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Discussion on Action Strategies of China's Carbon Peak and Carbon Neutrality

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Abstract

China's carbon peak and carbon neutrality action is a huge system engineering with national coverage, country-led and universal participation, long-term sustainable implementation, requiring definite, tenacious, and adaptable action strategies. Here, based on summarizing the current situations of "carbon peak and carbon neutrality", the action strategies, technological approaches, and scientific and technological supports are discussed to achieve the "dual carbon" targets in China. It is suggested that China's "dual carbon" action should insist on "one basic concept", achieve "two macroscopic targets", implement the "three-pronged comprehensive", and "four-way simultaneous" technological paths, and practice the macro layout of "five coordination" in the national land space control and the coordinated industrial development. It is required to strengthen scientific research on climate change and earth system carbon cycle and technological revolution for decarbonization and low-carbon industry. In the field of global change and ecological economics for national "dual carbon" action, more attention should be paid to key scientific issues. There are the construction of the multi-factors, multi-processes, multi-interfaces, and multi-scales collaborative monitoring system for carbon cycle process, carbon storage and flux in Earth system, and the systematic cognition and precise assessment of the carbon sink function and its potential of Chinese regional ecosystems. For the moment, it is urgent to build and complete the scientific and technological supporting system in seven aspects:scientific basis, observation and simulation, energy structure transformation, industrial structure adjustment, ecological carbon conservation and sink increase, national strategy and approach route, collaborative governance, and management policy.

Keywords

carbon peak carbon neutrality action strategies climate governance emissions reduction and increment of carbon sink ecosystem carbon cycle

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Discussion on Action Strategies of China's Carbon Peak and Carbon Neutrality

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Abstract: China's carbon peak and carbon neutrality ("dual carbon") action is a huge system engineering with national coverage, country-led and universal participation, and long-term sustainable implementation, requiring definite, tenacious, and adaptable action strategies. This paper first summarizes the current situations of carbon peak and carbon neutrality, and then discusses the action strategies, technological approaches, and scientific and technological supports to achieve the "dual carbon" targets in China. It is suggested that China's "dual carbon" action should insist on "one basic concept", achieve "two macroscopic targets", implement the "three-pronged comprehensive", and "four-way simultaneous" technological paths, and practice the macroscopic layout of "five coordination" in the national land space control and the coordinated industrial development. It is required to strengthen the research on climate change and earth system carbon cycle and the technological revolution for decarbonization and low-carbon industry. In the field of global change and ecological economics for national "dual carbon" action, more attention should be paid to key scientific issues, the construction of the multi-factors, multi-processes, multi-interfaces, and multi-scales collaborative monitoring system for carbon cycle process, carbon storage and flux in Earth system, and the systematic cognition and precise assessment of the carbon sink and its potential of Chinese regional ecosystems. For the moment, it is urgent to build and improve the scientific and technological supporting system in seven aspects: scientific basis, observation and simulation, energy structure transformation, industrial re-structuring, ecological carbon conservation and sink increase, national strategy and approach route, collaborative governance, and management policy. **DOI:** 10.16418/j.issn.1000-3045.20220121001-en

Keywords: carbon peak; carbon neutrality; action strategies; climate governance; emissions reduction and increment of carbon sink; ecosystem carbon cycle

Global climate change is one of the severe challenges facing the development of the human society [1]. The Paris Agreement ① has established the goal of controlling the global average temperature increase well below 2 °C above pre-industrial levels while pursuing means to limit the increase to 1.5 °C for reducing the risks and impacts of climate change [2]. Carbon dioxide (CO_2) is the primary greenhouse gas in the atmosphere, contributing approximately 66% of global warming. In 2020, the global average concentration of CO_2 has reached a new highest level of 413.2 ppm ② and is still rising ③. According to predictions of numerous models, the global temperature will increase by 2 °C–5 °C [3] due to the doubling of atmospheric CO_2 (based on the pre-industrial CO_2 concentration). Therefore, the international community has proposed that global emissions of CO_2 need to reach a carbon peak by 2025 [4] and the climate governance goal of carbon neutrality should be archived by 2050 [1] ④.

Global climate governance is not only an important issue requiring the collective response of the human society to global change, but also a civilizational achievement of the human history and scientific progress. From the perspective of human ecology focusing on human survival and socio-economic

① The Paris Agreement, the second legally binding climate agreement after the Kyoto Protocol, was adopted at the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (Paris Climate Conference) on December 12, 2015. The climate change agreement signed by 178 parties from around the world is a unified arrangement for global response to climate change after 2020.

② Data from the World Meteorological Organization (The state of greenhouse gases in the atmosphere based on global observations through 2020. Greenhouse Gas Bulletin, 2021. https://reliefweb.int/report/world/wmo-greenhouse-gas-bulletin-state- greenhouse-gases-atmospherehere-based-global-1).

③ Monitoring data are from the Global Monitoring Laboratory (GML) of the National Oceanic and Atmospheric Administration (NOAA) [2021-11-30]. https://gml.noaa.gov/dv/iadv).

④ UN. The race to zero emissions, and why the world depends on it. (2020-12-02)[2021-12-24]. https://news.un.org/en/story/2020/12/1078612.

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development, the global carbon peak and carbon neutrality (hereinafter referred to as "dual carbon") action has the following significance. (1) It is the self-correction of the human population and social development pattern, as well as an artificial orderly intervention on the evolution of the biosphere. (2) It is the practical exploration of the human society to collaboratively restructure the global environmental governance system and reshape the community of nature and life. (3) It is a major project implemented by the human society to jointly control the material cycle mode and process of the Earth system. The "dual carbon" targets require scientists to deeply understand the relationship between the natural succession law of the biosphere and the sustainable development of mankind, explore the theoretical and technical approaches to reshape the nature and human community with a shared future, and design a systematic engineering scheme to collaboratively regulate the global eco-environment, considering the responses to global changes.

Achieving the "dual carbon" targets is a strategic decision made by the CCP Central Committee with Comrade Xi Jinping as the core to balance China's domestic and international interests [5]. A correct understanding of the scientific, economic, and social significance of China's "dual carbon" targets plays an overall, strategic, and guiding role in the formulation of "dual carbon" action strategies. In China, the "dual carbon" action has the following strategic significance. (1) It is a grand measure taken by China to respond to the profound changes unseen in a century and achieve social transformation, scientific development, and national rejuvenation in the next 50 years. (2) It is China's political commitment to participate in global governance and an autonomous action to implement the temperature control goal of the Paris Agreement. (3) It is a reversely forced mechanism to change the socio-economic development pattern, curbing the deterioration of eco-environment, promoting the technological revolution for decarbonization, and fostering low-carbon industry. (4) It is a new engine to drive China's ecological civilization construction, govern the national land spatial environment, and achieve the development goal of building a prosperous, beautiful, and healthy modern country.

However, China's "dual carbon" action faces great challenges. Developed countries have gone through the period of rapid economic growth in agriculture and industrialization. Their CO_2 emissions have reached the natural peak in the process of economic transformation and globalization, and they are now in a new phase of post-peak carbon neutrality. However, since the world's energy-consumptive industries, such as material and manufacturing industries, are still shifting toward developing countries, the majority of developing countries are still in the rising or plateau phase of CO_2 emissions. How will China as a major developing country balance its socio-economic development with the "dual carbon" strategy to form a development pattern characterized by the coordination of decarbonization, carbon reduction, emissions and pollution reduction, carbon sink increase, and sustainable growth? How to formulate a technically feasible and cost-effective action plan that coordinates social development with the "dual carbon" action? These are not only challenging strategic issues but also major scientific and technological issues for balancing social development, ecological civilization construction, and environmental governance.

This paper first summarizes the current situations of carbon neutrality in response to global climate change, and then discusses the action strategies, technological approaches, and potential contribution of ecosystem carbon sink to achieve the "dual carbon" targets in China. Further, it analyzes the challenges of China's "dual carbon" targets, the coordination of carbon sink increase paths in the terrestrial, freshwater, and marine ecosystems, and the core scientific issues of ecological research to cope with global change and increase ecosystem carbon sink. It is hoped that this paper can provide theoretical reference for formulating systematic solutions with tenacity and adaptability under the guidance of the national "dual carbon" strategy.

1 Current situations of global "dual carbon" issue

According to the data of Global Carbon Project, the global average annual anthropogenic CO_2 emissions are approximately 38.9 billion tons from 2011 to 2020, in which the carbon emissions from energy consumption and land use change account for 89% and 11%, respectively. Moreover, 48% of the anthropogenic CO_2 emissions remain in the atmosphere, while the remaining 29% and 26% are absorbed and fixed by terrestrial and marine ecosystems, respectively ⑤ (Figure 1) [6].

On the basis of the near-linear relationship between cumulative CO_2 emissions and the global maximum surface temperature increase caused by CO_2, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimated that the allowable increases in global anthropogenic CO_2 reserves after 2020 under the global temperature control targets of 1.5 °C and 2 °C (67% probability) would be 400 billion tons and 1 150 billion tons, respectively [1]. This means that if no reduction measures are taken, the global atmospheric temperature will rise by more than 1.5 °C and 2 °C by 2030 and 2050, respectively, according to the global average annual rate of anthropogenic CO_2 emissions

⑤ In the global carbon equilibrium equation, the combined contribution of atmosphere, land, and ocean is 103%, with the excess 3% derived from the uncertainty of the assessment.

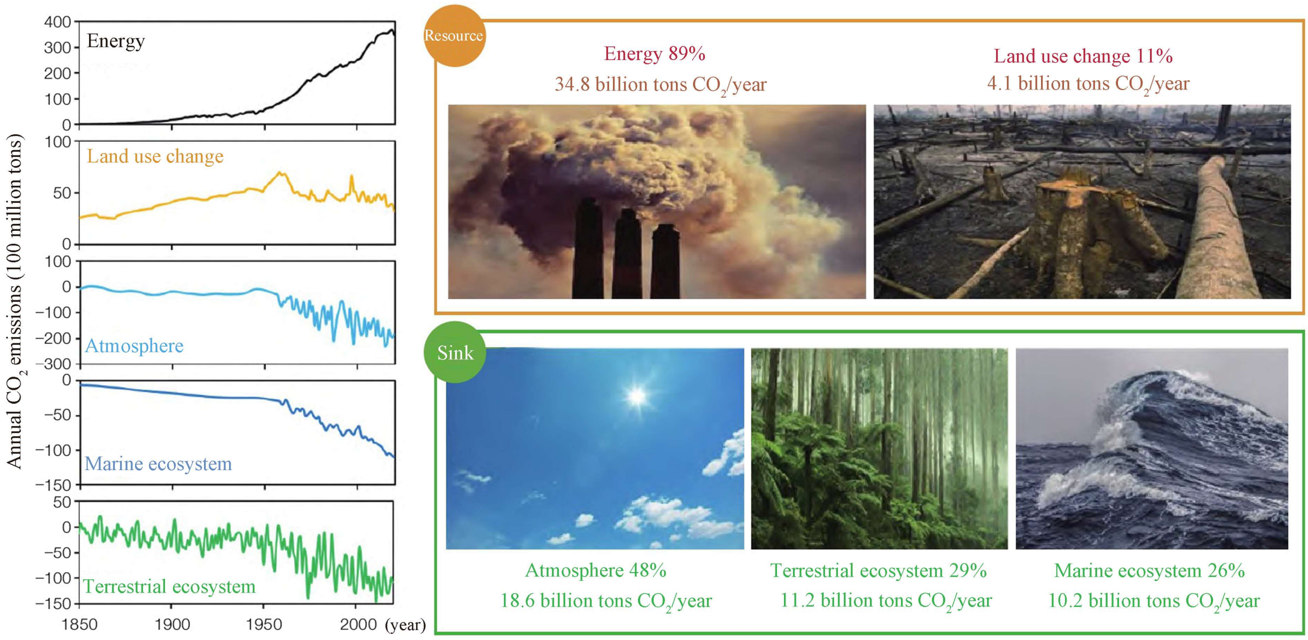

Figure 1 Statistical analysis of global anthropogenic carbon dioxide budget [6]

from 2011 to 2020 (38.9 billion tons CO_2/year). The global coordinated control of anthropogenic carbon emissions by the implementation of "dual carbon" action is an inevitable choice for the human society to deal with global climate change. Meanwhile, considering the complex nonlinear responses of the global carbon cycle, atmospheric CO_2 concentration, and warming to atmospheric CO_2 removal, achieving the global "dual carbon" targets may require more efforts.

To achieve global temperature control, equal attention needs to be paid to the control of non-CO_2 greenhouse gas emissions. There is a need to neutralize the climate effects of all anthropogenic greenhouse gas emissions with those of greenhouse gases removed by natural and anthropogenic absorption, which is known as global climate neutrality. In view of the concept of global climate neutrality, the global annual greenhouse gas emissions should be limited to about 27.5 billion tons of CO_2 equivalent in 2030 and 7 billion tons of CO_2 equivalent in 2050 under the atmospheric warming control goal of 1.5 °C in 2100. However, according to the current emissions, the total greenhouse gas emissions in 2030 will be 52 billion to 58 billion tons of CO_2 equivalent [7–9]. In terms of CO_2 alone, the emissions are expected to peak (approximately 42 billion tons/year) in 2025, which means that the temperature control goal of 1.5 °C is basically unattainable under the historical development pattern. The climate model analysis indicates that to limit the global warming to 1.5 °C, the global annual net CO_2 emissions in 2030 and 2050 need to be limited within 20.3 billion tons and −0.5 billion tons, respectively, and 10.2 billion tons of CO_2 should be fixed from the atmosphere annually by the year 2100 (Figure 2) [9]. It is estimated that with the peak CO_2 emissions in 2025, the global annual net CO_2 emissions need to be reduced by 4.3 billion tons and 1.7 billion tons on average in 2025–2030 and 2025–2050, respectively, to limit warming to 1.5 °C and achieve global carbon neutrality by 2050.

2 Current situation of China's "dual carbon" issue

2.1 CO_2 emissions

In terms of the total annual CO_2 emissions and its proportion in global total annual CO_2 emissions, China now ranks first in the world. In 2019, China's annual CO_2 emissions (including cement production + fossil fuels) are 10.17 billion tons, accounting for 28% of the global total CO_2 emissions of the year (Figure 3). Excluding the carbon absorption by land use change (0.65 billion tons of CO_2), the net average annual carbon emissions from anthropogenic sources are 9.52 billion tons of CO_2 [6] ⑥, and the annual emissions per capita are 7.32 tons of CO_2, which is higher than the global average level of 4.76 tons of CO_2. However, from 1959 to 2019, China's cumulative CO_2 emissions per capita are 175.5 tons of CO_2, which is well below that in the developed countries and regions such as Europe, the United States, and Japan, and even lower than the global average level. It is only 15% of cumulative CO_2 emissions per capita of the United States (Figure 4).

⑥ Carbon emission accounts & datasets for emerging economies. [2021-12-17]. https://www.ceads.net.cn/data; FAO. Food and agriculture data. [2021-12-16]. https://www.fao.org/faostat/en/#data/GT.

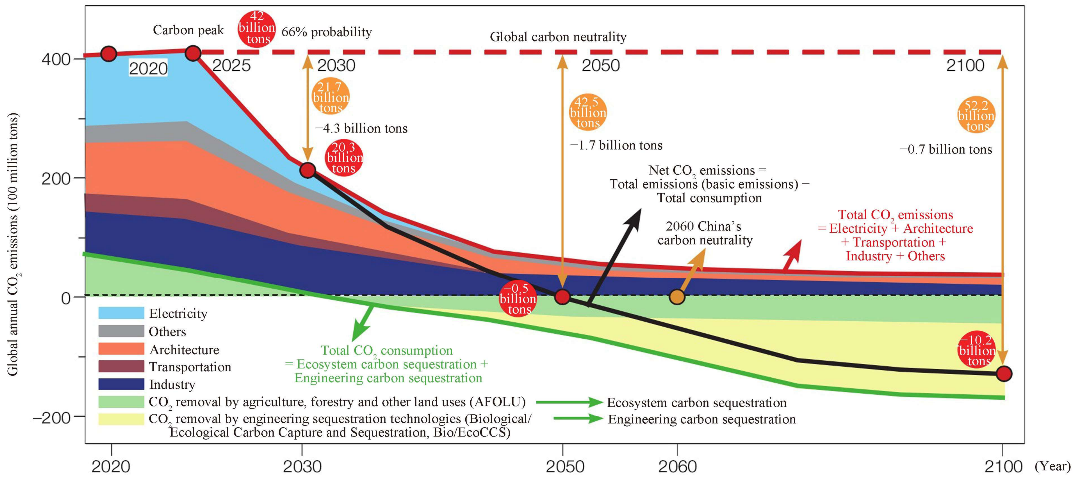

Figure 2 Control target and technology path of global carbon emission

This figure was adapted from Ref. [9], and data is for the decarbonization scenario limiting warming to 1.5 °C. Net amount of CO_2 emissions is the difference between total amount of CO_2 emissions and total amount of CO_2 removed from the atmosphere, where total CO_2 emissions, also called base CO_2 emissions, include industry, transport, buildings, electricity and other, and total CO_2 removal is the sum of ecosystem carbon sequestration (i.e., AFOLU) and engineering carbon sequestration (i.e., Bio/EcoCCS).

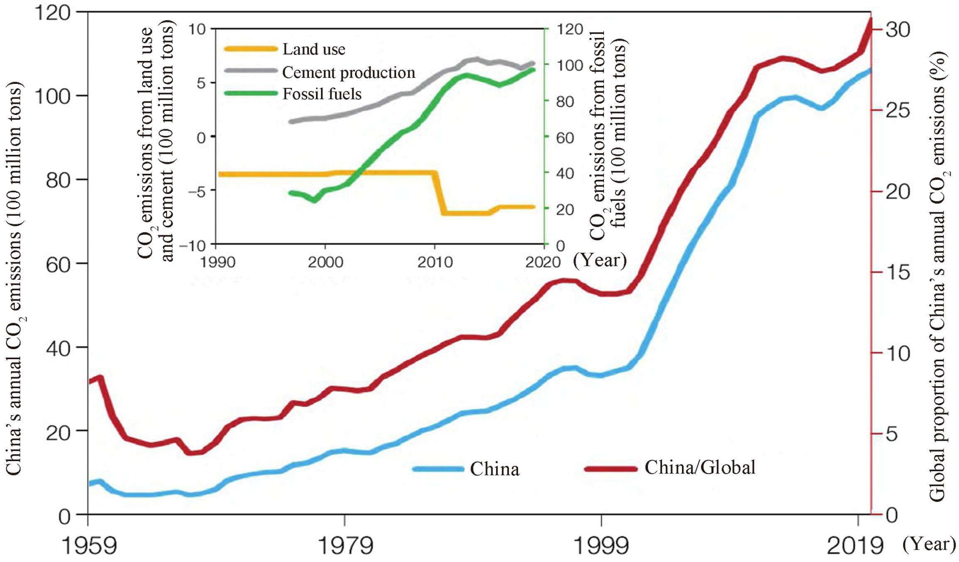

Figure 3 China's CO_2 emissions and its proportion in global total emissions from 1959 to 2019

Data of carbon emissions from land use is derived from FAO, and data of carbon emissions from fossil fuels and cement is from CEADs. The panel in the upper left of the figure shows the CO_2 emissions from land use, fossil fuels, and cement.

2.2 Quantitative tasks of "dual carbon"

The CPC Central Committee and the State Council recently released the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy. The Working Guidance specifies to adhere to the strategic principles of overall planning, conservation priority, two-wheel drive, internal and external coherence, and risk prevention, and sets a quantitative stage objective ⑦, pointing out the direction of China's "dual carbon" action. At present, the average annual carbon emissions from anthropogenic sources in China are approximately 10 billion tons of CO_2, and it is estimated that the value may reach 10 billion to 11 billion tons of CO_2 during carbon peak by 2030 [10]. Therefore, China's quantitative tasks to achieve "dual carbon" can be expressed as how to reduce the current anthropogenic CO_2 emissions of about 10 billion tons per year by technological approaches while maintaining the expected economic development goals in the next 40 years (Figure 5).

⑦ Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy. [2022-01-04]. http://www.gov.cn/xinwen/2021-10/24/content_5644613.htm.

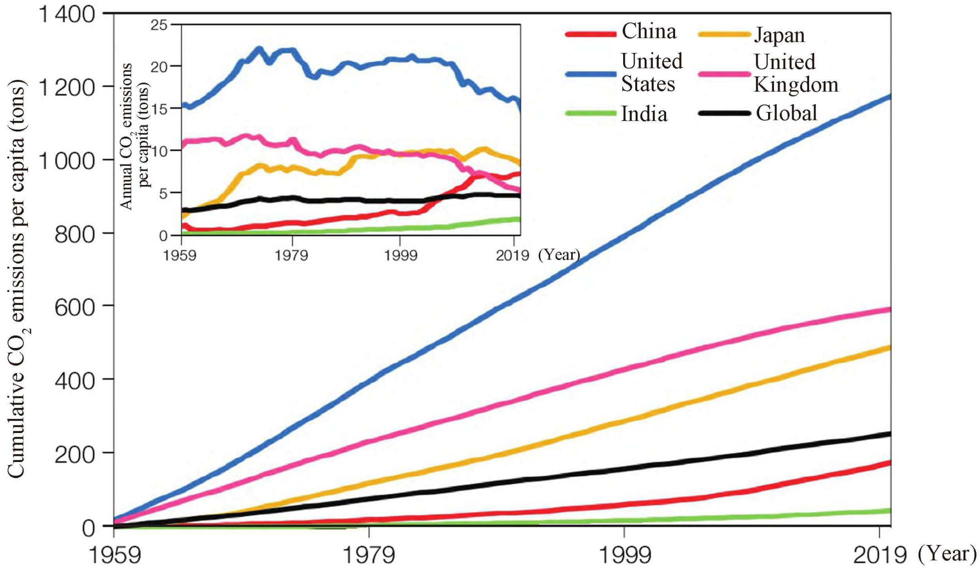

Figure 4 Cumulative CO_2 emissions per capita globally and in some countries from 1959 to 2019

Data is derived from Global Carbon Project. The panel in upper left shows annual CO_2 emissions per capita globally and in some countries.

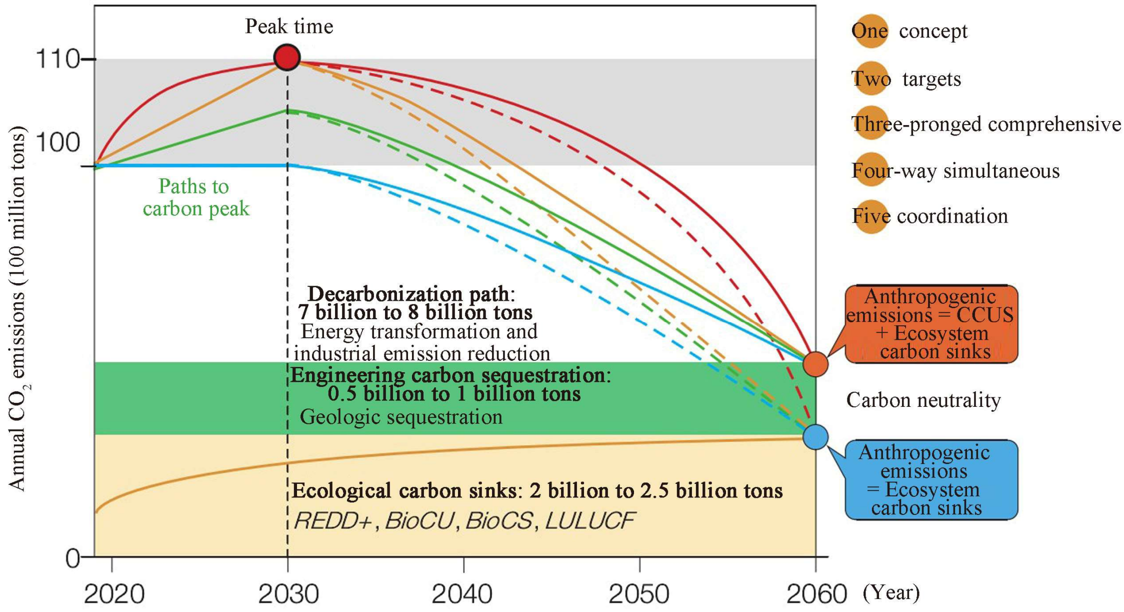

Figure 5 Tasks and potential solutions of "dual carbon" action in China

REDD+ represents reducing emissions from deforestation and forest degradation; BioCU represents biological carbon capture and utilization; BioCS represents biological carbon capture and storage; LULUCF represents land use, land use change, and forestry.

A carbon neutrality scheme with reference significance in China is as follows. Through energy transformation and industrial emission reduction, the anthropogenic emissions of 7 billion to 8 billion tons of CO_2 will be directly reduced each year, which will reduce the annual direct anthropogenic emissions to around 3 billion tons of CO_2 by 2060. For this part of anthropogenic emissions, firstly, 2 billion to 2.5 billion tons of CO_2 per year should be neutralized by ecosystem carbon sinks, and then 0.5 billion to 1.0 billion tons of CO_2 can be stored annually by engineering carbon capture, utilization, and storage (CCUS), which will help to achieve the carbon budget goal of balancing anthropogenic carbon emissions with natural and anthropogenic carbon absorption. The scheme implies setting aside around 3 billion tons of anthropogenic carbon emissions per year for national development. In other words, basic anthropogenic carbon emissions to sustain economic development and national security can be neutralized by the conservation and increase of ecosystem carbon sinks (Figure 5).

2.3 Challenges to achieve "dual carbon" targets

China's "dual carbon" targets is a national action with the largest emission reduction and the shortest time in the world. It is an arduous task with time constraints and lack of scientific and technological support. Under the current economic development goals and the energy and industrial structure, we need to reform the economic development pattern and technological system and decouple the economic development and carbon emissions as soon as possible to achieve the "dual carbon" targets while ensuring the stable economic development. In this process, we will face the challenges in civic awareness, lifestyle, science and technology, and social management system.

(1) Rigid demand for economic development. To achieve the Two Centenary Goals and build a prosperous, beautiful, and healthy China, we need to quadruple the current gross domestic product (GDP) by 2050 to match the average level in developed countries. With the existing energy structure and energy consumption per unit of GDP, the annual emissions of fossil energy consumption in 2050 will be as high as 39 billion tons of CO_2 ⑧. In this context, balancing the relationship between carbon emissions and economic development is one of the major challenges affecting the eco-environment, people's well-being, and the country's right to development.

(2) Difficult transformation for energy decarbonization. Focusing on the national strategic needs of energy security and energy autonomy and control, it is the key task of the "dual-carbon" action to replace the traditional energy with low-carbon new energy quickly, efficiently, and economically. However, high carbon-based energy dominates in China, with fossil energy consumption accounting for 85% of total energy consumption. Even if the proportion of non-fossil fuels in total energy consumption reaches an ideal 62.8% in 2050 [11], the annual emissions of fossil energy consumption will still exceed 17 billion tons of CO_2 due to the increase in rigid energy demand for the quadrupling of GDP. Therefore, how to balance the relationship between development and carbon emissions, develop low-carbon alternative energy in a short time, and decouple economic development and carbon emissions as soon as possible are the major challenges.

(3) Difficult re-structuring of industries. The industrial re-structuring is a breakthrough point for promoting the synergy of pollution reduction and carbon reduction, which is of great significance to achieve the "dual carbon" targets. In 2020, China's industrial output accounts for 30.8% of GDP, while the carbon emmissions from industrial energy consumption accounts for 65% CO_2 emissions from energy consumption. China's manufacturing industry is dominated by the energy-consumptive heavy chemical industry, which, however, is an important part of the national economy. A considerable amount of the energy-consumptive products is the national strategic raw materials, which plays a role in supporting the stable market supply, the integrity of the industrial system, and the steady growth of the economy.

(4) Shortage of technology. Scientific and technological innovation is the fundamental momentum for realizing the "dual carbon" targets. At present, China's technology for decarbonization and carbon reduction is still at the initial stage of development, and the current scientific and technological innovation reserve cannot support the "dual-carbon" action. It is urgent to develop the problem- and goal-oriented transformative technologies, especially in the energy field and industrial re-structuring.

(5) Limited carbon sink of natural ecosystems. Before major breakthroughs and large-scale applications of decarbonization and carbon reduction technologies that focus on energy supply and consumption are achieved, the carbon sink of ecosystems can play a key role in controlling the basic anthropogenic carbon emissions for economic development and national security. Despite vast natural ecosystems in China, such as alpine ecosystems, wilderness, desert, and saline-alkali soil, the carbon sink of these ecosystems is limited. In addition, due to the limitations of the national land space, climate, water and soil resources, and environmental carrying capacity, it is a long way to achieve the "dual carbon" targets with high quality in a short time.

3 China's macroscopic strategies for achieving "dual carbon"

3.1 Paths to achieve "dual carbon" targets

National development and rejuvenation are the top priority. Technological innovation is the only path, and the development path can be continuously optimized. In the face of China's "dual-carbon" task, how to set the peak target and determine the neutrality paths are the major scientific issues. Long-term layout should be designed based on national conditions. While promoting energy transformation and developing industrial emission reduction technologies, we should explore the potential of ecosystem carbon sequestration and anthropogenic carbon sequestration, thereby striving to retain a certain level of carbon emission space for fossil fuels while achieving carbon neutrality. This is of strategic significance for reducing the economic cost of "dual carbon" action and resisting social risks.

The path to achieve the "dual-carbon" targets is not a priori, vested, or immutable. It should be dynamically adjusted

⑧ Based on data of carbon emission accounts & datasets for emerging economies (CEADs). [2021-12-17]. https://www.ceads.net.cn/data.

and continuously optimized according to technological development and social demand. The systematic solutions with tenacity and adaptability should be adopted under the guidance of national strategies. We believe that China's macroscopic strategies for achieving the "dual carbon" targets can be expressed as insisting on "one basic concept", achieving "two macroscopic targets", implementing the "three-pronged comprehensive", adopting "four-way simultaneous" technological paths, and practicing the macroscopic layout of "five coordination". "One basic concept": development and rejuvenation are the top priority; innovation and transformation is the fundamental path; the development path must be optimized. "Two macroscopic targets": forcing energy and industrial emission reduction to promote technological progress and development transformation; driving comprehensive management of the eco-environment and cultivating ecological economy. "Three-pronged comprehensive": energy structure transformation, industrial re-structuring, and eco-environment governance. "Four-way simultaneous": emission reduction, carbon sink increase, carbon conservation, and carbon sequestration for the emerging decarbonization economy, the sink increase economy, the industrial economy, and the ecological economy, respectively. "Five coordination": technological revolution and economic development transformation, carbon reduction and environmental governance, ecological carbon conservation and sink increase, land space utilization and comprehensive governance, and collaborative management of organic/inorganic carbon sinks and non-CO_2 greenhouse gases.

3.2 "Three-pronged comprehensive" innovation strategy and "four-way simultaneous" technological path

The realization of the "dual carbon" targets depends on the "three-pronged comprehensive" innovation strategy: decarbonization by energy structure transformation, emission reduction by industrial re-structuring, and carbon sink increasing by eco-environment governance. This requires the establishment of a "three-pronged comprehensive" technical system from three aspects (Figure 6). (1) Decarbonization of energy supply and consumption. It is suggested to replace fossil energy for power generation and hydrogen production with non-carbon-based energy, such as solar energy, wind energy, and hydroenergy and thus construct a new power/energy supply system dominated by clean energy. In the major carbon emission fields, such as residential life, transportation, industrial production, agriculture, and architecture, efforts should be made to replace fossil energy consumption with non-carbon-based energy, such as clean electricity, hydrogen energy, geothermal energy, and solar energy. (2) Low-carbon transformation of industrial structure for the development of ecological economy. In energy-consumptive industries, such as steel, non-ferrous metals, petrochemicals, chemicals, and building materials, the priority should be given to the development of low-carbon process industries, low-carbon building materials, green transportation systems, and low-carbon transformation of fossil resources, thus establishing a low-carbon industrial system and ecological economic development pattern. (3) Eco-environment governance of anthropogenic carbon sequestration. Basic anthropogenic carbon emissions can be neutralized through combined technologies and projects such as eco-environment construction, soil carbon sequestration, and atmospheric CCUS. Before breakthroughs are made in key energy technologies, the most effective, greenest, most economical, and largest-scale technological approach is to consolidate and enhance the carbon sink of the ecosystem through ecological engineering. It is also highly compatible with the national goal of ecological civilization construction, and can be regarded as the cornerstone to achieve the "dual carbon" targets and the stabilizer for socio-economic development.

Emission reduction, carbon sink increasing, carbon conservation, and carbon sequestration are widely recognized as the effective paths to achieve the "dual carbon" targets. China's "dual-carbon" action should take a coordinated technical path with simultaneous adoption of the four paths (Figure 6). Emission reduction is to promote technological progress in energy supply and industrial consumption and take the path of developing decarbonization and low-carbon industries, thereby directly reducing the anthropogenic carbon emissions. Carbon sink increasing refers to the use of ecological engineering and land management to increase the carbon storage and sequestration of terrestrial and marine ecosystems. Carbon conservation aims to protect the carbon storage and sequestration capacity of existing terrestrial and marine ecosystems. Carbon sequestration means to adopt geological engineering, biotechnological, and ecological measures to capture, utilize, and store atmospheric CO_2.

Only by implementing the "three-pronged comprehensive" technological revolution of energy structure transformation, industrial re-structuring, and eco-environment governance, and the "four-way simultaneous" technological paths of emission reduction, carbon sink increasing, carbon conservation, and carbon sequestration, can we achieve the arduous and ambitious "dual carbon" targets at low cost. Meanwhile, the conflict between economic development and carbon emission reduction can be solved, and the coordinated integration of scientific and technological progress, economic transformation, pollution control, ecological restoration, and ecological civilization construction can be achieved. Finally, a new situation of coordinated development of decarbonization, carbon reduction, emission reduction, carbon sink increasing, and sustainable growth can be formed, ensuring the tenacity and adaptability of the strategic layout of economic development.

3.3 Macroscopic layout of "five coordination"

To achieve the "dual carbon" targets, China needs to adhere to three basic principles: (1) promoting social development and technological innovation, and strengthening energy conservation and emission reduction; (2) exploring the potential of ecological carbon sequestration and engineering carbon sequestration, and retaining appropriate carbon emission space; (3) reducing economic costs and social risks, and cultivating the new ecological economy. On the basis of implementing the three basic principles, the "three-pronged comprehensive" innovation strategy, and the "four-way simultaneous" technological paths, efforts should be made to implement the "five coordination" layout in the whole industrial field and the whole national land space, and promote the comprehensive integration of "dual carbon" action with economic transformation, industrial carbon reduction, ecological civilization construction, comprehensive national land space governance, and scientific implementation of systematic thinking (Figure 6).

(1) Coordination of social development, economic transformation, and cultivation of new ecological economy. With the momentum for achieving "dual carbon" targets and ecological construction, it is necessary to accelerate the transition from a carbon-based industrialized society to an ecological economy based on new energy. While ensuring the macroeconomic progress and stability, we should guide the formation of new ecological economic theories and markets, and establish an incentive mechanism for the country, enterprises, and the public to participate in the "dual carbon" action.

(2) Coordination of emission reduction, carbon reduction, and air quality control. Greenhouse gases and atmospheric pollutants share the same basic characteristics. Coordinating "dual carbon" action and air pollution prevention and control is the acting point of China's current ecological civilization construction. It can provide systematic and multi-dimensional solutions and governance countermeasures for achieving the "dual carbon" targets and clean air.

(3) Coordination of ecological carbon conservation, carbon sink increasing, and construction of a beautiful China. The ultimate goal of promoting ecological civilization construction is to build a prosperous, beautiful, and healthy modern country, and achieve the sustainable development of the Chinese nation. The "dual carbon" targets are undoubtedly the most powerful flagship action and starting point for ecological civilization construction in the new era. Ecological carbon conservation and carbon sink increasing are not only the key paths to achieve the "dual carbon" targets but also an important ecological guarantee for building a beautiful China.

(4) Coordination of carbon sink increasing paths in terrestrial, freshwater, and marine ecosystems. The terrestrial, freshwater, and marine ecosystems play a role of carbon sink, protecting, consolidating and enhancing the carbon stock of the natural ecosystems in the national land space. Comprehensively exploring the potential of terrestrial, freshwater, and marine ecosystems in carbon sink is an important technical path to achieve the "dual carbon" targets.

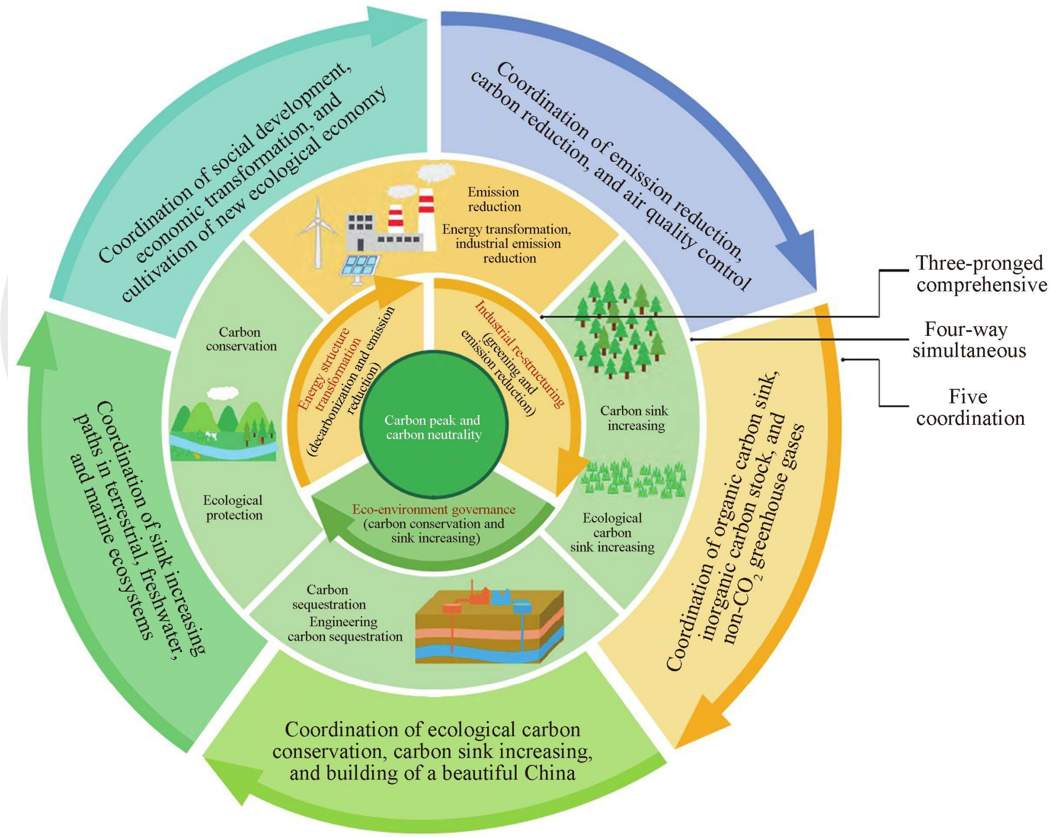

Figure 6 Potential technological paths and measures to achieve carbon peak and carbon neutrality

(5) Coordination of organic carbon sink, inorganic carbon stock, and non-CO_2 greenhouse gases. Soil organic and inorganic carbon in ecosystems jointly determine the soil carbon stock. Inorganic carbon exchange between the land surface and the atmosphere, carbon emissions or absorption of geological processes, non-CO_2 greenhouse gas emissions, and greenhouse effect have attracted increasing attention from the academic community. Therefore, it is far from enough for the national "dual carbon" action to focus only on the control of the organic carbon cycle in the ecosystem. It is essential to take into account and accurately balance the relationship between organic carbon sink, inorganic carbon stock and non-CO_2 greenhouse gases to ensure the integrity of the solution for the "dual carbon" action.

4 Scientific and technological support for implementation of "dual carbon" action

The major changes in science, technology, and society driven by the "dual carbon" targets will change China's traditional development pattern, industrial division of labor, and scientific and technological system, which presses for strong scientific and technological support. Therefore, the scientific and technological supporting system should be built in seven aspects (Figure 7).

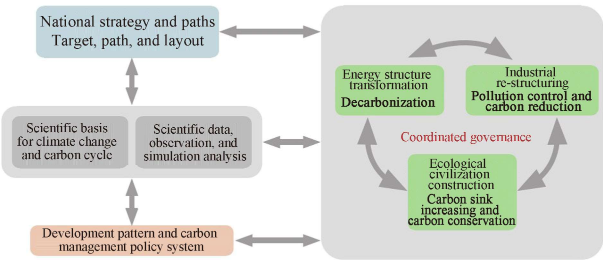

Figure 7 Scientific and technological supporting system for carbon peak & carbon neutrality action

(1) Scientific basis. The scientific basis for achieving the "dual carbon" targets includes global climate change, global carbon cycle, and their feedback mechanism. There are still uncertainties in the basic theories and methodologies applied to guiding the "dual carbon" targets, such as the evolution of the Earth system and climate system, interaction mechanisms of atmosphere, hydrosphere, lithosphere, and biosphere, as well as the carbon cycle and the interactions of Earth geological system, land surface system, terrestrial and marine ecosystems, and socio-economic system. The basic scientific questions directly related to the "dual carbon" targets that need to be answered urgently include the technical principles of new energy and low-carbon industries, climate effects of carbon neutrality measures, mechanisms of formation and maintenance of natural carbon sinks, capacities and increase potentials of natural and anthropogenic carbon sinks, feedback mechanisms of terrestrial and marine carbon cycles and climate changes, and synergy effects of multiple greenhouse gases.

(2) Observation and simulation. Timely and accurate scientific and technological information is the basis for decision-making. On the one hand, timely and accurate information is needed in the decision-making process; on the other hand, scientific observation and assessment are needed to analyze the implementation status and performance of decision-making. China's "dual carbon" action requires the establishment of an inspection system for the carbon emissions from industries, enterprises, and regions; the improvement of a scientific data integration and simulation metrology system; the development of a new generation of terrestrial-marine connected carbon cycle model, a nature-economy-society composite system model, and a high-resolution regional climate-ecology-economy simulation model; the construction of a three-dimensional networked dynamic observation system for terrestrial and marine carbon cycle parameters; the establishment of an industrial emission factor database and a high-resolution emission inventory system; and the provision of a data analysis platform for monitoring, assessment, inspection, and decision-making in response to climate change.

(3) Energy structure transformation. Energy structure transformation is the fundamental path to achieve carbon neutrality. The core issue is to accurately determine the available technical path for energy structure transformation, understand the scientific principles of key technologies for energy transformation, and develop the effective path to break through the bottleneck of decarbonization. In terms of emission reductions, the key technologies, such as zero emission/emission reduction, hydrogen industry, and energy storage are particularly important. In the field of energy, considering China's basic national condition of fossil fuels as the dominant energy, we should devote to the multi-point breakthrough, integrated innovation, and comprehensive demonstration of key technologies for efficient and clean utilization of fossil energy, renewable energy, advanced nuclear energy, energy storage, and multi-energy integration. Meanwhile, it is suggested to learn from the international experience and understanding of energy consumption structure, and give full play to the role of digital information technology (such as big data, artificial intelligence, blockchain, and Internet of Things) and civic awareness education.

(4) Industrial re-structuring. Industrial re-structuring is an important measure to achieve the "dual carbon" targets. Its core issues are to develop the scientific basis for new industries and social systems on the basis of new energy technologies and energy replacement processes, and establish a new generation of multi-scale research paradigm. At present, the important technical fields that should be highlighted include low-carbon process industries, low-carbon building materials, low-carbon transformation paths for green transport systems, carbonization industries and key technologies for carbon utilization, a new generation of low-carbon industrial

models and systems. The decisive role of the government and the market in social resource allocation should be given full play to promote the upgrading of the industrial structure composed of energy-consumptive industries such as steel, non-ferrous metals, petrochemicals, chemicals, and building materials, curb the blind development of energy-consumptive projects with high emissions, and develop low-carbon industries.

(5) Conservation and increase of carbon sinks. It is considered that using ecosystem carbon sequestration to protect the stability of vegetation, soil and cryosphere carbon pools and enhancing natural and anthropogenic carbon sinks are the cost-effective and scale-effective technical paths for carbon neutrality. Although significant progress has been made in the understanding of patterns and characteristics of the terrestrial and marine carbon cycle in China, there are still many uncertainties and unknown points. The core issues are to understand the mechanism of the carbon cycle process in ecosystem and the spatiotemporal variability of carbon sink, as well as the interaction and feedback between ecosystem carbon sink and global climate change. In the conservation and increase of carbon sinks in the national land space, it is necessary to systematically understand the stability of carbon sinks in ecosystems as well as the carbon sink effect, sustainability, and technical and economic feasibility of sink increasing technologies. In addition, it is suggested to develop new technologies for carbon capture, utilization and sequestration in biological, ecological and engineering fields, and evaluate the comprehensive carbon sink management effectiveness in key and national ecological functional areas.

(6) National strategy and path. The "dual carbon" action is a major socio-economic, scientific and technological transformation covering the entire national land space as well as all industries and industrial systems. It is a huge systematic project that demands for the coordinated promotion of decarbonization by energy structure transformation, emission reduction by industrial re-structuring, and carbon sink increasing by eco-environment governance, requiring clear national strategic guidance and optimized path. The strategic layout and technical route selection of carbon neutrality in country, regions, and industries are the decisive factors for the success or failure of the "dual carbon" action. The core issue of carbon neutrality at the national level is the selection and optimization of potential strategies and technological paths under the established national development goals and existing and future resource structures, technical background, and economic conditions. We need to answer the strategic questions of decarbonization and emission reduction, such as the peak emission amount, the dynamic path for carbon neutrality, the technologicalpath and the iteration of key technology systems. In addition, we need to answer the major scientific and technological questions related to national economic stability and energy security, such as the basic carbon emission space, the carbon neutrality capacity of carbon sinks and carbon sequestration in ecosystems, the carbon storage and carbon sequestration capacity of China and its regional ecosystems, and the sink increasing potential of traditional ecological engineering and new biological paths.

(7) Collaborative governance and management policy. The goal of carbon neutrality in response to global change is highly compatible with China's goals of eco-environmental governance, environment conservation, and ecological restoration. It is a national governance measure that can achieve multiple benefits. The eco-environmental governance of the entire national land space is a specific measure to implement the carbon conservation and sink increasing program of the natural ecosystem. The core scientific and technological issues involved are how to achieve the coordinated development of environmental pollution reduction and industrial carbon reduction, the coordinate protection of climate, environment, human health, and species, and the coordination between the national land space control and carbon neutrality policy. Policy and governance are the political, economic and legal guarantees for achieving carbon neutrality. The core issue is how to coordinate the "dual carbon" path and socio-economic development of the country, provinces, and industries from the policy and governance levels. At present, policy and governance issues that need to be addressed include: ① impacts of carbon emissions and extreme weather events on economic development; ② industrial policies for carbon sink increasing and carbon emission reduction, economic and social costs for carbon neutrality, and carbon pricing and its regulatory mechanisms and financial policies; ③ policies, business models, and regulatory mechanisms of disruptive energy technology and carbon removal technology; ④ climate resilience assessment and macro strategy, climate adaptation technology and policy management; ⑤ national and global climate governance reporting and monitoring, certification and verification, international cooperation and funding policies, and the construction of legal and regulatory systems.

5 Conclusions

China's "dual carbon" action is of great significance. It is a challenging major task that requires not only the joint efforts of the government, enterprises and the public, but also the comprehensive scientific knowledge, key technologies, data information, and management policies from the scientific and technological community. In the field of energy and industrial emissions reduction, to ensure the national energy security and industrial development, we should focus on the strategic needs of low-carbon energy and clean industries and carry out key technology research to promote the efficient and low-carbon utilization of fossil energy, the large-scale development and utilization of renewable energy, the development of advanced technologies for the safe use of nuclear energy, the large-scale application of energy storage technology systems, and the low-carbon technological revolution in the industries of steel, non-ferrous metals, petrochemicals, chemicals, and building materials. In the field of carbon sinks in ecosystems, we need to carry out comprehensive observation of the carbon cycle process, carbon storage, and flux of ecosystems, and establish a ground-, air-, and space-based carbon source and sink monitoring system. Efforts should be made to study the mechanism, dynamic evolution, geographical distribution, and management of carbon budget in China, comprehensively assess the carbon sinks of terrestrial, freshwater, and marine ecosystems, and develop an integrated theoretical and methodological system for analyzing the evolution of natural carbon sinks based on ecological principles and the anthropogenic carbon neutrality measures of emission reduction, carbon sink increasing, carbon conservation, and carbon sequestration.

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