

EDITORIAL

Interdisciplinarity, systems thinking, and
systematic design: The core paradigm for deep
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The global carbon neutrality strategy has entered a critical stage of overall layout and in-depth implementation. Different from traditional environmental governance and single energy transformation, the carbon neutrality goal of balancing carbon sources and sinks involves the whole industrial chain, energy chain, and ecological chain of social and economic operation, featuring multi-scale, multi-agent, multi-factor coupling and complex dynamic evolution characteristics. A large number of practical practices have proved that relying on single engineering technology, independent economic policy, or isolated ecological management means is difficult to solve the systematic contradictions between low-carbon transformation, energy security, industrial development, and ecological protection, and even easily leads to problems such as high transformation cost, regional development imbalance, and technical application mismatch.¹⁻³

The fundamental breakthrough to solve the above dilemmas lies in abandoning the fragmented linear thinking and single-discipline research paradigm, and taking interdisciplinary integration, systems thinking and systematic design as the core support of carbon neutrality construction. Disciplinary intercross breaks the boundary barriers between natural science, engineering technology, social science, and management science, and builds a multi-dimensional knowledge system for carbon neutrality research and practice. Systems thinking provides a holistic cognitive method for grasping the operation rules of the carbon neutrality complex system. Systematic design transforms macroscopic cognitive logic into operable whole-process and whole-chain implementation schemes, realizing the organic unity of theoretical cognition and practical application. This editorial focuses on the internal logical relationship between the three core elements and carbon neutrality systemic transformation, discusses the current development bottlenecks and optimization paths, and points out the future research and practice direction of carbon neutrality cause.⁴⁻⁶

Interdisciplinarity represents an inevitable requirement of the carbon neutrality transition because carbon neutrality is a comprehensive strategic challenge that cannot be addressed within the boundaries of a single discipline. Its realization process involves the collaborative iteration of technical innovation, economic regulation, social governance, and ecological restoration, which inherently requires the deep integration of multiple disciplines. Traditional disciplinary settings focus on professional segmentation and independent research, which is easy to form a “disciplinary silo” effect. For a long time, low-carbon-related research and practice mostly stay in the single dimension of energy engineering, environmental science, or economic management, lacking multi-dimensional collaborative breakthroughs, resulting in many local low-carbon technologies and policies that cannot produce overall systematic benefits.^{3,7}

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Disciplinary intercross for carbon neutrality is not a simple superposition of multiple disciplines, but a problem-oriented organic integration of disciplinary theories, research methods and technical means, forming a complete research chain of “core problem guidance-multi-disciplinary support-systematic solution output.” In the technical level of zero-carbon system construction, the cross-integration of energy science, material science and digital science promotes the iterative upgrading of new energy power generation, carbon capture, utilization and storage, and intelligent energy scheduling technologies, laying a technical foundation for the reconstruction of low-carbon energy systems. At the economic and governance level, the cross-integration of environmental economics, public management, and law provides theoretical support for carbon accounting, carbon pricing, carbon market operation, and low-carbon policy formulation, and standardizes the institutional system of carbon neutrality transformation. At the ecological sink level, the cross-collaboration of ecology, geography, and environmental science optimizes the layout of ecological carbon sink projects such as forest carbon sequestration and wetland restoration, and improves the natural carbon balance capacity of regional ecosystems.^{4,8}

At present, global carbon neutrality research is accelerating the transformation from single-discipline exploration to interdisciplinary integration. A series of international research programs and institutional collaborations, such as the Intergovernmental Panel on Climate Change (IPCC) climate change assessment research and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) biodiversity and climate synergy research, have fully proved that interdisciplinary collaborative research is an inevitable trend to break through the bottleneck of carbon neutrality basic research and practical application. Only by breaking disciplinary boundaries and integrating multi-dimensional professional resources can we accurately grasp the multi-scale coupling law of carbon neutrality complex systems and solve the systematic problems in the transformation process.

Systems thinking constitutes the core cognitive paradigm of carbon neutrality governance because it provides the foundational approach to address complex systemic problems. It is also the ideological premise for the effective play of interdisciplinary values and the scientific implementation of systematic design. Different from linear thinking that focuses on single factors and local effects, systems thinking adheres to the holistic, collaborative, and dynamic evolutionary perspective, focusing on the interaction, mutual restriction, and

overall optimization of various elements in the carbon neutrality system. The carbon neutrality system is a huge complex system integrating the natural ecological system, economic operation system, energy consumption system, and social governance system. All links are closely coupled and mutually influential, and local optimal solutions often cannot match the overall development needs.^{5,9}

The application of systems thinking in carbon neutrality practice is mainly reflected in three dimensions. First, holistic cognition requires moving beyond isolated local governance, adopting the entire life cycle of carbon emissions and carbon sinks as the analytical perspective, and comprehensively considering the coordination among energy transformation, industrial upgrading, ecological protection, and economic development. This approach helps avoid the one-sided problem of “reducing carbon locally but increasing carbon globally.” Second, multi-factor collaborative governance emphasizes the interactions among technological, policy, market, and social factors and promotes the coordinated advancement of technological innovation, policy guidance, market incentives, and public participation rather than relying on a single means to promote low-carbon transformation. Third, dynamic adaptive optimization recognizes that carbon neutrality systems continuously evolve in response to socioeconomic development and technological progress. Systems thinking emphasizes real-time perception of system changes, timely adjustment of transformation paths, and realization of long-term dynamic balance between carbon emission reduction and social and economic sustainable development.^{10,11}

The lack of systematic thinking is an important reason for many dilemmas in current carbon neutrality construction. For example, the blind layout of new energy projects without considering grid matching and energy storage supporting capacity leads to resource waste; the single emphasis on industrial carbon reduction without considering the transformation cost and industrial development vitality leads to the contradiction between low-carbon supervision and economic growth. Therefore, taking systems thinking as the basic paradigm to guide carbon neutrality work is the key to realizing high-quality and sustainable low-carbon transformation.

Systematic design provides the implementation pathway for whole-chain optimization in the carbon neutrality transition. Whereas interdisciplinary integration provides the necessary knowledge base and systems thinking offers cognitive guidance, systematic design serves as the key mechanism for translating theoretical understanding into practical outcomes. Centered on the overarching goal of carbon neutrality, systematic design follows whole-process, whole-element, and whole-chain principles. It clarifies the

logical relationships among the various components of a carbon system, establishes a hierarchical and classified implementation framework, and seeks to optimize the carbon neutrality system as a whole rather than merely improving individual components.¹²

The systematic design of carbon neutrality needs to build a three-dimensional implementation system covering macroscopic strategy, mesoscopic industry, and microscopic technology. At the macroscopic strategic level, it is necessary to carry out top-level design of regional and industrial carbon neutrality paths, coordinate the phased goals of carbon peaking and carbon neutrality, balance the relationship between short-term emission reduction tasks and long-term zero-carbon transformation, and build a scientific overall development layout. At the mesoscopic industrial level, focusing on high-emission fields such as energy, industry, transportation and construction, carry out whole-industry chain systematic design, optimize industrial structure, energy consumption structure and supply chain layout, realize coordinated emission reduction in upstream and downstream of the industrial chain, and eliminate emission reduction blind spots and weak links. At the microscopic technical level, take system matching as the standard, carry out targeted design and iterative optimization for low-carbon emission reduction technologies, carbon sink enhancement technologies and carbon cycle utilization technologies, ensure the docking and compatibility of various technical systems, and improve the overall efficiency of technical emission reduction.^{6,13}

In addition, systematic design needs to focus on the coordination of multiple benefits of the system. The carbon neutrality system involves multiple benefit goals such as low-carbon emission reduction, energy security, economic growth, and ecological protection. Systematic design should adhere to the principle of comprehensive benefit optimization, avoid single emission reduction orientation, realize the deep integration of pollution reduction and carbon reduction, ecological protection and low-carbon development, technological innovation and industrial upgrading, and finally build a green, low-carbon, safe and sustainable modern economic system.

The synergistic evolution of interdisciplinary integration, systems thinking, and systematic design will shape the future developments of carbon neutrality initiatives. These three paradigms are mutually supportive and logically progressive, forming an integrated core paradigm to support carbon neutrality systemic transformation. Disciplinary intercross breaks the knowledge barrier of single research, provides multi-dimensional theoretical and method support for systems

cognition and systematic design; systems thinking guides the direction of interdisciplinary research, avoids fragmented and isolated research orientation, and ensures that disciplinary integration serves the overall optimization of the carbon neutrality system; systematic design is the ultimate landing form of interdisciplinary achievements and systematic thinking results, realizing the transformation from theoretical innovation to practical governance effect.

Looking forward to the deep advancement of the global carbon neutrality cause, the three core paradigms will further evolve and iterate in coordination. In terms of disciplinary development, it is urgent to build a more systematic carbon neutrality interdisciplinary discipline system, cultivate compound innovative talents integrating technology, economy, and governance, and solve the problem of insufficient supply of interdisciplinary professional resources. In terms of cognitive innovation, it is necessary to further deepen the application of complex system theory, big data, and artificial intelligence means, improve the accurate cognition and dynamic prediction ability of carbon neutrality complex systems, and enhance the scientificity of decision-making. In terms of practical design, it is necessary to promote the standardized and refined development of carbon neutrality systematic design, build a whole-process evaluation and optimization mechanism covering scheme formulation, implementation supervision and effect feedback, and continuously improve the operational efficiency and comprehensive benefit of the carbon neutrality system.

Carbon neutrality is a systematic project spanning multiple fields, levels and links, and its deep transformation cannot be separated from the support of interdisciplinary integration, systems thinking and systematic design. In the new stage of carbon neutrality construction, we must completely abandon the traditional fragmented, single-dimensional and linear development model, take the three core paradigms as the fundamental guidance, break disciplinary boundaries, optimize cognitive logic, and improve the design system. Through the deep integration of multi-disciplinary resources, holistic systematic cognition and whole-chain systematic design, we can effectively resolve various systematic contradictions in low-carbon transformation, break through the bottlenecks of technology, system and governance, and steadily promote the realization of global carbon neutrality goals and sustainable social and economic development.

Conflict of interest

The authors declare no competing financial interests or personal relationships that could have appeared to

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