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Policy and Management of Carbon Peaking and Carbon Neutrality: A Literature Review

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ABSTRACT

The vision of reaching a carbon peak and achieving carbon neutrality is guiding the low-carbon transition of China's socioeconomic system. Currently, a research gap remains in the existing literature in terms of studies that systematically identify opportunities to achieve carbon neutrality. To address this gap, this study comprehensively collates and investigates 1105 published research studies regarding carbon peaking and carbon neutrality. In doing so, the principles of development in this area are quantitively analyzed from a space–time perspective. At the same time, this study traces shifts and alterations in research hotspots. This systematic review summarizes the priorities and standpoints of key industries on carbon peaking and carbon neutrality. Furthermore, with an emphasis on five key management science topics, the scientific concerns and strategic demands for these two carbon emission-reduction goals are clarified. The paper ends with theoretical insights on and practical countermeasures for actions, priority tasks, and policy measures that will enable China to achieve a carbon-neutral future. This study provides a complete picture of the research status on carbon peaking and carbon neutrality, as well as the research directions worth investigating in this field, which are crucial to the formulation of carbon peak and carbon neutrality policies.

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1. Introduction

Global climate change is the most significant environmental problem and one of the most complex challenges confronting humankind in the 21st century [1]. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global surface temperature has increased by 1.09 °C during the period from 1850–1900 to 2011–2020. Many of the changes that have already occurred due to greenhouse gas (GHG) emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets, and global sea level. The international community has carried out several rounds of climate negotiations to address climate change. With a series of international treaties having been adopted and signed, including the Kyoto Protocol and the Paris Agreement[†], real progress has been made toward national mitigation commitments. Nevertheless, prior studies have pointed out that the current nationally determined contributions made under the 2015 Paris Agreement may not align sufficiently with achieving the target of limiting the increase in global temperature to 1.5 °C or well below 2 °C [2,3]. Even if all the ratified parties of this agreement deliver on their climate pledges, the world is heading for a global temperature rise of more than 3 °C over preindustrial levels [4,5]. Thus, stabilizing the atmospheric GHG concentrations at a level that can hold the Earth on a sustainable path is a difficult and far from complete task.

Under such grim circumstances, the allowance for future GHG emissions will be extremely stringent for a relatively long period. The IPCC has suggested that the 1.5 °C target requires the global

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[†] The Paris Agreement aims at limiting global warming to well below 2 °C and commits nations to "pursuing efforts" to hold it to 1.5 °C.

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achievement of net-zero carbon dioxide (CO_2) emissions by 2050, a goal commonly known as "reaching carbon neutrality" [1]. A total of 124 countries had already made net-zero pledges before the United Nations (UN) Climate Summit was held in November 2020 [6]. The majority of these countries, including the European Union, the United States, the United Kingdom, Canada, Japan, New Zealand, and South Africa, have pledged to achieve carbon neutrality by 2050. Inspiringly, China, as a responsible developing country, has consistently committed to ensuring that its CO_2 emissions peak by 2030 and attaining carbon neutrality before 2060.

With many nations proposing their carbon neutrality agenda, climate change mitigation stands at a historical crossroads, ushering in a critical era of opportunity that creates new requirements for further research on carbon emissions reduction [7]. Hence, it is an ideal time to summarize the knowledge that is currently available in order to guide future research on achieving a carbon peak and carbon neutrality. Thus, the purpose of this study is to perform a broad review of the research findings on carbon peaking and carbon neutrality, refine important scientific concerns and strategic demands for carbon neutrality, and provide further thoughts on future research directions.

The first concern is to define the terms "carbon peak" and "carbon neutrality," which will have an immediate impact on the scope and subject matter of this review. According to the IPCC report and worldwide consensus [1,8,9], a "carbon peak" is defined as the point at which CO_2 emissions stop growing and begin to decline, and "carbon neutrality" refers to the point at which the anthropogenic CO_2 emissions associated with a certain entity are balanced by anthropogenic removals over a specific period.

An important issue that follows is the logical relationship between carbon peak and carbon neutrality goals. In terms of objective regularity, the two carbon targets have profound theoretical and practical grounding, reflecting economic implications such as the decoupling theory of economic progress and carbon emissions, as well as the Environmental Kuznets Curve (EKC) hypothesis [10,11]. To some extent, the peak of a carbon emissions curve under the carbon neutrality scenario can be perceived as the turning point in the EKC (Fig. 1). Subjectively, the vision of "two carbon goals" also accords with the human desire to seek a better life after satisfying basic material needs [12]. Furthermore, the time point and level of a carbon peak directly determine the amount of emission reductions and the time required to transition from the peak to carbon neutrality. Thus, the mitigation actions for reaching a carbon peak must be scheduled with the carbon neutrality goal as a guide and restriction.

Another critical issue is how to meet the two emission-reduction goals. Prior studies have employed integrated assessment models (IAMs) to identify the most plausible paths to achieving emission-reduction goals under various socioeconomic scenarios. However, the current research appears to be fragmented and context-dependent due to uncertainties concerning the economic development stage, technical progress, energy demands, policy measures, and climate risks [13]. Even with the same scenario and issue, the research findings are frequently inconsistent and difficult to compare. Despite the fact that new research is constantly emerging, providing theoretical foundations on and scientific insight into carbon peaking and carbon neutrality, the complex and scattered research results make it difficult to determine how to meet carbon neutrality. Thus, a systematic review of the studies on these topics, which is currently absent from the literature, is required. Such a review will enable researchers to swiftly comprehend the development context of related studies, determine crucial points and research hurdles, and conduct follow-up research more efficiently, pointedly, and systematically.

Thus, the purpose of this study is to address two questions: What is the current status of research on carbon peaking and carbon neutrality, and what research directions are worth investigating in the future? To answer these questions, we trace relevant international trends and development principles through space and time, analyze the research status and changes in relevant "hot topics" from an industrial standpoint, and determine an implementation path and priorities to support the two carbon goals. We then examine the academic implications of carbon peaking and carbon neutrality, as well as new challenges in management science. Finally, we propose countermeasures for future theoretical studies and practical actions related to the two carbon goals in regard to the implementation path, priority tasks, and policy implications.

2. Method for bibliometric analysis

An integrated data-to-knowledge system developed by the authors for structured literature analysis is adopted in this study [14]. The framework of this method, which integrates bibliometric and typological analytical tools, is detailed in Fig. 2. The system may be used to analyze the structure, characteristics, and evolution of a subject and can be used to statistically measure the performance of current studies by mapping the essential components of the literature.

The literature data was derived from the Web of Science (WoS) Core Collection—Citation Indexes (i.e., the Science Citation Index Expanded database and the Social Sciences Citation Index database). The WoS database is one of the most well-known electronic literary databases in the world, containing a wide range of academic materials on the natural and social sciences. It has been extensively applied in scientometric analysis [15–17].

The first step in our analysis was to gather literature from the WoS database. We used a keyword search strategy to extract literature on the review topic. Section S1 in Appendix A contains a detailed description of our retrieval strategies. A process of "purification" of the collected literature followed. This second step, which

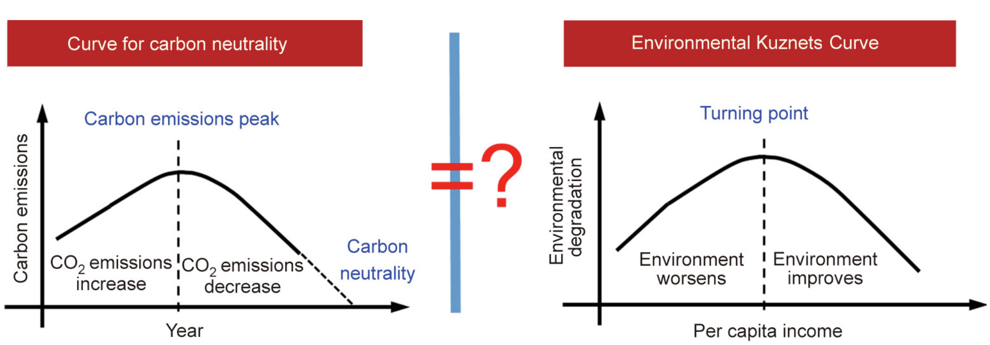

Fig. 1. The economic implications of carbon peaking and carbon neutrality.

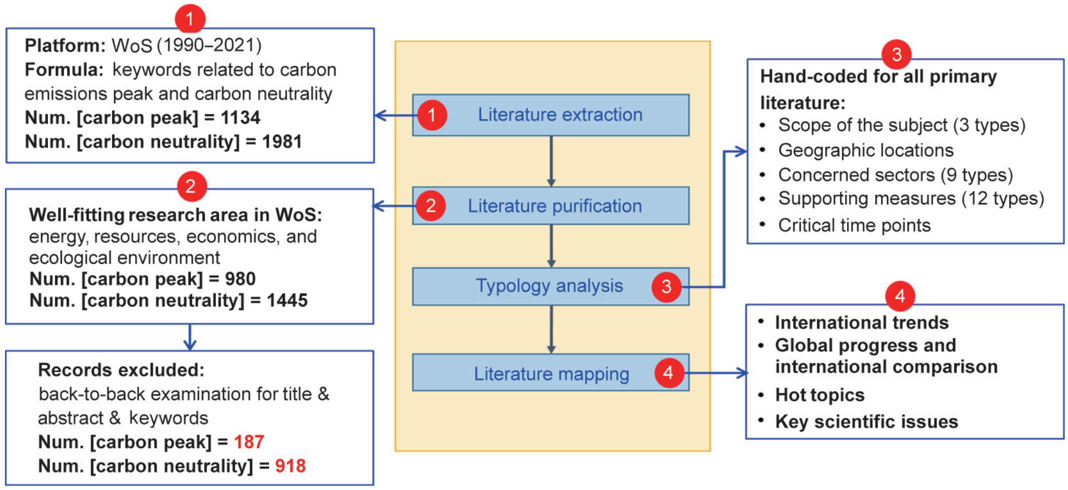

Fig. 2. Framework of the integrated data-to-knowledge system, where Num. refers to the number of studies remaining in the analysis. There are three types of subjects: time series, sectors, and technologies. The nine sectors are power, iron and steel, transportaton, cement, chemical, building, residents, agriculture, and others. The 12 types of supporting measures are behavior change; zero-carbon waste treatment; zero-carbon craft; zero-carbon material; carbon-neutral demonstration; biomass; carbon capture, utilization, and storage (CCUS); ecosystem carbon sinks; other negative emission technologies (NETs); bioenergy with carbon capture and storage (BECCS); artificial photosynthesis; and energy system optimization.

was initially automated, preserved just the literature from the WoS-defined Research Area and Category on energy, resources, policy, economics, and the environment (see Table S1 in Appendix A for details). After this automatic filtering, we double-checked the remaining literature by reviewing the abstracts and content. Irrelevant studies were meticulously weeded out in this manner. Finally, we retained 187 articles on carbon peaking and 918 articles on carbon neutrality for subsequent analysis.

The remaining articles were then manually coded using typological analysis according to the scope of research subjects, geographic locations, concerned sectors, supporting measures, and critical time points. Throughout this step, each member of the review team conducted an individual assessment of the literature typology. A face-to-face debate was further performed to reach a consensus on any differing points of view.

In the final phase, we employed knowledge mapping for visual analysis. The current state of knowledge in this field was evaluated accordingly, with global progress and hot topics explored and key scientific concerns recognized.

3. Research trends and hot topics

This section presents a bibliometric analysis of trends and hot topics concerning carbon peaking and carbon neutrality using our data-to-knowledge system, which makes it possible to identify the knowledge stocks and characteristics of these topics.

3.1. Spatial and temporal analysis of the current literature

In terms of temporal trends, the first study on carbon neutrality within the scope of our review was published in 1995 (Fig. 3). Schlamadinger et al. [18] developed a carbon-neutral evaluation index to examine whether biomass energy, which can be used to replace fossil fuels, is actually carbon neutral. Carbon neutrality has progressed from a vague scientific idea to a prominent topic in the climate change debate over the last 15 years. With the enactment of the Climate Change Act in 2008, the United Kingdom became the first country to legislate for GHG reductions [6]. Following that, the 1.5 °C climate target outlined in the Paris Agreement calls for worldwide net-zero CO_2 emissions by 2050. In 2018, the IPCC released a special report titled Global Warming of 1.5 °C, in which it clearly defines carbon neutrality [2]. In response to the international convention's advocacy, many governments have pledged their commitment to carbon neutrality. Relevant research is likewise growing at a rapid pace.

In contrast, studies on carbon peaking began later, with the first article being published in 2000. De Vries et al. [19] utilized the Integrated Model to Assess the Global Environment (IMAGE) to estimate a peak in global carbon emissions of 12.8 Gt carbon per year in 2040, based on the IS92 scenarios in the 1994 IPCC assessment. According to their findings, the global temperature rise by 2100 was predicted to be only 1.4 °C. However, the actual growth in carbon emissions has departed dramatically from their original expectations.

Reaching a peak in carbon emissions as soon as possible while sustaining high economic growth is an extremely challenging task for developing countries. Surprisingly, at the China–US Joint Announcement on Climate Change in 2014, China pledged for the first time to peak its carbon emissions by 2030. As a result, extensive research is being conducted in order to provide advice to developing countries such as China on carbon peak pathways.

In terms of spatial distribution (Fig. 4), the literature is classified as global, national, or regional based on the empirical object. The findings suggest that carbon peaking studies are mostly focused on the national level and particularly on China, which is the concern of approximately 66% of all studies. These studies on China are mainly concerned with how China's energy-intensive industries [20,21], low-carbon pilot cities [22], and urban agglomerations [23,24] can achieve a carbon peak. As most developed countries have reached their emissions peak, carbon peak research focuses primarily on developing countries where emissions are still growing. In contrast, a significantly larger proportion of carbon neutrality research focuses on a regional scale. Developed countries, as represented by the European Union member states, have emerged as the research objects under focus in carbon neutrality studies.

3.2. Sectors of concern in the current literature

Carbon neutrality and carbon peak research differ in terms of their focuses and development trends across sectors (Figs. 5 and 6). Earlier carbon peak research is concentrated on the

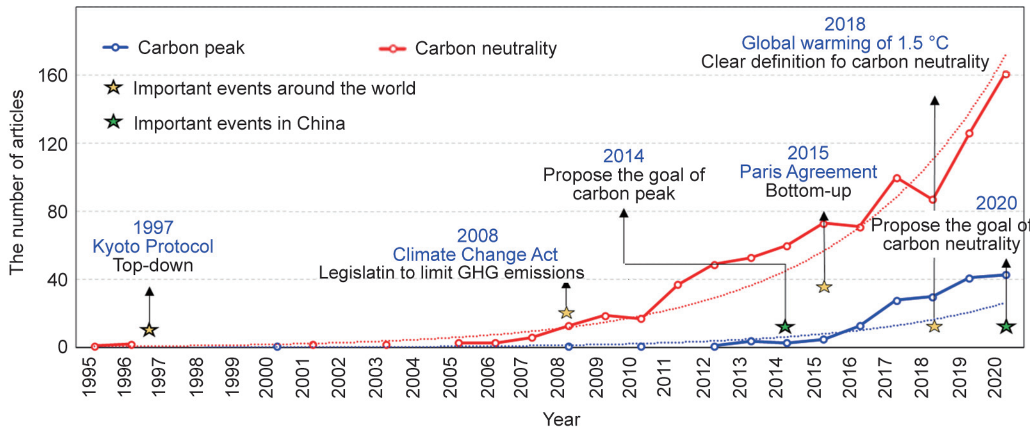

Fig. 3. Temporal trends in publications on carbon peak and carbon neutrality.

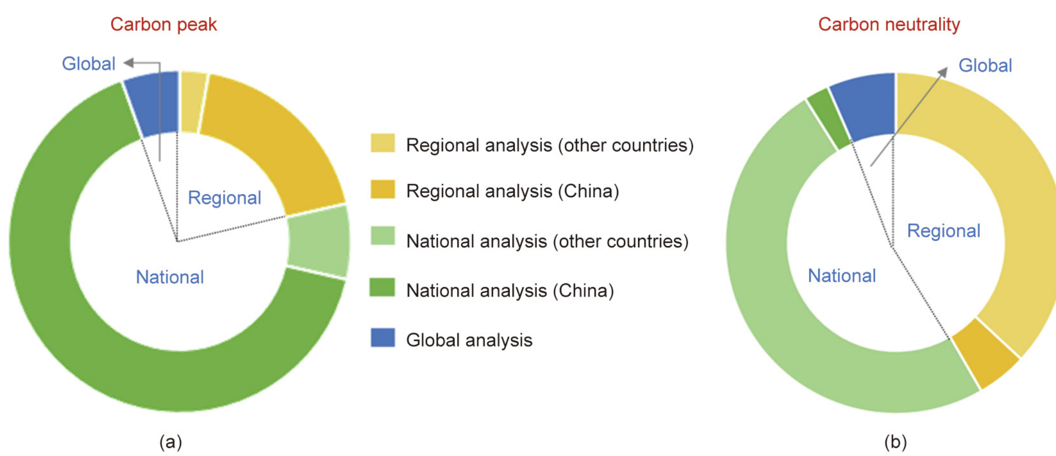

Fig. 4. Carbon peak and carbon neutrality research interests in terms of spatial scale. (a) Regional, national, and global research account for 21.4%, 73.1%, and 5.5%, respectively, of all carbon peak studies; (b) regional, national, and global research account for 41.7%, 51.8%, and 6.5%, respectively, of all carbon neutrality studies.

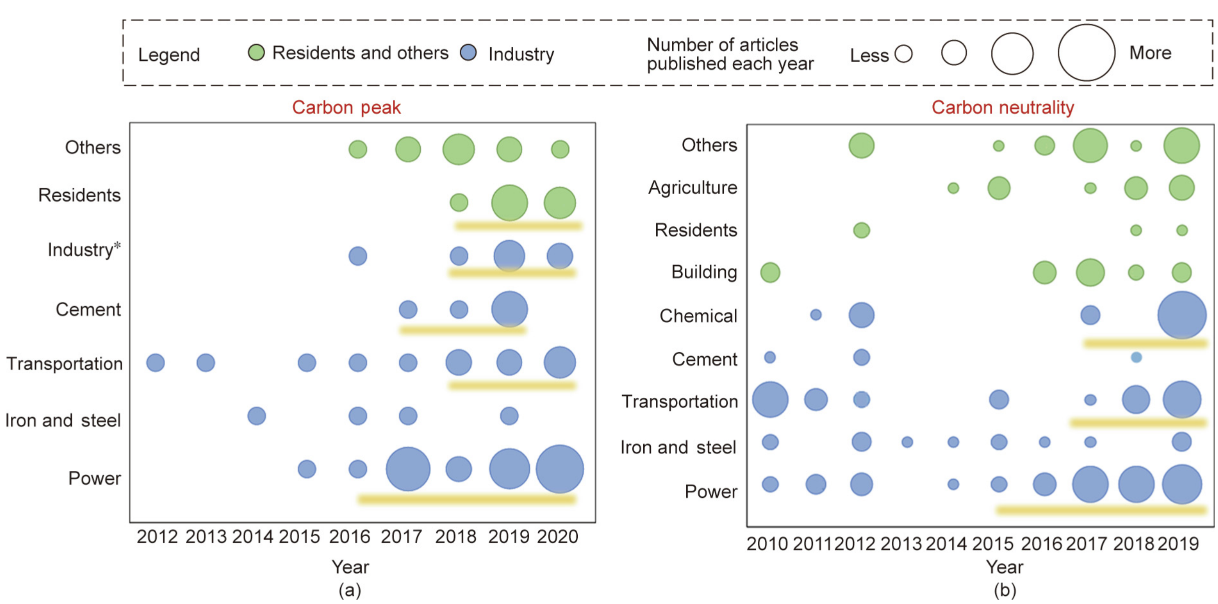

Fig. 5. Research hot topics on (a) carbon peaking and (b) carbon neutrality from the industry perspective. * Indicates studies focusing on the entire industry rather than specific sectors; the number of articles for each circle is displayed in Tables S2 and S3 in Appendix A.

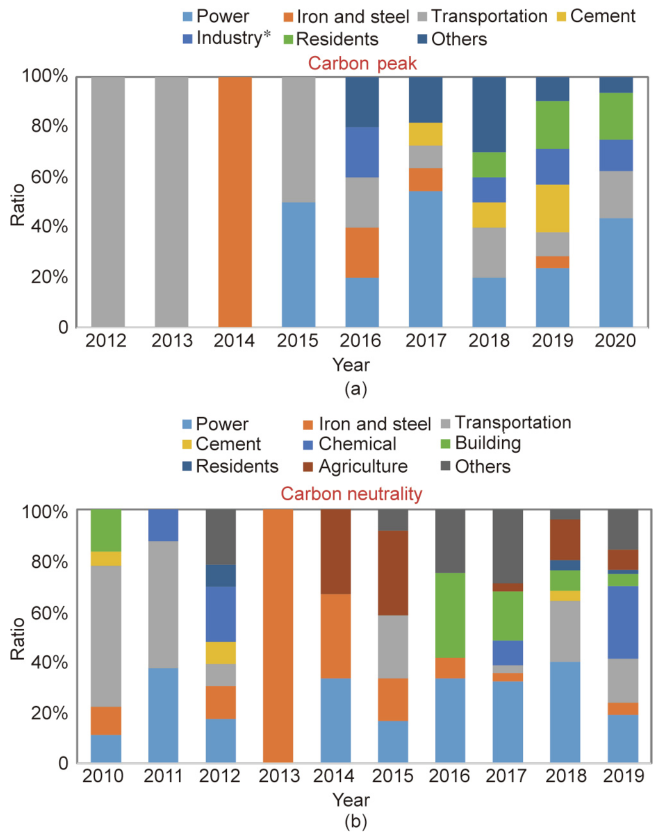

Fig. 6. Proportion of concern for different sectors in related research over the years. * Indicates studies focusing on the entire industry rather than specific sectors.

transportation sector, with a subsequent shift to a greater emphasis on the power sector. Lately, the peak path and carbon level of the residential sector [25,26] and the cement sector [27,28] have emerged as new hot topics.

Regarding carbon neutrality research, it appears that feasible technologies for and the widespread impacts of reaching carbon neutrality in the power and transportation sectors are gaining more attention. Agriculture, construction, and the chemical industries, in particular, have become new focal points [29–31]. This is because power (44.3%), industry (22.4%), and surface transport (20.6%) are the primary contributors to global fossil CO_2 emissions [32]. To meet the peak target, these conventional energy-intensive industries must lead the way. Peaking emissions as soon as possible allows for more preparation time to be reserved for achieving carbon neutrality. In comparison with the peak target, the time available for carbon neutrality goals is extremely limited, and the task is very difficult. Hence, the comprehensive green upgrading of primary, secondary, and tertiary businesses and infrastructure is urgently needed. It is equally important to promote cleaner production and renewable energy use in agriculture, manufacturing, the service sector, and information technology.

3.3. Supporting measures for carbon peaking and carbon neutrality in the current literature

Priorities and targeted support measures must be identified in order to seize the initiative to support the achievement of a carbon peak and carbon neutrality (Fig. 7). For carbon peak research, we have summarized four major types of supporting measures: zero-carbon technology breakthroughs, emission-reduction market mechanisms, energy market reforms, and energy system optimization. Among these, energy system optimization is the most important strategy for reaching a carbon peak. It is becoming increasingly evident that, in addition to technical solutions, market-based instruments are required to achieve the carbon peak goal [33].

For carbon neutrality, research mainly focuses on implementation effects, technology combinations, and systematic implications of supporting measures. These measures are grouped into 12 categories: behavior change; zero-carbon waste treatment; zero-carbon craft; zero-carbon materials; carbon-neutral demonstration; biomass; carbon capture, utilization, and storage (CCUS); ecosystem carbon sinks; bioenergy with carbon capture and storage (BECCS); other negative emission technologies (NETs); artificial photosynthesis; and energy system optimization. Although the era of carbon neutrality implies a decoupling of economic growth and CO_2 emissions, the idea is to maintain economic competitiveness while satisfying human energy needs. The energy system exhibits significant development inertia as well as path dependence. Accordingly, China's commitment to carbon neutrality is a challenging task compared with that of developed countries [34]. Under the new development mode, technological advancement and innovation will be the principal driving forces behind the energy revolution, as well as the primary driving forces for achieving carbon neutrality. According to the research summary, carbon-neutral technology, biomass energy, CCUS, and NETs are emerging hot topics. How to organically link them with traditional energy systems to aid in the fundamental optimization of the energy structure is an important issue deserving future investigation.

4. Pathway toward carbon neutrality

Based on the bibliometric results, four emerging frontiers in the research field are selected in this paper, and the priority tasks in further research are analyzed.

4.1. Negative emissions technology

In a world predicated on the 1.5 °C target, NETs are essential [35]. The ability of NETs to remove and store CO_2 from the atmosphere is essential to achieving carbon neutrality. NETs are concerned with global climate governance and ecological security, but they may also become a new field of technological rivalry in the future. Existing research focuses mostly on negative emission concepts such as BECCS, biochar, direct air capture, and ecosystem carbon absorption when considering the deployment and economic feasibility of large-scale NETs. Management studies on the development potential and system planning of NETs are undertaken largely from three perspectives: cost-effectiveness, resource consumption, and environmental impact.

Economic analysis of NETs mainly focuses on evaluating the cost versus benefit of certain technologies [36,37] and examining the macroeconomic effects of NET adoption using IAMs [38]. Many studies assess and compare the cost of specific carbon-negative technology implementation schemes based on assumptions of energy costs and technical parameters. These are incorporated into the optimum package for combating climate change, together with other emission-reduction and adaptation technologies, to evaluate the socioeconomic system's welfare and changes in losses [39,40]. However, scientific studies have revealed that the development of NETs requires the use of natural resources, and the application of some NETs to natural environments may result in secondary hazards, such as external influences on biodiversity, land use patterns, and ecosystems [41,42]. To address these concerns, researchers have begun to investigate the availability of the external resources required for the development of NETs and their external ecological

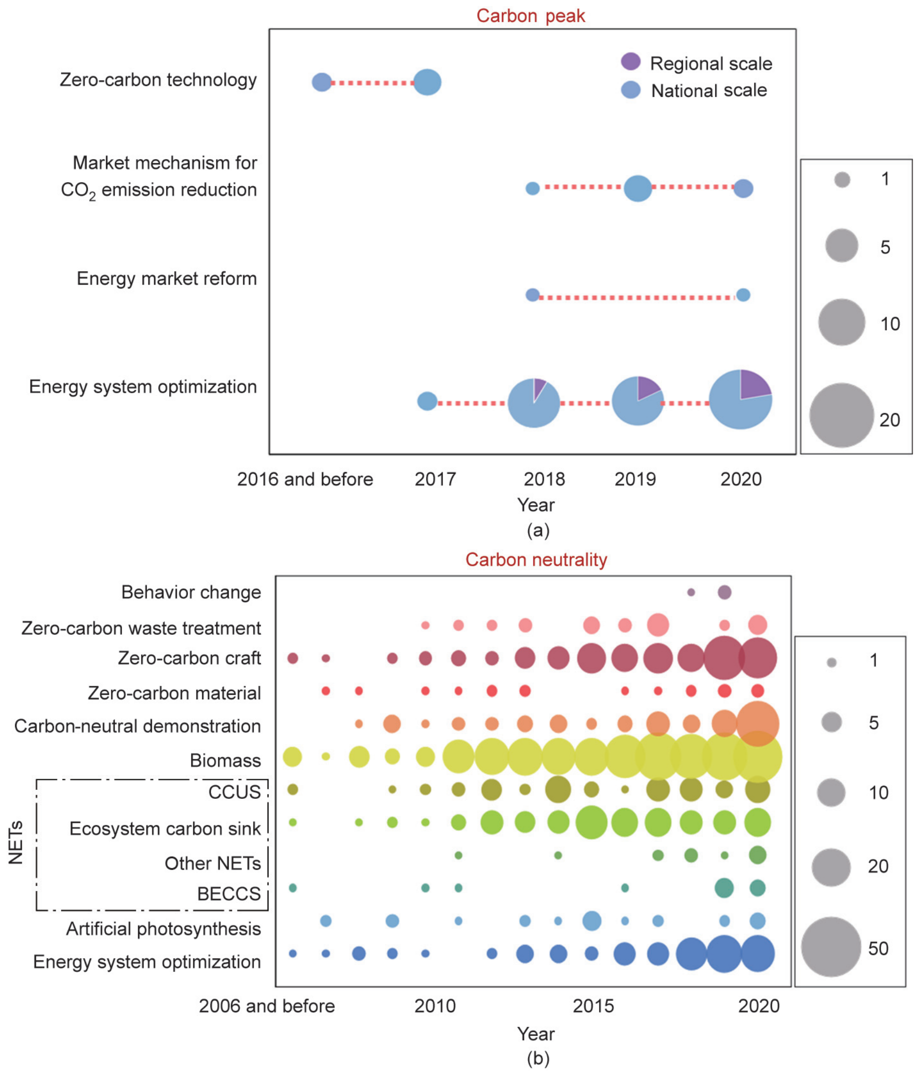

Fig. 7. Supporting measures for carbon peaking and carbon neutrality in the current literature. The year refers to the time when the relevant literature was published; the size of the circle refers to the number of studies published.

implications using geographic information analysis, life-cycle assessment, material flow analysis, and other model methodologies [43,44].

The existing research presents guidelines for large-scale NET deployment. However, in terms of research objects, perspectives, and methodologies, these works are largely incommensurable, and further investigation is required to obtain common characteristics and consistent and comparable scientific principles from among the results. We propose three emerging research fronts based on these studies: ① the feedback mechanism between the development of negative carbon emission strategies and the socioeconomic ecosystem; ② the coordination between the deployment of NETs and sustainable development; and ③ ethical and equity challenges originating from the development of negative emission strategies.

4.2. Zero-carbon technology/craft

Industry has always been the main emitter to be reckoned with. Traditional industries are characterized by high levels of investment, energy consumption, and GHG emissions. Thus, carbon peak and carbon neutrality goals will compel carbon-intensive traditional industries to innovate and make significant changes. Because there is a theoretical upper limit to energy conservation and consumption reductions, the development and promotion of carbon-neutral technologies is gaining popularity. Among such technologies, carbon-neutral methanol technology, new zero-carbon fuel cells, photoelectrochemical hydrolysis, green hydrogen production, zero-carbon building materials, and bio-based composite materials are current research foci. A series of studies on the various aspects of the process management of these technologies have been carried out.

To realize the transformation and upgrading of conventional industries, green manufacturing is a crucial way forward. Substitution of low-carbon raw materials and clean process transformation are important technical routes and key directions for reducing carbon emissions from industrial processes [45]. In addition, scientists are seeking new techniques to decompose CO_2 molecules to produce valuable carbon-based fuels, chemicals, and other products. Through emerging catalysts and bio-based materials, CO_2 can be converted from a pollutant to a resource [46,47]. High-value CO_2 utilization not only has the potential to cut carbon emissions and alleviate the greenhouse effect but can also yield significant social and economic value. However, determining whether these processes are low-carbon or even zero-carbon is a critical management issue that necessitates scientists taking into account both standard design and technological requirements in their research. Carbon neutrality is a notion that extends throughout the life cycle of materials and products. According to this viewpoint, implementing suitable life-cycle carbon emission evaluation and accounting standards is a prerequisite for boosting the green upgrading of processes [48]. In this manner, enterprises, industries, and countries may quantify carbon emissions on the same basis, using a unified system. This will provide scientific support for the development and enhancement of market-based policy measures to reduce carbon emissions, as well as a fair voice in international climate negotiations.

4.3. Carbon pricing mechanism

The use of market forces to solve the problems of CO_2 emissions has a long history. Currently, the carbon pricing mechanism consists mostly of price-based instruments (e.g., carbon taxes) and quantitative tools (e.g., carbon trading markets). According to World Bank statistics, 61 carbon pricing mechanisms are being implemented or are planned to be implemented globally by 2020; 31 of these are carbon emissions trading systems, and the rest are carbon taxes. These mechanisms, which involve a total of 12 billion tonnes of CO_2, account for approximately 22% of worldwide GHG emissions [49].

Because of the unique national circumstances of each country, the applicability of various pricing tools to economic sectors varies. Researchers have compared the effects and pathways of two carbon pricing schemes for distinct market entities [50,51], providing decision support for a larger and more liquid worldwide trading market. The implementation of carbon pricing policies will result in costs being incurred. A great many studies have found that the implementation of the carbon pricing system raises concerns about the unfairness of future regional and industrial growth [52]. In particular, for developing countries in transition, with a significant social divide between the rich and poor, the income distribution effect of the carbon pricing mechanism requires a more comprehensive pre-assessment [53,54].

The enterprise is the main body of action under the market mechanism. The quality of corporate carbon management will have a direct impact on the survival of enterprises with emission-reduction needs in the carbon market [55]. At the national level, the key to efficient enterprise carbon management is identifying the scope of companies that need to reduce emissions and accurately verifying and monitoring carbon emissions data. In this case, reasonable emission-reduction targets for different companies can be formulated based on their emission-reduction potentials. Whatever pricing mechanism is adopted, science, justice, and efficiency should always be the guiding principles of market mechanism design, ensuring that market forces can play a role in lowering emissions.

4.4. Demonstration and standard formulation

A demonstration is a replicable and extendable example of implementation that integrates technology, industry, policy, and other multidimensional elements. Carbon neutrality is a systematic initiative that requires a long-term and holistic vision to guide countries, industries, companies, and individuals to collaborate at all levels. Demonstration is the surest proof of the long-term feasibility of a carbon-neutral system. Different types of demonstrations and pilots are being carried out in various fields around the world. For demonstration projects, NETs, zero-carbon technologies, and carbon pricing mechanisms are all viable options for reaching carbon neutrality. For example, the 2022 Beijing Winter Olympics will be operational with 100% green power or renewable energy. To achieve carbon neutrality throughout the competition, the carbon emissions generated in other stages can be further absorbed by adopting a CO_2 transcritical direct cooling system, establishing a carbon inclusion mechanism, participating in carbon market transactions, and ecological restoration of the venue area. Apple's new headquarters in the United States will use 100% renewable energy, serving as a model and reference for carbon neutrality programs at the corporate level [56]. The Vidyasirimedhi Institute of Science and Technology (VISTEC) University in Thailand has achieved a zero-carbon power supply on the university grounds through the integration of water photovoltaics, rooftop photovoltaics, and charging piles with a smart energy storage system. Germany is also actively pursuing a "carbon-neutral university" initiative, with Greifswald University serving as a template [57]. In the future, these demonstration cases could provide operational technological paths for small-scale parks, smart campuses, and zero-carbon buildings in other countries and regions. Researchers have analyzed the construction of cities with a leading role in carbon neutrality using structured surveys and interviews and have explored the best solutions for sustainable cities [58,59]. Pioneering cities include Helsinki in Finland, which demonstrates sustainable waste and recycling practices; Masdar, a zero-carbon new city located in the desert in the United Arab Emirates; and San Jose, the capital of Costa Rica, known as the "green country." Although the existing research includes some discussions on carbon neutrality demonstrations and supporting technology, we believe that three management issues need to be strengthened further: the management of the construction of carbon neutrality demonstration projects and internal energy supply and demand; the market promotion and scientific layout of carbon neutrality demonstration-related technologies; and the preferred policies to support various carbon neutrality demonstration projects.

5. The future is now: Calling for carbon neutrality management

Many countries have already provided their own various action plans and programs to achieve carbon neutrality and a shared future community for humankind, resulting in a wealth of practical cases. Regardless of the course of practice chosen, scientific ideas, data, and evaluations are required for support and guidance. The carbon peak and carbon neutrality goals not only pose new challenges for production and technological development in economic and social systems, but also require the overall management to be more scientific. In this complex system transformation, by adequately embracing management science tools, such as forward thinking, overall planning, and strategic layout, strategic misconceptions may be avoided, allowing carbon peak and carbon neutrality goals to be achieved at the lowest social cost and fastest speed possible. On that basis, this research proposes five significant management science challenges that should be highlighted in the study of these dual carbon goals.

5.1. Inherent connections and key influencing factors of dual emission-reduction goals

Accelerating the carbon peak will gain time for and increase confidence in achieving carbon neutrality at a low cost. The emissions and time to peak will directly determine the urgency and arduousness of achieving carbon neutrality. On this basis, part of the research focuses on the timetable for and path toward carbon peaks in key industries and fields [21,60]. The current target year for China's commitment to achieving a carbon peak is less than ten years. Given the diversity of energy use patterns, technical routes, product performance, and other aspects, various industries have different roles and schedules in carbon peaking [6,61]. Where conditions allow, local key industries and firms should be promoted to take the lead in achieving the carbon peak. To avoid "one size fits all" approaches, it is essential to consider industry distinctions in the establishment of management objectives while treating all enterprises in the same industry impartially and carrying out carbon emission-reduction activities under the same standards. Under this premise, some studies have conducted economic and environmental effect analyses for various peaking strategies, as well as comprehensively optimizing the system path across several dimensions, such as technical measures, transformation costs, and environmental benefits [20,62,63].

In contrast to bottom-up research, some studies have employed classic methods such as decomposition analysis and machine learning to identify the key drivers of carbon emissions, quantify and evaluate long-term emission-reduction potential, and concisely explain representative paths and models that conform to regional or sectoral features [64,65]. With the advancement of research, the discussion on the main factors driving the development of the low-carbon economy has gradually expanded from population size, economic development levels, energy intensity, and carbon emissions per unit of energy consumption to a broader scope involving the energy consumption structure, industrial structure, urbanization, the division of labor for international trade, and disruptive technologies. On this basis, the degree of influence of each main factor deserves more attention, and the main direction of emission reduction could be locked in based on the degree of influence. Second, research should focus on whether there is a synergistic relationship between different driving factors and whether they can be considered jointly for emission reduction; and third, research should consider the regional and industrial heterogeneity of driving factors, and then investigate emission reductions systematically. After considering the heterogeneity of emission-reduction objects, these research results can serve as an important theoretical foundation for precise policy implementation.

5.2. Internal mechanism and realistic conditions for decoupling carbon emissions from economic development

The proposed carbon peak and carbon neutrality goals completely embody the development concept of decoupling carbon emissions from economic growth. The existing studies began with the internal mechanism for decoupling carbon emissions from economic development, clarified the characteristics of the stages for emission reductions, and analyzed the progress of the low-carbon transition of economic development by comparing stages and evaluating indicators to better determine how the economic and social system can achieve a low-carbon transition [66]. However, the abundance of descriptive assessment studies rather than quantitative analyses of progress makes it challenging to compare and judge the effects of implementing policies and activities across time and locations. In the future, there should be a greater focus on the evolutionary features of the relevant economic structure and the dynamic mechanism for different development stages. In addition, emission-reduction objectives at different stages should be defined to improve the scientific basis and efficacy of supporting policies. Moreover, the decoupling of carbon emissions from economic development depends on the actual conditions in different regions. The existing literature has explored the social, economic, and technical conditions for decoupling carbon emissions from economic development, and researchers have also conducted a series of horizontal and vertical comparative studies that combine the resource endowments, development phases, and industrial structures of different countries or regions [67,68]. Industrial transformation and technological innovation may continue to be the driving forces behind developing countries' efforts to decouple carbon emissions from economic growth. Future studies should focus on highlighting the conditional advantages of specific industries, areas, or subjects, as well as identifying their significant development barriers.

5.3. Uncertainties and their impacts on the low-carbon transition of socioeconomic systems

Uncertainty is an inherent feature of economic and social systems, posing a huge challenge to the choice of future transformation paths. However, scientists can improve the accuracy of future predictions through mathematical modeling [69]. Therefore, identifying the key uncertainties in the low-carbon transition path of the economic and social system is a primary task. This study summarizes five significant uncertainties in the transition path, according to the existing literature: namely, the social, economic, technological, behavioral, and policy dimensions. These uncertainties are not completely separate from each other; they constitute the uncertainty of the entire socioeconomic system together in the carbon-neutral process.

(1) **Social transformation is uncertain.** Social uncertainty mainly revolves around demographic changes. Because of the uncertainties surrounding the population size, age structure, and urbanization rate, the process and direction of social transformation are fraught with possibilities [70,71]. Future social transformations may appear as abrupt discontinuities or as relatively continuous changes over a long period. Therefore, discussing how to address the social transformation challenges brought about by the low-carbon transition is a key direction for further research and provides a cornerstone for the academic value and practical significance of future research.

(2) **Economic development is uncertain.** The uncertainty created by market fluctuations at the economic level may disturb macroeconomic trends and micro individual decision-making. In particular, the unpredictability of economic development will have a macro-level impact on the enthusiasm for and effectiveness of low-carbon transition policies, as well as a direct impact on the behavior patterns of and resource allocation for emission-reduction entities at the microlevel. Many previous studies have measured the uncertainty of investment, employment, and economic output using the volatility of time series data, such as gross domestic product (GDP) growth rate, stock price index, or exchange rate [72]. As globalization has progressed, the sources of uncertainty in economic development have expanded beyond traditional cyclical fluctuations to include the outbreak of major emergencies, such as trade frictions, regional conflicts, and local disasters [73]. These additional changes make accurately quantifying the system's economic uncertainty more difficult, raising the bar for the robustness of future carbon-neutral scenarios.

(3) **Technological progress is uncertain.** Almost every industrial revolution has been driven by technological breakthroughs. In practice, there are numerous dynamic paths and technology portfolios to achieve a carbon peak and carbon neutrality. Researchers have discussed the technological evolution path and structural characteristics of the energy system under the visions of carbon peaking and carbon neutrality, based on various technological development scenarios, taking into account the potential for technological cost reduction and the advent of disruptive technologies [74,75]. It is notable that the current analysis concentrates on the positive impact of technological innovation on the low-carbon transition and ignores the possible negative consequences, such as regional inequality and rising unemployment. This necessitates related research, particularly in developing countries, to strengthen the attention paid to and protection of key areas and populations that are likely to be affected by technological revolutions, and to ensure a fair and impartial transition.

(4) **Consumer behavior is uncertain.** The ultimate purpose of production is consumption, while consumption is at the root of carbon emissions. Achieving a carbon peak and carbon neutrality requires not only a reduction in the production side of emissions but also changes in consumer behavior patterns. Existing studies generally employ a mixture of survey and statistical data to assess the possible decrease in carbon emissions induced by behavioral changes [76,77]. Behavior patterns typically have a degree of inertia, which may have a lock-in effect on consumer carbon emissions [78]. In addition, consumption and energy usage behavior are influenced by income level, social culture, and cognition. Therefore, basic research on carbon peaking and carbon neutrality cannot disregard carbon emissions on the consumer side. Scientific research should be used to assist governments in formulating timely policies that are efficient, operable, and acceptable, as well as to effectively steer the green and low-carbon behavior of enterprises and individuals.

(5) **The relevant policy is uncertain.** Achieving the goals of carbon peaking and carbon neutrality will necessitate significant changes in the economy, energy, and technology. This requires the world's governments to provide a sound guarantee to their citizens, along with support of various kinds and incentive mechanisms. However, economic and social system transformation is a long-term process, and the ambiguity of the macro-political environment and industrial policy complicates this process [79,80]. Such policy and political uncertainty may arise from government-level elections, political events, reforms, and transformations, along with other events that raise concerns about future policies and government actions [81,82]. The vision of carbon neutrality as a new global target constraint will encourage the successive introduction of various supporting policies, and, in turn, the inflection point of such policies will affect the future reform of the social–economic–energy–technological system. For this reason, we should conduct in-depth research on the relationship between policy uncertainty and the low-carbon transition, or incorporate this uncertainty into the policy research framework, and explore how to improve and optimize policy measures, regulatory systems, and institutional frameworks in uncertain circumstances.

The key to reducing system transformation risk and improving the robustness of the transformation path is to identify major uncertain variables through limited calculations and to avoid related risks and repercussions. Based on this, we propose five questions to be investigated further in the future: ① What is the mechanism by which uncertain elements influence alternative transformation paths? ② How can the effects of uncertainty be accurately described? ③ In the face of unpredictable future development scenarios, how can a low-risk, economically optimal transition path be designed? ④ How well do different transition pathways withstand high levels of uncertainty interference? and ⑤ What is the mechanism of action of various solutions for dealing with uncertainty?

5.4. Integrated management mechanism of regional cooperation and co-governance under the carbon neutrality goal

Complex systems engineering is required to achieve a carbon peak and carbon neutrality. A comprehensive evaluation mechanism at the provincial level should be implemented to find regional collaborative optimization paths for reaching carbon peak and carbon neutrality goals. An urgent and critical topic is how to apply effective policies to attain regional low-carbon growth and coordinated development between regions; research on governance mechanisms for regional cooperation can help answer this question. Enthusiasm for voluntary emissions reduction in a region may be fostered by creating an ecological compensation system based on regional carbon emissions and carbon sink surveys; in this way, serious social problems caused by inequitable transformations can be avoided [83]. In addition, to ensure that the verification of interregional carbon trading or compensation is scientific and rigorous, it is necessary to develop a method or system with unified boundaries, comparable data, and calculable models. Building on this foundation, there is a requirement for in-depth quantitative research on the quantitative accounting of regional carbon emissions, the fairness assessment of carbon leakage, and the establishment of cross-regional carbon market mechanisms. This will provide scientific support for regional collaboration and common governance strategies under the carbon neutrality goal.

In China, key regions such as Beijing–Tianjin–Hebei, the Yangtze River Delta, Guangdong–Hong Kong–Macao, and the western areas should be nominated as carbon peak and carbon neutrality pilot demonstration areas for case studies. A slew of studies have underscored the significance and urgency of taking the lead in implementing green development strategies in these locations [84,85]. This suggestion is also reflected in China's programmatic document for carbon peaking and carbon neutrality. The collaborative governance model of low-carbon pilot cities should be prioritized, and the ecological environment's carrying capacity of various locations along the carbon neutrality path should be investigated. The demonstration effect will be generated from point to surface by implementing a multi-regional, complementary, and interactive development mechanism, which will then advance the new pattern of national low-carbon development.

5.5. Design of market-based instruments and flexible operation of carbon markets and hybrid policy

To combat climate change and meet emission-reduction targets, effective emission-reduction policies are required. Emissions reduction by market-based instruments is generally favored because of their greater economic efficiency, and such instruments have been widely practiced all over the world. China has built eight regional carbon market pilots since 2013 and launched a nationwide carbon market in 2017 [86]. Following the proposal of the dual carbon target, China has been accelerating the improvement of its national carbon market. In July 2021, the Ministry of Ecology and Environment of the People's Republic of China announced the official launch of the national carbon market and the start of trading. Products that can be traded in the national carbon market include spot carbon allowances, national certified voluntary emission reductions (CCERs), and long-term carbon allowances. This study summarizes the management science concerns that have been discussed in the literature.

Related research on carbon trading focuses on three aspects: first, setting total quotas, determining coverage and quota allocation principles, and other *ex-ante* analyses; second, designing flexible control mechanisms and quota-withdrawal mechanisms during trading; and third, the *ex-post* evaluation of the effect of carbon trading policy [87–89]. The literature on carbon taxes commences with the design of the tax system, focusing on tax rate formulation, tax neutrality research, and the implications of carbon taxes on the economy, environment, distribution, and substitution [90,91]. Many studies have demonstrated that the hybrid mechanism is more efficient and aligned with the actual policy frameworks of various countries [92]. Research on hybrid mechanisms is becoming increasingly popular, manifesting itself in two forms. Implementing price-control measures based on the existing carbon market optimizes emission-reduction costs; moreover, research into the dual-track parallel system of carbon markets and carbon taxes may provide many countries, including China, with ideas for adopting hybrid mechanisms. Nevertheless, some argue that the current low carbon price is insufficient to spur substantial emission reductions. There are currently few empirical evaluations of the effectiveness of market mechanisms; thus, the mechanisms and their effectiveness should be thoroughly investigated. This is different from the general market mechanism policy effect evaluation mentioned above around the European and American carbon markets or Chinese pilot markets. We must sort out the mechanism of how market instruments work. The greatest difficulty is eliminating the impact of other environmental policies on carbon emissions reduction when evaluating the efficiency of carbon market mechanisms. Once the carbon management market mechanism's impact on emission reductions is understood, the carbon pricing level under the carbon peak and carbon neutrality goals can be scientifically stated, providing guidance for the market mechanism's policy design.

6. Conclusions and implications

This study traces the international trends and development principles of the field from a spatial and temporal perspective, evaluates the research status and hot topics from a technical perspective, and explores the pathway and key points to achieve the carbon peak and carbon neutrality goals from an industrial viewpoint by sorting through 1105 publications related to carbon peaking and carbon neutrality. The scientific implications of the carbon peak and carbon neutrality goals are clarified, and essential management issues are proposed. Based on the literature review, some recommendations for priority tasks for future study are provided.

Achieving carbon neutrality is a classic issue of multi-agent collaborative governance involving multiple regions and industries. Management theories of carbon neutrality are currently in high demand in the construction of ecological civilizations. Against this background, it is necessary to incorporate carbon neutrality into the overall framework for constructing an ecological civilization, to study the theoretical implications of this concept in depth, and to create a carbon neutrality management theory and methodology system within the framework of ecological civilization. The construction of a China-specific ecological civilization is expected to provide scientific insights into worldwide challenges related to industrial civilization transformation and the realization of sustainable development.

The carbon peak and carbon neutrality vision promotes a long-term, systematic, revolutionary, and forward-thinking low-carbon transition. To better address the long-term management science problems indicated in the preceding section, we recommend the following priority research directions that are worthy of special attention in this inevitable broad and profound systemic change: ① investigate methods for calculating binding indicators, including total carbon emissions and growth rate, to aid in the development of action plans for carbon peak and carbon neutrality goals; ② simulate the path to peak emissions at the industry level to support the design of the industry's carbon peak plan; ③ conduct research on carbon taxes and carbon emissions trading systems to enhance the effectiveness of market-based instruments; ④ explore the mechanism for the impact of the optimization of the industrial structure on carbon emissions to facilitate industrial transformation; and ⑤ quantify the potential and contribution of CCUS to carbon neutrality to support the development of significant projects.

To assist in the integration of multiple disciplines, the construction of a think-tank platform that merges production, education, and research is recommended. Cross-disciplinary technology innovation teams, including but not limited to the areas of economics, society, energy, geography, meteorology, ecology, environmental health, and healthcare, should be organized to strengthen scientific and technological capabilities to achieve carbon peak and carbon neutrality goals. Basic research on climate change economics should be simultaneously bolstered by the formation of interdisciplinary teams and a national key laboratory or research center. Climate economic databases and knowledge bases should be built in accordance with the primary strategic tasks of achieving a carbon peak and carbon neutrality, with basic science and applied scientific research serving as the foundations. Furthermore, long-term and continuing simulations and assessments of national and global climate policies are essential for providing scientific decision-making support for high-quality development and improved involvement in the global climate governance system.

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Compliance with ethics guidelines

Yi-Ming Wei, Kaiyuan Chen, Jia-Ning Kang, Weiming Chen, Xiang-Yu Wang, and Xiaoye Zhang declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2021.12.018.

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