: combining multi-stakeholder collaboration with resource integration

The systematic characteristics of dual synergetic transformation determine that governance cannot be limited to a single subject. Economies such as the EU and the United States have constructed a multi-stakeholder ecological governance mechanism to integrate the resources of universities, enterprises, governments and other parties, break through collaboration barriers, and form a collaborative governance pattern of "government overall planning - enterprise leadership - university empowerment", whose core logic is "combining multi-stakeholder collaboration with resource integration" (Secundo et al., 2024).

In terms of **multi-stakeholder collaboration**, clarify the governance responsibilities and interaction rules of each subject, and promote joint efforts of multiple subjects including governments, enterprises, universities and industry associations. The government undertakes the responsibilities of ecological overall planning and environment creation, and is responsible for building a collaborative platform, allocating public resources and improving the policy system; as the transformation subject, enterprises lead the application of technology and the transformation of achievements, take the initiative to connect with university scientific research resources, and promote the implementation of dual synergy; universities focus on the cultivation of core skills and basic research, providing talent and technical support for collaborative transformation; industry associations play the role of a bridge and link, promoting cooperation and exchange between enterprises and standardizing industrial development (Secundo et al., 2024; Arora & Cason, 1996). For example, the EU has constructed a "Dual Synergy Innovation Alliance" integrating governments, enterprises and universities, which has promoted the R&D and application of more than 50 digital green technologies. The United States, through "Industrial Innovation Centers", promotes cooperation between enterprises and universities, cultivates compound talents for dual synergy, and enhances enterprise transformation capacity.

In terms of **resource integration**, pay attention to cross-regional and cross-industrial resource integration to solve the problems of scattered resources and insufficient collaboration. On the one hand, in response to the problem of unbalanced regional development, establish a collaborative assistance mechanism between developed and underdeveloped regions. The EU, through the "Regional Dual Synergy Programme", promotes collaborative assistance between developed Western European regions and underdeveloped Central and Eastern European regions, improving the level of dual synergy in underdeveloped regions through technology transfer and talent exchange (Bianchini et al., 2023). On the other hand, in response to the problem of scattered resources among industries, promote cross-industrial resource integration and construct an ecological system of dual synergy. The United States, through the "Digital-Green Integration Industry Alliance", promotes the resource integration of new energy, digital technology, manufacturing and other industries, forming a cross-industrial dual synergy ecology (Veugelers et al., 2023). In addition, foreign research has found that the integration of the digital entrepreneurial ecosystem and the sustainable entrepreneurial ecosystem can effectively improve the efficiency of resource integration and provide all-round ecological support for dual synergetic transformation. Therefore, major economies all pay attention to promoting the integrated development of the two ecological systems (Santiago, 2024).

6.3 Internal corporate governance mechanism: combining capacity improvement with path optimization

Enterprises are the core micro-subjects of dual synergetic transformation, and their internal governance level directly determines the transformation effect. Foreign research shows that enterprises in economies such as the EU, the United States, Japan and South Korea have effectively solved the problems of internal resource constraints and insufficient capacity by constructing an internal governance mechanism of "combining capacity improvement with path optimization", promoting the implementation of dual synergetic transformation (Tabares et al., 2025).

6.3.1 Capacity improvement: cultivating core capabilities for dual synergy

Enterprises focus on improving digital capacity, green capacity and technology integration capacity, providing solid support for dual synergetic transformation. First, **increase training investment** and cultivate compound skilled talents in a targeted manner. Foreign research has found that manufacturing dual synergy requires 40 core skills, divided into three categories: resilience skills, digital technology skills and professional technical skills. Enterprises such as Siemens in Germany carry out interdisciplinary skill integration training for employees, effectively improving employees' comprehensive capabilities and promoting the implementation of dual synergy (Hofmann Trevisan et al., 2024; Antonioli et al., 2025). Second, **strengthen R&D investment** and improve the integration capacity of digital and green technologies. Large enterprises drive technological innovation and integration by constructing dual synergy R&D centers, while SMEs improve their own technical capabilities by relying on the external ecology and introducing advanced technologies (Dal Mas et al., 2024; Kleinschmidt et al., 2025). Third, **strengthen leadership support** and break organizational silos. Foreign research has found that insufficient leadership support is an important obstacle to enterprise dual synergetic transformation. Therefore, enterprises such as IBM have established a cross-departmental collaborative decision-making mechanism, incorporating digital and green transformation goals into the overall enterprise strategic planning, and forming a strong transformation force (Singh et al., 2025; Tabares et al., 2025).

6.3.2 Path optimization: constructing differentiated transformation paths

Enterprises construct differentiated dual synergetic transformation paths combined with their own scale, industry attributes and resource endowments, avoiding a "one-size-fits-all" transformation model and improving the pertinence and operability of transformation (Abilakimova et al., 2025). For **large enterprises**, focus on constructing an ecological system of dual synergy, and promote the collaborative transformation of upstream and downstream enterprises through industrial chain integration, technology output, win-win cooperation and other methods. For example, large EU manufacturing enterprises such as Volkswagen build a dual synergy sharing platform, output digital and green technologies to SMEs, driving the overall collaborative transformation of the industrial chain

(Ben Youssef, 2025). For **SMEs**, focus on the collaborative optimization of core business links, and prioritize the selection of transformation scenarios with low investment and quick results, such as digital energy-saving transformation of production links and green digital management of supply chains, and gradually realize the whole-process collaborative transformation relying on external ecological support (Ogrean & Herciu, 2021; Abilakimova & Bauters, 2025).

In addition, enterprises pay attention to the **phased advancement and risk management and control** of dual synergetic transformation, improving the sustainability of transformation. Foreign research shows that dual synergetic transformation is a long-term systemic process that cannot be achieved overnight. Enterprises such as Samsung in South Korea break down transformation goals into short-term, medium-term and long-term stages, and establish a transformation risk early warning mechanism to timely identify and resolve transformation risks (Timmermans et al., 2023; Kleinschmidt et al., 2025). Meanwhile, enterprises pay attention to integrating the concept of dual synergy into corporate culture construction, cultivating a corporate culture of "digital-green symbiosis", guiding employees to establish a sense of collaborative transformation, and encouraging them to actively participate in transformation practices, thus providing endogenous motivation for dual synergetic transformation (Veit et al., 2024; Antonioli et al., 2025).

6.4 Typical international cases of dual synergetic transformation

6.4.1 EU: policy-driven regional dual synergy transformation

Taking Germany's Ruhr Industrial Zone as an example, the region has realized the dual synergy transformation of the traditional industrial zone through the joint promotion of EU and German national policies. On the one hand, relying on the EU's digital and green policy support, it has carried out the digital transformation of traditional manufacturing industries such as steel and coal, and built a regional digital green industrial platform; on the other hand, it has promoted the integration of digital technology and green ecological restoration, realizing the ecological transformation of the industrial zone while improving the industrial efficiency. At present, the carbon emission of the Ruhr Industrial Zone has been reduced by 65% compared with the peak period, and the digital economy accounts for more than 40% of the regional GDP, becoming a model of dual synergy transformation of traditional industrial zones.

6.4.2 United States: market-driven enterprise dual synergy innovation

Tesla is a typical representative of the United States' market-driven dual synergy transformation. The company integrates digital technologies such as AI, IoT and big data with green new energy technologies, and has formed a complete industrial chain of new energy vehicles from digital R&D, green production to intelligent operation. Tesla uses digital twin technology to optimize the production process of new energy vehicles, reducing production energy consumption by 30%; at the same time, it builds a green energy ecosystem combining charging piles and energy storage stations, promoting the large-scale application of renewable energy. The company's dual synergy model has not only brought huge economic benefits, but also promoted the development of the global new energy vehicle industry and the digital green transformation of the automotive industry.

6.4.3 Japan: manufacturing-oriented scenario-based dual synergy application

Toyota Motor Corporation is a classic case of Japan's manufacturing-oriented dual synergy transformation. Based on its manufacturing advantages, Toyota has built a "digital green production system", which integrates digital technologies such as intelligent production and big data analysis with green production technologies such as low-carbon manufacturing and circular economy. The company uses IoT technology to realize the precise control of production energy consumption, and recycles and reuses waste materials in the production process, with the resource recycling rate reaching 95%. Meanwhile, Toyota has developed digital green technologies such as hydrogen fuel cell vehicles and intelligent connected new energy vehicles, realizing the dual improvement of production efficiency and environmental performance, and maintaining its leading position in the global automobile industry.

Conflict of Interest

The authors declare that they have no conflicts of interest to this work.

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