

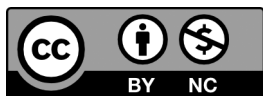
“Education-Technology-Industry” Cyclic Linkage: Research on the Collaborative Mechanism of Industry-Education Integration Empowering Carbon Neutrality

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Abstract: Guided by the “Dual carbon” strategy, this study utilizes the “Education-Technology-Industry” cyclic linkage framework to construct a curriculum support system for carbon neutrality goals. It establishes a core closed-loop concept: Education cultivates talent, talent drives technology, technology upgrades industry, and industry feeds back into education. The research proposes a new construction model featuring “Curriculum ideology and politics” as the value guide, a “Knowledge internalization→Ability conversion→Practice externalization” integrated teaching method, and diversified comprehensive evaluation. Translating collaborative modes, such as curriculum co-construction and platform sharing, into actionable plans, the system aims to cultivate composite talents possessing green technological capabilities and social responsibility. This approach offers a systematic solution for cross-domain collaborative education reform facing carbon neutrality.

Keywords: Carbon neutrality; Industry-education integration; Curriculum construction; Cyclic linkage; Carbon neutrality education



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1 Introduction

The severe challenge of global climate change has driven China to establish the strategic goals of “Carbon peaking and carbon neutrality,” marking a profound systemic transformation in the nation’s economic and social development. Achieving this ambitious goal requires not only a technological revolution in the energy system and the green transformation of industrial structures, but also places urgent demands for systemic innovation on the talent cultivation models of higher education. Carbon neutrality is essentially a complex engineering system involving multiple dimensions such as technology, economics, and policy. It requires future talents to not only master professional technical knowledge but also possess interdisciplinary integration capabilities, complex problem-solving skills, and sustainable development values. However, the current higher education system faces severe structural contradictions in

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supporting carbon-neutral talent cultivation: the current state of knowledge systems faces challenges in keeping pace with rapid technological advancements.

These contradictions are concentrated at two key levels. First, there are institutional obstacles to deep industry-education integration. Although school-enterprise cooperation has been practiced for many years, the misalignment between educational supply and industrial demand is particularly prominent in the emerging frontier field of carbon neutrality. There is an inherent tension between the long cycle of university talent cultivation and the rapid iteration of industrial technologies, resulting in graduates often requiring a long adaptation period to meet job requirements. Simultaneously, the channel for transforming university research innovation results into industry is not fully unimpeded, and a large amount of frontier knowledge fails to be timely converted into educational resources. Second, there is a systemic lag in curriculum construction. Existing carbon neutrality-related courses are mostly fragmented, lacking interdisciplinary systemic integration; teaching content emphasizes theoretical exposition while detaching from practical application scenarios; and value-leading elements are not organically integrated into the professional knowledge system, making it difficult to fully release the comprehensive efficacy of talent cultivation.

To solve this predicament, it is urgent to build a new theoretical framework and educational practice model. This study introduces the “Education-Technology-Industry” cyclic linkage framework as the core analytical perspective. Derived from the Triple Helix theory in innovation research, this framework emphasizes the new relationship of blurred boundaries, overlapping roles, and collaborative evolution among educational institutions, research systems, and industrial sectors in a knowledge society. In the specific context of carbon neutrality, this framework manifests as a virtuous cycle system of “Education cultivates talent — Talent drives technology — Technology upgrades industry — Industry feeds back into education”. In this ecosystem, education is not only a place for knowledge dissemination but also the source of innovative ideas and green culture; technological research and development (R&D) becomes the bridge connecting theory and practice; and industry provides the ultimate field for value realization and the key source of demand feedback.

However, a significant transformation gap remains between the conceptualization of cyclic linkage and concrete educational practice, particularly in curriculum construction — the core link of talent cultivation. Existing research either focuses on macro-level discussions of industry-education integration mechanisms or concentrates on micro-level development of single courses, lacking a systematic construction of an actionable, replicable, and assessable curriculum support system at the meso-level. This is the core concern of this study: how to systematically translate the “Education-Technology-Industry” cyclic linkage concept into practical curriculum construction schemes, thereby truly empowering the cultivation of carbon neutrality professionals.

Based on this, the study aims to build a systematic curriculum construction support system. This system takes “Curriculum ideology and politics” as the value guide, the “Knowledge internalization → Ability conversion → Practice externalization” three-dimensional integration as the teaching method, the intra-curricular and extra-curricular dual loop as the team guarantee, and diversified comprehensive evaluation as the quality orientation. This system focuses not only on the updating of knowledge content but also on the innovation of teaching methods, the optimization of faculty structures, and the improvement of evaluation mechanisms, striving to organically integrate industrial needs, technological frontiers, and educational laws to provide a complete solution for the cultivation of composite talents in the field of carbon neutrality.

Theoretically, this study combines the Triple Helix innovation theory with China’s specific practice of industry-education integration. It implements it into the micro-carrier of curriculum construction, helping to enrich the

educational reform theory system oriented toward major national strategic needs. Practically, the constructed curriculum support system provides an operable reference framework for higher education institutions to carry out carbon neutrality-related major construction and curriculum reform, helping to promote higher education to better serve the national “Dual carbon” strategy.

2 Literature Review

2.1 Sustainable Education

Since the “Brundtland report” formally proposed the concept of sustainable education in 1987, education has been endowed with a core role in global transformation. Its core philosophy has evolved from early environmental education focused on knowledge dissemination to education for sustainable development (ESD), emphasizing critical thinking, systems thinking, future orientation, and value shaping, aimed at empowering learners with the knowledge, skills, attitudes, and values to address complex sustainability challenges (Sterling & Orr, 2001; Wals, 2014).

In higher education, the integration of sustainable education has undergone a deepening process from adding independent courses to promoting institution-wide transformation. Research indicates four main implementation paths: injecting sustainability content into existing courses; developing specialized interdisciplinary sustainability courses or minors; making sustainability a core principle of institutional operations and culture; and collaborating with communities and enterprises on project-based learning rooted in real-world problems (Lozano et al., 2013; Strielkowski et al., 2025). Recent studies have particularly focused on how education responds to the urgent issues of climate change and carbon neutrality. Leal et al. (2023) systematically reviewed global university practices in addressing climate change, pointing out the necessity of synergy among curriculum reform, campus carbon neutrality actions, and community outreach (Leal et al., 2023).

However, the implementation of sustainable education concepts still faces deep-seated challenges. First is the risk of superficiality, where sustainability is merely attached as a label to traditional courses without triggering profound changes in teaching paradigms and learning experiences (Cotton et al., 2013). Second is the lack of systemic design; most practices remain at the level of fragmented projects, lacking overall design from training objectives and curriculum systems to teaching methods and evaluation standards (Brundiens et al., 2010). Third is the disconnection between educational content and the rapidly developing green technology and industrial needs. Although the concept emphasizes future orientation, course content often lags behind technological innovation and business model iteration in fields like clean energy and the circular economy. Therefore, constructing a resilient education system capable of dynamically responding to external green transformation demands has become a frontier topic in current sustainable education research (Borazon & Chuang, 2023).

2.2 Industry-Education Integration Models

As a key mechanism connecting education and industry, industry-education integration has evolved in the Chinese context from school-enterprise cooperation to deep integration in policy and practice. The issuance of documents such as the “Implementation plan for national industry-education integration construction pilots” marks its elevation to an important institutional arrangement for national education reform and human resource development. Its theoretical connotation is

constantly enriching, understood as a process of optimizing the allocation of educational and industrial resources, and the organic connection of the industrial chain, innovation chain, education chain, and talent chain (Qi & Feng, 2025).

In the field of green and low-carbon development, industry-education integration has been given a new mission. Scholars have explored collaborative education mechanisms oriented toward strategic emerging industries such as new energy and energy conservation and environmental protection, emphasizing the need to dynamically adjust professional directions in combination with industrial technology roadmaps (Kong, 2025; Zhuang & Zhou, 2023). However, regarding the cross-field, multi-dimensional systemic goal of carbon neutrality, existing industry-education integration practices reveal obvious limitations. First, cooperation content is mostly concentrated on skills training and internship provision, with insufficient intervention in industrial frontier technology R&D, complex engineering problem solving, and the upstream innovation chain, leading to a lack of innovation and foresight in talent cultivation (Zhu & Ouyang, 2024). Second, the stability and sustainability of cooperation face challenges, often constrained by factors such as short-term corporate interest fluctuations, unclear intellectual property rights, and a lack of long-term benefit-sharing mechanisms (Liu et al., 2025). Third, most industry-education integration projects have failed to effectively build a closed-loop system that couples real industrial needs and technological R&D processes with educational activities in real-time and at depth. This makes it difficult for the education side to accurately capture and quickly respond to the rapidly changing technological and format changes under the carbon neutrality goal.

2.3 Triple Helix Theory

The “Triple Helix” theory, proposed by Etzkowitz and Leydesdorff in the 1990s, provides a classic analytical model for understanding the interactive relationship between university, industry, and government in the modern knowledge economy (Etzkowitz, 2003). The core argument is that under the innovation-driven development model, the boundaries of the three major institutional spheres — university, industry, and government — tend to blur, functions overlap, and they form a spiraling collaborative innovation relationship through continuous interaction and collaboration, rather than simple linear transfer or static division of labor. Among them, universities increasingly assume entrepreneurial roles in addition to traditional teaching and research functions; industries not only engage in production but also strengthen R&D and learning functions; and the government acts not only as a regulator but also as a builder and partner of the innovation ecosystem (Rådberg & Löfsten, 2024; Rafiq et al., 2024).

This theory has been widely applied and verified in areas such as regional innovation systems and industrial cluster development. Research shows that successful innovation ecosystems often rely on intensive knowledge flow, resource exchange, and role complementarity among the three forces (Cai & Etzkowitz, 2020). For example, universities generate new knowledge through basic research to provide technology and talent for industry; Industry provides direction and resources for university research through applied research and market feedback; And the government guides and catalyzes cooperation through policies, funding, and platform construction (Leydesdorff & Meyer, 2006). In recent years, the Triple Helix model has been further expanded to analyze innovation oriented toward social challenges, such as sustainable development and climate change, emphasizing that “University-Industry-Government” needs to build mission-oriented innovation alliances around specific social goals (Schot & Steinmueller, 2018).

In China, the “Triple Helix” theory is widely cited to analyze industry-university-research cooperation, science park construction, and innovative city development (Xiong et al., 2025). Scholars have combined China’s unique institutional environment to explore the dominant role of the government in the synergy of “Government-Industry-University-

Research-Application” and the emergence of hybrid organizations such as new R&D institutions (Xia & Zhang, 2025). However, the systematic application of the Triple Helix theory to guide the educational process itself, especially curriculum and teaching reform, is insufficient. Existing applications mostly remain at the level of macro-institutional mechanisms and rarely delve into the micro-teaching level of talent cultivation.

Therefore, this study focuses on the university dimension in the Triple Helix on its core educational function, retains the production and innovation function of the industry dimension, and internalizes the government’s macro-policy role into the powerful external driving and normative force of the national “Dual carbon” strategic goal, while taking the technology dimension as the key bridge connecting education and industry. The resulting “Education-Technology-Industry” cyclic linkage framework is a concrete and operational extension of the Triple Helix theory into the field of curriculum and teaching under the major era proposition of carbon neutrality, aimed at revealing how the three can realize the dynamic circulation and collaborative appreciation of knowledge, resources, and values in micro-teaching practice.

3 “Education-Technology-Industry” Cyclic Linkage

The core of the “Education-Technology-Industry” cyclic linkage concept lies in breaking the long-standing institutional barriers and functional segregation between education, technology, and industry. It views the three as an organic, dynamic, and symbiotic innovation ecosystem, as shown in Figure 1.

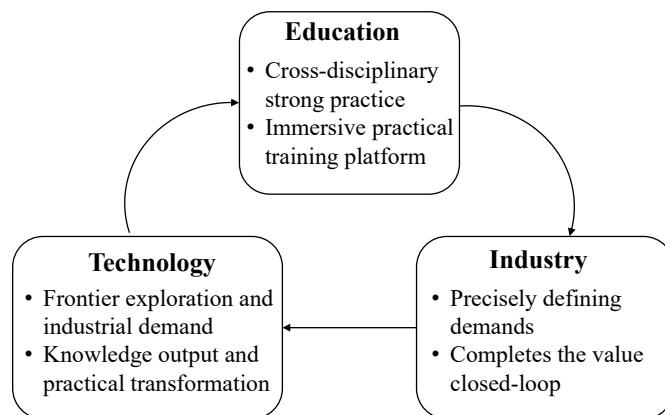


Figure 1 The “Education-Technology-Industry” Cyclic Linkage

3.1 Unified Goals

The primary prerequisite for the cyclic linkage is to establish a national “Dual carbon” strategy that transcends departmental interests and commands the overall situation. On the education side, the carbon neutrality goal translates directly into new standards for talent cultivation, promoting professional settings to align with emerging fields like new energy and carbon management, and integrating core knowledge modules such as life cycle assessment (LCA) and carbon footprint accounting into the curriculum system. On the technology side, it clarifies the priority of R&D breakthroughs, guiding research funding and intellectual resources toward key low-carbon technology areas like high-efficiency photovoltaics, new energy storage, and CCUS (Carbon capture, utilization, and storage). On the industry side, it constitutes the core driving force for transformation and upgrading, compelling enterprises to replan technology

roadmaps, invest in green capacity, and innovate business models. Therefore, the vision of carbon neutrality acts like a powerful strategic gravitational field, integrating the dispersed forces of the three parties into a resultant force pointing in the same direction, ensuring that all activities from classroom experiments and research topics to industrial projects have an intrinsic, consistent strategic directionality, fundamentally avoiding goal drift and short-term behavior in cooperation.

3.2 Education Dimension

The core mission of the education sector within this cycle is to function as an incubator for green innovation talents and a source of carbon neutrality knowledge. This effectiveness operates on two levels: First, establishing a “Cross-disciplinary - Strong practice” dynamic curriculum system. This involves transcending traditional disciplinary boundaries to offer intersectional courses (e.g., Carbon finance, Smart energy systems) and co-building content with leading enterprises to integrate the latest industry standards and real project cases instantly, and second, creating an immersive practical ability training platform. Beyond standard internships, this requires co-building industrial laboratories or on-site engineering colleges with external partners, allowing students to directly participate in pilot tests of carbon reduction technologies or carbon verification projects, thereby tempering complex problem-solving abilities within authentic professional environments.

3.3 Technology Dimension

The technology sector serves as the power source of the cyclic linkage; its core function is to provide frontier knowledge and key technical solutions through continuous R&D innovation. Its effectiveness relies on achieving two crucial connections. First, the connection between frontier exploration and industrial demand must be guaranteed. Research topics should directly respond to common technical challenges facing the industry, such as advanced methods for industrial decarbonization or innovative materials for transportation electrification. This ensures that R&D activities are precisely aligned with industrial needs, maximizing the foresight and application potential of research results. Second, the connection between knowledge output and practical transformation requires emphasis. Output must extend beyond patents and publications to include engineering development and the maturation of technology models through establishing proof-of-concept centers and pilot incubation bases. Consequently, new technological solutions necessitate coordinated input, including cross-disciplinary talent from the education sector and real-world engineering capacity from the industry sector, to progress from laboratory research to customized, implementable solutions.

3.4 Industry Dimension

The core function of the industry sector is transforming knowledge and technology into productive forces and driving front-end evolution through market and practice feedback. Industry’s effectiveness begins with precisely defining demands, keenly capturing market bottlenecks and future talent capability requirements (such as composite skills), which provide the necessary navigation signals for educational and research activities. Furthermore, it plays a vital role in providing real verification scenarios; production lines and operational data serve as the ultimate touchstones for testing technical feasibility, economy, and safety. A technology’s ability to pass this “scenario test” determines its successful transformation into a marketable product. Crucially, industry completes the value closed-loop by realizing commercial value and feeding back into the cycle, both by offering continuous financial support and by acting as an indispensable extension classroom. This deep involvement ensures that the cycle’s outputs effectively meet market and societal demands.

3.5 Achieving Synergistic Effects

The ultimate goal of the cyclic linkage is to generate systemic value-added effects. In the education dimension, value is reflected in dual improvements: enhancing talent supply adaptability by closely aligning cultivation with industrial needs, and improving research social utility by sourcing topics from real industrial bottlenecks, thus boosting result conversion rates. In the technology dimension, value is manifested as a multiplication of R&D efficiency; demand-oriented research reduces resource mismatch, joint breakthroughs accelerate knowledge flow, and early industrial verification significantly shortens the innovation cycle. In the industry dimension, value translates into sustainable competitive advantages; enterprises gain stable, high-quality customized talent and internalize frontier technologies into core assets. Ultimately, this collaborative system maximizes overall social value by promoting large-scale innovative talent cultivation, clustered key technological breakthroughs, and systemic industrial green transformation at a lower total social cost, demonstrating the emergent properties of the collaborative network.

4 Designing the “Education-Technology-Industry” Linkage

4.1 Curriculum Co-construction

Collaborative curriculum co-construction is key to grounding the cyclic linkage concept at the front end of talent cultivation. This mode establishes a dynamic adjustment mechanism driven by industrial demand, led by technological frontiers, and guided by educational laws. The core involves forming a joint team, comprising university program heads, research experts, and senior industry engineers, to jointly determine curriculum objectives and reconstruct modules based on the carbon neutrality industrial technology roadmap and professional capability standards. Specific implementation includes developing modular course packages and co-building loose-leaf textbooks and dynamic case libraries, integrating real enterprise cases and the latest research findings. As shown in Figure 2, this ensures the avant-garde nature, systemic integrity, and practical orientation of course content, synchronizing talent cultivation schemes with industrial development dynamics.

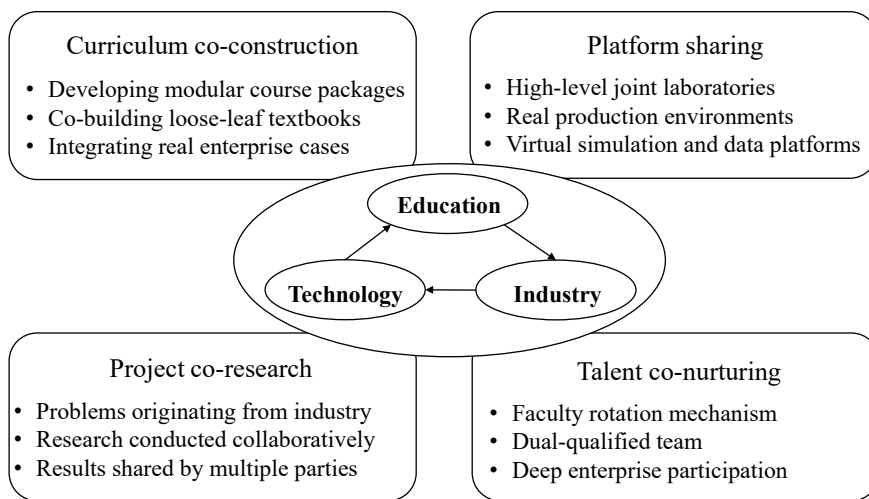


Figure 2 Mode Design of “Education-Technology-Industry” Cyclic Linkage

4.2 Platform Sharing

The collaborative sharing of platforms provides fundamental physical support and scenario carriers for the cyclic linkage, aiming to build an open, shared, and functionally complementary network of physical and virtual resources. Main forms include co-building three types of platforms: First, high-level joint laboratories focusing on specific low-carbon technologies (e.g., hydrogen energy, carbon capture), where all parties invest resources and intellect; these also serve as training bases. Second, regional internship and training bases, where leading enterprises provide real production environments, transforming workshops into classrooms via standardized internship projects. Third, virtual simulation and data sharing platforms, utilizing digital twin technology to simulate complex systems (e.g., smart energy networks), achieve low-cost, high-safety immersive teaching and research pre-enactment. Establishing clear property rights, usage charters, and cost-sharing mechanisms is crucial for effective platform sharing.

4.3 Project Co-research

Collaborative co-research is the core engine driving the cyclic linkage to produce substantive technological outputs and cultivate innovative talents, following the principle of “problems originating from industry, research conducted collaboratively, results shared by multiple parties”. This mode establishes an institutionalized joint R&D mechanism. Typical implementation includes setting up “list-unveiling” projects, where enterprises publish specific technical problems and needs, and universities and research institutes form interdisciplinary teams with student participation to accept the challenge. Another path is jointly undertaking national and local major science and technology projects to conduct systemic breakthroughs. Crucially, a forward-looking intellectual property agreement must be established to clarify the ownership, use, and revenue distribution of results. Project outputs are internalized into real engineering cases for teaching, directly cultivating students’ innovative thinking and complex problem-solving abilities.

4.4 Talent Co-nurturing

Collaborative co-nurturing focuses on establishing sustainable development paths across the education, research, and career lifecycle, facilitating the orderly flow and value appreciation of human capital. The core of this model is a two-way embedded channel supporting diversified professional growth. Specific mechanisms include implementing a joint mentorship system, where graduate thesis topics are directly derived from cooperative R&D projects under the guidance of both academic and industry mentors. Furthermore, a faculty rotation mechanism is utilized, enabling teachers to work in industry R&D while industry experts are hired as adjunct faculty, thus building a dual-qualified team. Additional paths involve specialized classes with deep enterprise participation (selection, customization, assessment) and the joint development of credit mutual recognition systems to standardize the accumulation of learning outcomes.

5 Curriculum Construction Support System

To ensure the comprehensive implementation of curriculum reform concepts, this study constructs a logically rigorous, four-in-one implementation and guarantee system, as shown in Figure 3. This system organically combines value shaping, teaching methods, faculty collaboration, and effect evaluation, covering the entire process from design

and implementation to assessment and improvement, jointly supporting the realization of the “Education-Technology-Industry” cyclic linkage goals.

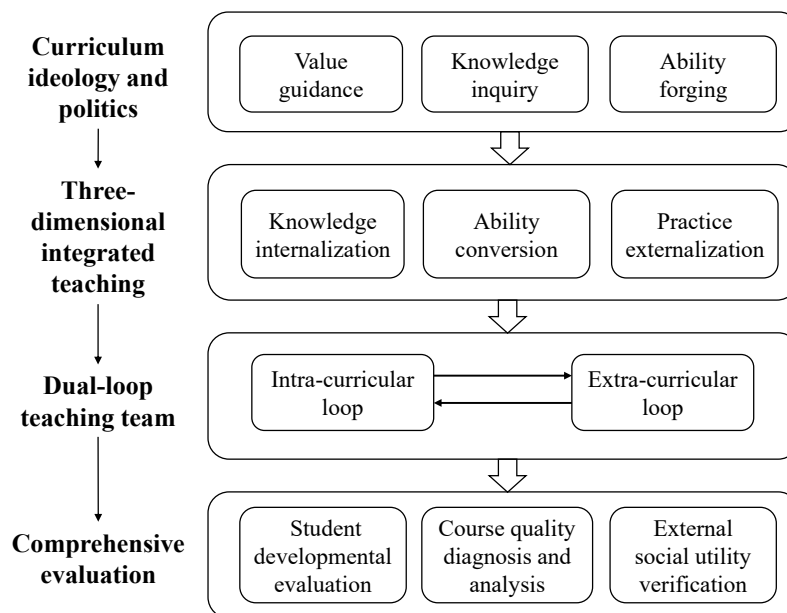


Figure 3 Structure of the Curriculum Construction Support System

5.1 Curriculum Ideology and Politics

The core of this scheme is to establish a three-in-one teaching objective framework: value guidance, knowledge inquiry, and ability forging. Implementation involves clearly listing ideological and political mapping points in the syllabus for each knowledge module, linking technical lessons (like carbon capture) with national strategic significance or ethical principles in global governance. A high-quality ideological and political case library is developed, featuring typical stories (e.g., China’s photovoltaic industry growth or ecological restoration projects) to convey patriotism, technological ethics, and the spirit of craftsmanship. Finally, a value reflection module is designed in the practice link, requiring students to submit analysis reports on social benefits and ethical risks when completing projects, achieving a closed loop between value judgment and professional practice.

5.2 Three-Dimensional Integrated Teaching

The three-dimensional integrated teaching method follows the logic of “Knowledge internalization → Ability conversion → Practice externalization”, building a closed loop of unity between knowledge and action. The internalization stage focuses on building the learner’s stable cognitive structure through structured seminars and problem chain guidance. The conversion stage is the key hub where students use internalized knowledge to model, decide, and iterate in highly simulated digital platforms, transforming declarative knowledge into procedural problem-solving ability. The externalization stage is the final test; students engage in real industrial scenarios under dual mentor guidance, producing technical solutions available for adoption. These three stages are integrated and designed, ensuring task connection and forming a complete chain from theoretical cognition to value creation.

5.3 Dual-Loop Teaching Team

The dual-loop teaching team mode aims to build an institutionalized, cross-boundary teaching community to solve faculty structural disconnections. The intra-curricular loop, led by full-time university teachers, is responsible for systematic curriculum design, basic theory teaching, and academic evaluation, ensuring the scientific nature of pedagogy. The extra-curricular loop, driven by industrial mentors, participates in updating frontier content, designing practical topics, providing career consultation, and reviewing theses. Synergy is achieved through three key mechanisms: role-task binding, clarifying responsibilities and workload accounting for both parties; periodic rotation and joint teaching research, where university teachers practice in industry and mentors receive pedagogy training; and resource intercommunication, transforming industry-guided project results into teaching cases while feeding university research insights back into enterprise innovation.

5.4 Comprehensive Evaluation

A comprehensive evaluation system, built upon the outcome-based education (OBE) philosophy, is necessary to scientifically assess curriculum effectiveness, integrating internal improvement and external verification. First, student developmental evaluation is implemented, corresponding to the three-dimensional goals: concept maps diagnose knowledge depth, platform data assesses problem-solving capability, and dual mentor reviews verify practical contributions. Second, a continuous quality improvement mechanism provides an internal closed loop; evaluation data generate achievement radar charts and diagnostic reports for precise iteration of content and methods. Finally, external social utility verification tracks key indicators like graduate job adaptation and employer satisfaction. It calculates the conversion ratio of curriculum-derived results (e.g., projects adopted, joint patents), providing external evidence of social value and demand responsiveness.

6 Discussion and Conclusion

The “Dual carbon” goals necessitate a profound transition in China’s development, requiring systemic energy changes and, crucially, a matching high-quality talent supply and continuous technological innovation capability. Higher education, as the core site for talent and knowledge creation, faces urgent pressure to reform. Traditional models exhibit deficiencies, such as lagging knowledge and disjointed ability cultivation, especially against the interdisciplinary and rapidly iterating demands of carbon neutrality. Therefore, exploring a new educational paradigm that closely connects education, technology, and industry for deep synergy and cyclic empowerment has become an urgent task. Based on this, this study addresses the core issue of effectively translating macro carbon neutrality strategies into micro, operable curriculum practices. We systematically constructed a holistic curriculum support system centered on the concept of “Education-Technology-Industry” cyclic linkage. First, this study deepened and integrated the theory by recontextualizing the Triple Helix theory. It established “Carbon neutrality” as the common vision and concretized the traditional model into the dynamic Education-Technology-Industry cyclic linkage framework. This framework clarifies the collaborative logic of unified goals, complementary functions, resource circulation, and value added, extending the theoretical discussion from macro-institutional analyses to the meso-level curriculum and teaching domain. Second, the study provided systematic scheme designs regarding practical paths for implementing the cyclic linkage. It

constructed operable paths from two dimensions: mode and support system. On one hand, a four-in-one collaborative implementation mode was designed (curriculum co-construction, platform sharing, project co-research, and talent co-nurturing). On the other hand, a four-pillar curriculum support system was built (curriculum ideology and politics, three-dimensional integrated teaching, dual-loop team, and comprehensive evaluation). Finally, the proposed framework and system achieve the synergistic appreciation of educational quality, technological innovation efficiency, and industrial competitiveness, offering a complete and sustainable solution for the large-scale cultivation of composite and innovative talents in the field of carbon neutrality.

Future research could deeply explore differential implementation strategies and adjustment mechanisms of this framework in different types of universities and regional industrial environments. Furthermore, long-term tracking and quantitative research methods can be used to empirically assess its actual efficacy in enhancing graduates' green competitiveness, promoting low-carbon technology transformation, and even contributing to regional carbon emission reduction. Only through continuous practical testing and theoretical reflection can we constantly enrich and develop educational and teaching theories oriented toward major national strategic needs, making higher education truly a cornerstone force empowering a green future and driving profound changes.

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