ARTICLE IN PRESS

Chinese Journal of Population, Resources and Environment xxx (xxxx) xxx

Contents lists available at ScienceDirect

Chinese Journal of Population, Resources and Environment

journal homepage: www.keaipublishing.com/en/journals/chinese-journal-of-population-resources-and-environment

Comprehensive report on China's Long-Term Low-Carbon Development Strategies and Pathways

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1. Introduction

2020 is an unusual year in which the COVID-19 pandemic has raged through the globe, infecting tens of millions of people and killing hundreds of thousands. The pandemic has not only wreaked havoc on public health systems, economic activities, and people's lives, but also has greatly affected and will continue to reshape the world's political, economic, and trade patterns.

Just like the coronavirus pandemic, climate change is also a major and urgent global challenge facing humankind. The difference lies in that the coronavirus pandemic emerged as a sudden and pressing crisis affects human health and lives, whereas climate change is a longer-term and deeper challenge threatening humans' survival and development. We can observe that during the past decades, as greenhouse gas (GHG) concentrations continue to climb, climate change and more frequent extreme climate events are increasingly threatening humankind's survival and health, endangering terrestrial and marine ecosystems and harming biodiversity. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report elaborated on eight catastrophic risks brought about by climate change and pointed out that climate change is no longer a future challenge, but is already an immediate threat. United Nations Secretary-General António Guterres has said that the world is at a life-and-death juncture and has called for all countries in the world to join efforts in combating climate change, which is the most significant and urgent problem facing humanity today.

In 2020, in the face of grave crises, especially the coronavirus pandemic and climate change, people have begun to rethink about the relationship between humans and nature, and are increasingly aware that people and the environment are an interdependent community with a shared future. People should make more effort to respect, adapt to, and protect nature, should attach more importance to the harmonious coexistence of people and nature, and should coordinate present and future with a view to planning ahead for global challenges. This means that we must fundamentally change traditional production modes, lifestyles, and consumption patterns, promote transformation and innovation, and proceed on a green, low-carbon, and circular development path. Climate, development, and environment should not be isolated or addressed alone. Instead, climate actions, together with economic, social, environmental, health, employment, stability, security, and other issues, should be regarded as a large-scale system to achieve coordinated development. By taking the path of sustainable development, people of the world must deal with climate change, protect the environment, reverse the trend of biodiversity loss, and ensure the long-term health and safety of humankind.

After the outbreak of COVID-19 in 2020, it has become the universal consensus of the international community to achieve economic recovery through green and low-carbon development. On Earth Day on April 22, Secretary-General Guterres proposed a global initiative of green, high-quality recovery and urged countries to stress climate actions in economic recovery measures. As of October 2020, over 100 countries have already committed to being carbon neutral in 2050. The European Union (EU) unveiled its Green Deal at the end of 2019, and committed Europe to achieve carbon neutrality by 2050. Meanwhile, the EU has issued a roadmap for policies and measures in seven fields, namely, energy,

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https://doi.org/10.1016/j.cjpre.2021.04.004
Received 22 October 2020; Accepted 30 October 2020
Available online xxxx

industry, building, transport, food, ecology, and environmental protection, to facilitate a green recovery. Germany, which has the new Presidency of the Council of the EU, has proposed a recovery plan from the coronavirus pandemic in which there is strong support for green growth and climate change mitigation is listed as one of the three priorities. Even the US House of Representatives, which announced on a Climate Crisis Action Plan in June 2020, has proposed efforts to limit global warming to 1.5 °C by the end of this century. The plan points out that addressing climate change should be regarded as a national priority, aiming to reduce GHG emissions by 88% below 2010 levels in 2050 and to reach net-zero carbon dioxide (CO_2) emissions by 2050. The plan also details planned future measures in the areas of economy, employment, infrastructure, public health, and investment. It has been recognized and supported by Joe Biden, who has just won the 2020 presidential election.

China has more recently attached great importance to addressing climate change and has been adhering to green, circular, and low-carbon development as important strategic measures for promoting high-quality sustainable development. China has integrated tackling climate change into overall socioeconomic development. Since the 12th Five-Year Plan (2011–2015), China has been promoting low-carbon development based on the systematic and binding goal of reducing per capita GDP carbon intensity. In 2015, China set Nationally Determined Contributions (NDCs) of carbon emissions peaking around 2030 and peaking at the earliest time possible. Various policies and measures have been adopted, including adjusting the industrial structure, conserving energy and resources, improving utilization efficiency of energy and resources, optimizing energy structure, developing non-fossil fuels, developing a circular economy, increasing forests as a carbon sink, establishing and operating a carbon market, and South–South cooperation, to facilitate green and low-carbon transformation of the entire society. In 2019, per capita GDP CO_2 emissions in China dropped by 48% from 2005 levels, equivalent to a reduction of about 5.62 $GtCO_2$ (or 11.92 million tons of sulfur dioxide or 11.3 million tons of nitrogen oxides). GDP growth during 2005–2019 more than quadrupled, and 95% of the poor were lifted out of poverty. The proportion of the tertiary sector rose from 41.3% to 53.9% while coal consumption dropped from 72.4% to 57.7%, and non-fossil fuels accounted for 15.3% in primary energy, up from 7.4%. Average life expectancy increased from 72.9 years to 77.3 years. All the data show that policies and actions for addressing climate change will not hinder economic development, but will achieve the co-benefits of improving the quality of economic growth, cultivating new industries and markets, boosting employment, improving people's livelihood, protecting the environment, and enhancing people's health.

However, we should also note that, alongside the potential there are huge challenges in China's low-carbon transformation. First, the manufacturing sector, with its high energy and material consumption and low added-value rate, is still in the middle and low end of the international industrial value chain, posing daunting tasks of economic structural adjustment and industrial upgrading. Second, coal consumption still accounts for a high proportion of energy use (over 50%). CO_2 emissions per unit of energy consumption are about 30% larger than the world average, making the task of energy structural optimization formidable. Third, energy consumption per unit of GDP is still high at 1.5 times the world average and 2–3 times that of developed countries. Establishment of a green and low-carbon economic system is arduous work.

Addressing climate change meets the domestic demand for sustainable development. Looking to the future, as China's endeavor to achieve a modern socialist economy with Chinese characteristics enters a new era, the transformation to green and low-carbon development is a fundamental way to solve the problems of imbalanced and insufficient development, coordinate efforts for promoting economic development, improving people's livelihoods, eliminating poverty, and preventing or controlling pollution, and to realize the goals of building a moderately prosperous society in all respects. These goals would realize socialist modernization by 2035 and develop China into a prosperous, strong, democratic, culturally advanced, harmonious, and beautiful country by 2050.

Addressing climate change is the common mission of humankind. President Xi has pointed out clearly that China has been actively fostering international cooperation in its response to climate change, and has become an important participant, contributor, and torchbearer in the global endeavor for ecological civilization. From a global viewpoint, green and low-carbon development has become the irreversible trend in the economic, energy, technology, and governance systems of all countries, and is the fundamental path to dealing with humankind's common crises. China's efforts to promote green and low-carbon transformation around the world and to build a human community with a shared future under the guidance of Xi's thoughts on ecological civilization demonstrates tremendous political courage and a sense of mission of China as a great developing country.

Therefore, we need to, during the period of the 14th and 15th Five-Year Plans and even longer into the future, maintain strategic resolve, insist on a green and low-carbon development philosophy, promote ecological conservation, continue to adopt active policies and actions to respond to climate change, fulfill all of the NDCs, and strive to do even better than the NDCs. Faced with an increasingly difficult international situation at this historic juncture, it is particularly meaningful to conduct in-depth research on such topics as how China could plan low-carbon development strategies, pathways, and measures in a blueprint of socialist modernization in the new era, how China should assume international responsibilities and obligations suited to its national conditions and capabilities based on the principles in the Paris Agreement, and finally, how China should promote and lead the process of global climate governance.

To address the abovementioned topics, since the beginning of 2019, the Institute of Climate Change and Sustainable Development of Tsinghua University has been cooperating with dozens of research institutes to undertake a research project, *China's Long-Term Low-Carbon Development Strategies and Pathways*, supported by the Special Fund for Global Green Development and Climate Change of Tsinghua University Education Foundation and the Energy Foundation. The research institutes with which the institute has been cooperating include the National Center for Climate Change Strategy and International Cooperation, the State Information Center, the Institute for Urban and Environmental Studies of the Chinese Academy of Social Sciences (recently renamed the Institute for Ecological Civilization), the Institute of Science and Development of the Chinese Academy of Sciences, the Energy Research Institute of the National Development and Reform Commission, the Department of Communications and Education of the Ministry of Ecology and Environment, the Academy of International Trade and Economic Cooperation of the Ministry of Commerce, the Academy of Transportation Sciences of the Ministry of Transportation, and the Department of Energy and Power Engineering, Institute of Energy, Environment, and Economy, School of Environment and School of Architecture, Tsinghua University. Based on China's national conditions, the team, after comprehensively considering socioeconomic, policy, energy, and other macro-development trends and needs, has proposed suggestions on China's low-carbon development strategies, pathways, technologies, and policies until 2050 in order to realize the goals of building a great socialist modern country, a beautiful China, and to achieve the global warming goals set in the Paris Agreement alongside global sustainable development.

This comprehensive report builds on, extends, and enriches the reports for the 18 sub-projects in this overall project. We hope that our research findings can serve as reference for all sectors of society in their research efforts, offer support for the formulation and implementation of national low-carbon development strategies and policies, and help to tell China's stories well to the world in the general trend of global green, low-carbon development.

2. Guidelines and overall design

Reports from the 19th National Congress of the Communist Party (CPC) of China put forward the goals, basic policies, and main tasks for realizing socialist modernization in the new era. The reports outlined the goals of developing China into a great modern socialist country that is prosperous, strong, democratic, culturally advanced, harmonious, and beautiful by the middle of the century, becoming a global leader in terms of composite national strength and international influence, and realizing the Chinese dream of national rejuvenation. Signatories to the Paris Agreement on climate change reached consensus on targets to limit global warming to within a 2 °C increase in the average global temperature and even further to within 1.5 °C. Achieving this outcome would require all countries in the world to ramp up efforts to control and reduce GHG emissions and achieve near-zero CO_2 emissions or even carbon neutrality by 2050. The challenge of addressing climate change is a common one for humankind, and China, as the largest developing country in the world, should play a role as an important participant, contributor, and torchbearer.

China's long-term low-carbon emission development strategies should support the attainment of domestic development and global response to climate change. By the middle of the century, while realizing the goal of building a great modern socialist country, China should also achieve deep decarbonization development pathways fitted to the 2 °C global warming goal. To realize the harmonious coexistence of humans and nature as well as sustainable development, China should establish an industrial system of green, low-carbon, and circular development as well as a clean, safe, and efficient decarbonized energy system with new energy and renewable energy as the pillar. When researching and formulating China's development strategies for 2050, we should keep in mind both our internal and international imperatives, promote both domestic and global ecological civilization, and achieve the coordinated governance and win–win collaboration of both sustained domestic development and global ecological safety.

The period 2020–2035 marks the first stage of China's socialist modernization. By considering the strategies and tasks to realize modernization, as well as the goals and plans for ecological civilization and building a beautiful China, China not only would fundamentally improve the ecological environment, but also would achieve and strengthen the NDCs and emission reduction commitments; in this way, it would meet standards for both environmental quality and CO_2 emission reduction. High-quality economic development would be facilitated in coordination with economic, energy, and environmental efforts to address climate change for a win–win scenario. In the second period of 2035–2050, China should take on international responsibilities consistent with its ever-increasing composite national strength and international influence. In this study, we take the deep decarbonization targets and measures fitted to the 2 °C global warming target are an important part in China's overall strategy of socialist modernization for the new era, leading global climate governance and international cooperation, and enabling China to make new contributions to protect the environment and develop human society.

This project has combined a bottom–up and a top–down research methods. The bottom–up method includes both scenario analysis and technical evaluation of energy consumption and CO_2 technologies of all sectors. The top–down method involves a macro-model calculation and policy simulation. The study is oriented toward problem-solving and in-depth analysis targeted at China's actual national conditions and characteristics of its development stage by focusing on the trends, policies, and pathways of long-term low-carbon development. This study has conducted policy simulation with the goal of building a great modern country and realizing deep decarbonization pathways, and has analyzed emission reduction pathways, technology support, costs, and prices driven by the long-term deep decarbonization goal (refer to Fig. 1). Four scenarios have been designed and all topics studied and analyzed based on these four scenarios.

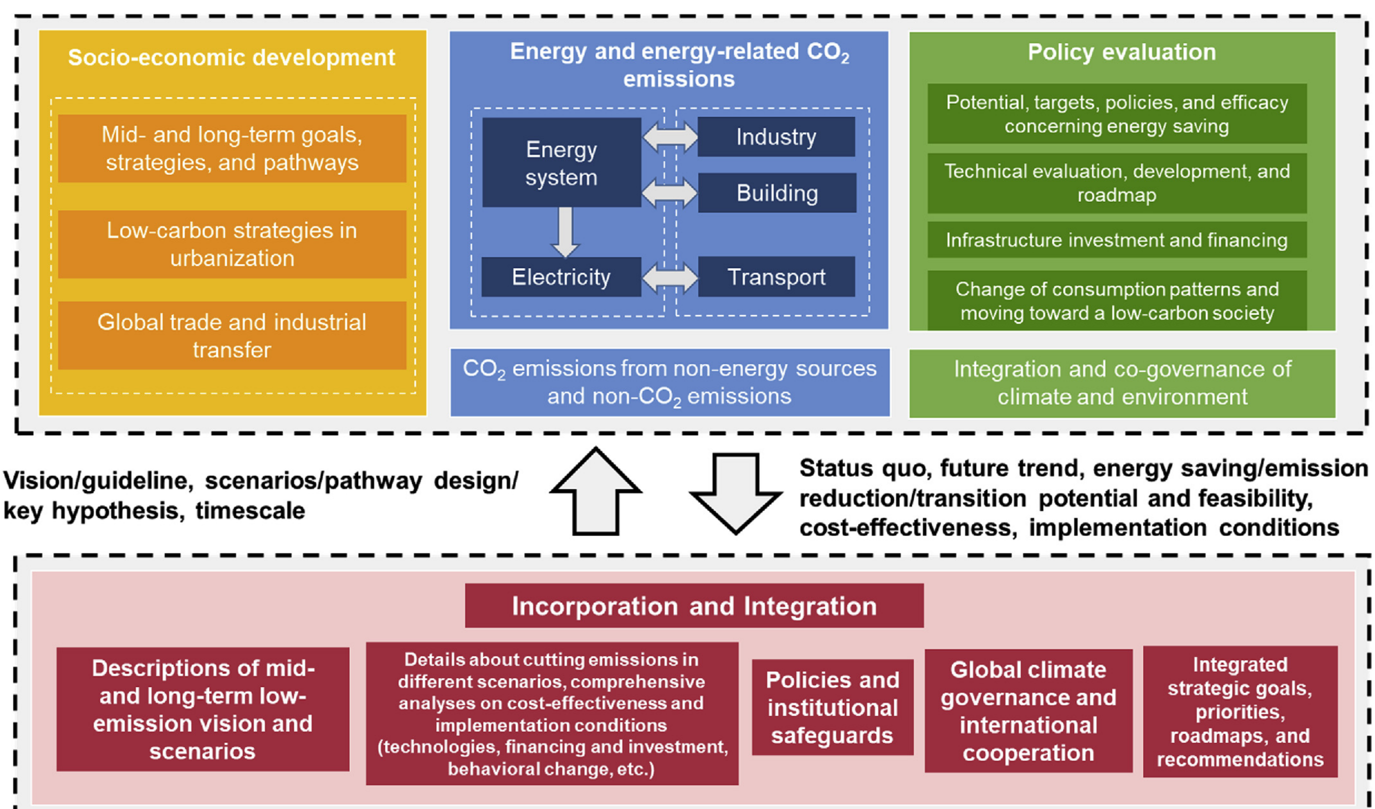


Fig. 1. Project study framework of China's Long-Term Low-Carbon Development Strategies and Pathways.

The four scenarios are summarized as follows.

(1) Policy scenario: supported by China's NDCs submitted in 2015 under the Paris Agreement, action plans, and relevant policies based on the assumption that the current low-carbon transformation trends and policies continue.
(2) Reinforced policy scenario: based on the policy scenario, this scenario further enhances the intensity and scope for reducing energy intensity (defined as energy consumption per unit of GDP) and CO_2 intensity (defined as CO_2 emissions per unit of GDP) and improves the proportion of non-fossil fuels in primary energy consumption. Under this scenario, we explore the potential for emission reduction, controlling total CO_2 emissions, strengthening policy support, and adapting to the enhanced and upgraded NDCs and actions under the Paris Agreement.
(3) The 2 °C scenario: based on the goal of controlling global warming to within 2 °C, this scenario considers the corresponding emission reduction pathways. In this scenario, we analyze emission reduction measures and roadmaps driven by the deep decarbonization goals to be achieved by the middle of the century, and we demonstrate and evaluate the associated technology and capital needs, costs and prices, and policy support.
(4) The 1.5 °C scenario: based on the goals of controlling global warming to within 1.5 °C and realizing carbon neutrality, this scenario demonstrates the possibilities and pathway options for the realization of net-zero emissions of CO_2 and deep reductions of other GHGs emissions by 2050, and we evaluate the possible social and economic impacts.

Among the four scenarios, the reinforced policy scenario and the 2 °C scenario are the primary points of focus of this study. Before 2030, 2035, the impact on the fulfillment and updating of the NDCs against the background of the reinforced policy scenario is the main target for the analysis, with focus on the impact of emission reduction pathways driven by the 2 °C goal on the targets and pathways for 2030 and 2035. After 2035, while realizing the goal of building a great socialist modern country, the emission reduction pathways and policy support driven by the 2 °C goal become the main targets for study. This study also explores feasible paths for realizing net-zero CO_2 emissions and deep emission reduction of other GHGs by 2050 to attain the 1.5 °C goal. Meanwhile, the connection with the NDCs before 2035 is considered, and the low-emission goals and strategies in these two stages are coordinated.

3. Overview of latest developments in China and the world

The Paris Agreement established a new global climate governance regime after 2020, promoting global cooperation based on the bottom–up NDC goals and action plans of the parties. However, there is still a large gap between current emission reduction commitments and the emission reduction path of achieving the goal of controlling the global temperature rise to within 2 °C. It is necessary to encourage countries to enhance their emission reduction ambitions and efforts. The world is now entering the implementation stage of the Paris Agreement, but it remains a challenge to achieve the objectives and principles of the agreement and to balance adaptation, mitigation, funding, technology, capacity building, and transparency. All parties need to increase their willingness to cooperate and take comprehensive actions.

The IPCC's report on *Global Warming of 1.5°C* highlights the urgency of tackling climate change. Achieving the 1.5 °C target could significantly reduce climate risks compared to the 2 °C target, and is more conducive to achieving the UN's 2030 Sustainable Development Goals, but would also involve greater costs. The negative impacts of climate change are manifesting earlier than originally expected, with larger scope, more severe disasters, and greater losses than originally projected. Bottom–up climate initiatives and institutions are flourishing at the subnational level, including in cities, regions, companies, communities, industries, and social groups. Various international rules, industry norms, and corporate standards that promote low-carbon development and transformation keep emerging. The global call to shoot for the 1.5 °C target and to achieve carbon neutrality by the middle of this century has become increasingly strong. Although the current COVID-19 pandemic has weakened countries' response to climate change, in the long run, we expect to witness stronger and stronger commitments. Developed countries are clearly pushing for the 1.5 °C target in recent climate negotiations.

While the COVID-19 pandemic is a sudden global public crisis, climate change is a deeper ecological crisis, yet both pose severe and urgent global challenges. The global climate goals, achievements, and negotiations between major powers will profoundly affect the post-pandemic recovery and development of the world economy and the reconstruction of the international governance order. Achieving a "green economic recovery" has increasingly become a consensus goal among countries. After the pandemic, the transition to a low-carbon economy in response to climate change is expected to become the guiding policy for economic recovery and development in most countries as well as a major field of competition and cooperation among major countries.

The Paris Agreement requires all parties to communicate and strengthen their NDC goals and actions in 2020 and to submit at the same time their long-term low-emission development strategy up to mid-century. A global stocktaking is due to be conducted in 2023 to encourage all parties to strengthen their actions. How countries will strengthen and update their NDC target by 2030 and set their deep decarbonization targets by 2050 has become the focal point of attention of the international community. China and other emerging developing countries have attracted special attention and high expectations. Meanwhile, China is aware of its need to formulate long-term deep decarbonization strategies to accommodate and lead global low-carbon development and transformation.

China has adhered to new development concepts since the start of its "new normal" of the economy. Economic growth has shifted focus from scale and speed to quality and efficiency, while the rapid growth of energy consumption and carbon emissions has been reversed. The average annual growth rate of energy consumption and carbon emissions decreased from the 6.0% and 5.4% in 2005–2013 to 2.2% and 0.8% in 2013–2018, respectively. Although there have been rebounds and fluctuations in the past 2 years, the overall growth rate has undoubtedly slowed. Total coal consumption has also basically stabilized. Carbon intensity per unit of GDP in 2019 dropped by 48.1% from 2005, enabling China to achieve ahead of schedule its international commitment of a 40–45% reduction by 2020 relative to 2005 levels. This has laid a good foundation for the country to achieve its 2030 NDC goals.

The COVID-19 pandemic has had a huge impact on the global economy, leading to severe recessions across the world. China's economic growth rate in 2020 is bound to drop sharply. The average GDP growth rate during the 13th Five-Year Plan period is expected to drop to less than 6%, but the energy and carbon reduction targets for the same period could still be achieved or exceeded. During the 14th Five-Year Plan period after the pandemic, China not only has to fully achieve healthy and sustainable economic development, but also adhere to the policy of "green recovery and low-carbon transformation" to accelerate its industrial transformation and upgrading and to promote high-quality development. Since the 11th Five-Year Plan period, China has aspired to maintain and even to strengthen its trend of energy conservation and carbon emission reduction by reinforcing various energy policies. During the 14th Five-Year Plan period, with expected average annual GDP growth rate of no less than 5%, energy intensity per unit of GDP is expected to fall by at least 14%, and the development of non-fossil energy should maintain an average annual rate of about 7%, as it did during the previous 5 years. At the end of the 14th Five-Year Plan period, the non-fossil share in primary energy consumption is set to reach about 20%, and carbon intensity to decrease by 19–20%. Carbon emissions of the industrial sector, especially energy-intensive heavy chemical industries, and the more developed cities in the eastern coastal areas are expected to peak first. The three goals of a cap on coal consumption, a cap on carbon emissions, and early peaking of carbon emissions will be coordinated. Furthermore, to achieve its low-carbon transition, China has to improve its policy infrastructure, investment and financing mechanisms, and the development of a national carbon market.

For China to achieve its NDC goals in 2030, the success of the 14th Five-Year Plan with respect to low-carbon transition goals, policies, and implementation is crucial. If the 14th Five-Year Plan does not progress enough, then the pressure and difficulty of reducing emissions during the 15th Five-Year Plan will increase. Therefore, to strengthen emission reduction efforts and actions, the decline rate of energy intensity during the 15th Five-Year Plan period should be no lower than that of the 14th Five-Year Plan, that is, 14%. If, by 2030, China achieves its target of non-fossil energy accounting for 50% of total electricity consumption (as set in the *Energy Production and Consumption Revolution Strategy (2016–2030)*), and if by then the share of primary energy used for power generation is about 50%, then non-fossil energy would account for 25% of primary energy consumption by 2030, while carbon intensity of GDP would reduce by 65–70% from the 2005 level. In that case, carbon emissions would peak around 2025 and stabilize before 2030, while peak carbon emissions from fossil energy consumption would be controlled to within 11 billion tons, and by 2035, would be significantly lower than that in the peak years.

4. Low-carbon transformation of end-use sectors

Strengthening energy conservation and efficiency and accelerating electrification have important implications for achieving low-carbon transformation. Industrial, building, and transport are the three major energy-using sectors, and thus, it is critical to improve demand-side management, promote energy-saving and low-carbon technological innovation and industrial-scale development, develop smart city infrastructure and management strategies, optimize resource utilization and production efficiency, and change public consumption patterns and lifestyles in these sectors. Meanwhile, electrification of end-use energy involving a large share of renewable generation to replace fossil energy end-use consumption could effectively reduce carbon emissions in these sectors and even the entire economy. Electricity accounted for 21.3% of total final energy consumption in 2015, and this proportion is expected to exceed 30% in 2030 and 70% in 2050. Consequently, electrification could play an important role in reducing carbon emissions.

Currently, China's industrial sector accounts for 65% of the country's total final energy consumption (67.5% for the secondary sector, including the construction industry), rendering it the most important sector for implementing climate policies. China has adopted the following policy tools: upgrade the industrial structure, reduce the proportion of heavy and chemical industries, promote industrial transformation and upgrading, improve production quality and efficiency, reduce energy and material consumption, improve energy and resource utilization efficiency, accelerate the development of the digital economy, develop high-tech industries and advanced manufacturing, promote high value-added production, reduce energy intensity per unit of industrial value-added, etc. See Table 1, Figs. 2 and 3 for end-use energy consumption and CO_2 emissions of the industrial sector under various scenarios (excluding CO_2 emissions during industrial production). In addition, it is necessary to promote the electrification of the industrial sector by replacing direct fossil energy consumption with electricity, which would effectively reduce carbon emissions and help to achieve the goal of carbon emissions peaking in the industrial sector during the 14th Five-Year Plan period. In the 2 °C scenario, end-use energy consumption of the industrial sector in 2050 will reduce by about 26% compared to 2015, and carbon emissions will reduce by more than 65%. To reduce carbon emissions from industrial processes, such as iron and steel, cement, and chemicals, it is necessary to develop advanced breakthrough technologies, such as zero-carbon iron-making technology using hydrogen as a reducing agent. That would help to achieve the deep decarbonization goal by the middle of this century.

Accelerating electrification plays an important role in the low-carbon transition of industries as electricity will become the primary energy source for industries. Specifically, the industrial electrification rate will reach 31% in 2050 under the policy scenario, 39.8% under the reinforced policy scenario, 58.2% under the 2 °C scenario, and 69.5% under the 1.5 °C scenario. Compared with the historical development trend, China's industrial electrification must significantly accelerate. From 2000 to 2015, China's industrial electrification increased by about 0.5% annually. Under the 2 °C scenario and the 1.5 °C scenario, it should increase by approximately 0.9% and 1.4% annually (see Table 2).

With electrification of the industrial sector, the proportion of direct fossil energy consumption will drop significantly. Fig. 4(a) and (b) show end-use energy mix of the industrial sector under the reinforced policy scenario and the 2 °C scenario, respectively.

Industrial processes in steel, cement, building materials, and chemical production result in carbon emissions during the use and decomposition of raw materials. Such emissions as well as emissions from energy activities can be reduced by raw material and fuel substitution, process optimization, system energy efficiency improvement, and low-carbon product development and innovation. This not only can reduce carbon emissions from energy activities, but also carbon emissions from industrial processes. Compared with 2020, CO_2 emissions in 2050 from industrial processes will reduce by approximately 30% under the policy scenario, 39% under the reinforced policy scenario, 64% under the 2 °C scenario, and 81% under the 1.5 °C scenario (See Table 3).

The reduction of carbon emissions from industrial processes, on the one hand, stems from industrial structure optimization, technological innovation, and the development of alternative raw materials and fuel technologies. For example, in cement production, low-carbon raw materials can be used instead of lime-based raw materials. Emission reduction can also be achieved in calcium carbide slag, blast furnace slag, fly ash, steel slag, etc. The flat glass industry can reduce its carbon emissions by half by replacing dolomite and limestone with magnesium oxide and calcium oxide. The coal chemical industry can significantly reduce its carbon emissions from industrial processes by developing pressurized coal water slurry gasification technology, pressurized pulverized coal gasification technology, and other new coal gasification processes. Meanwhile, because of the adjustment of the industrial

Table 1
Industrial end-use energy demand and CO_2 emissions.

	2020		2030		2050	
	Energy (billion TCE)	Carbon emissions ($GtCO_2$)	Energy (billion TCE)	Carbon emissions ($GtCO_2$)	Energy (billion TCE)	Carbon emissions ($GtCO_2$)
Policy scenario	2.18	3.77	2.67	4.54	2.44	3.69
Reinforced policy scenario	2.18	3.77	2.6	4.21	2.05	2.62
2 °C scenario	2.18	3.77	2.47	3.82	1.65	1.2
1.5 °C scenario	2.18	3.77	2.07	2.76	1.41	0.46

Note: The data in the table do not include CO_2 emissions from industrial processes.

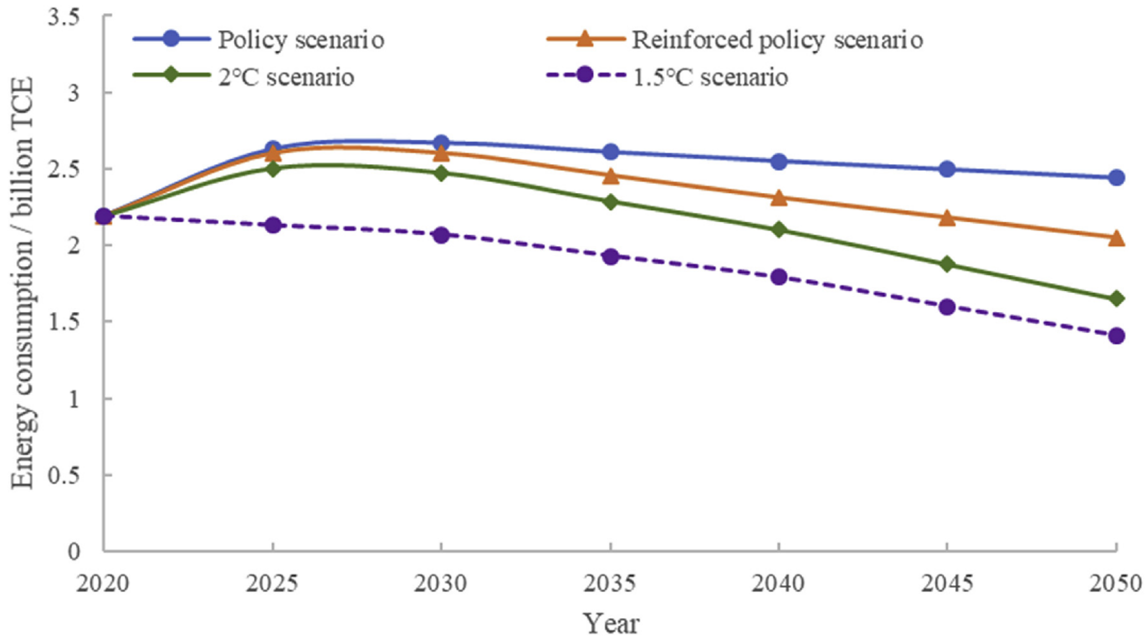


Fig. 2. End-use energy demand of the industrial sector under different scenarios.

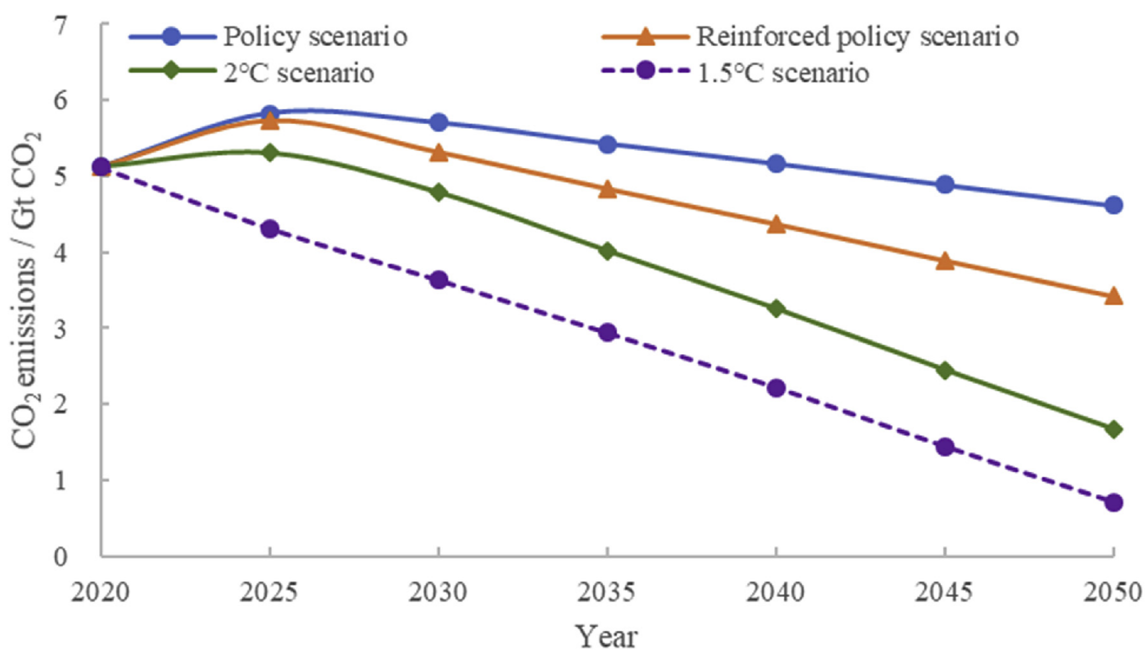


Fig. 3. Total carbon emissions of the industrial sector under different scenarios (including industrial processes).

Table 2
Electrification of industrial end use (unit: %).

	2020	2030	2050
Policy scenario	25.7	26.1	31
Reinforced policy scenario	25.7	27.8	39.8
2 °C scenario	25.7	30	58.2
1.5 °C scenario	25.7	37	69.5

structure and the upgrading of product quality, the demand for energy-intensive products will continue to decline. For example, under the policy scenario and the reinforced policy scenario, cement demand will drop by about 30% in 2050 relative to 2020, or about 62% and 71% under the 2 °C and 1.5 °C scenarios, respectively.

In 2018, the building sector accounted for about 20% of China's total final energy consumption. With an increase in the total building stock and improvement of people's living standards, total building energy consumption and its share in the national final energy consumption both show an increasing trend. Policy measures to cope with this challenge include keeping building stock within 74 billion m^2 by 2050 through planning and control; tightening building energy conservation standards; improving building heating technologies in northern China; replacing coal-fired boilers with low-grade heat sources, such as industrial and power plant surplus heat; using heat pumps and storage facilities; developing distributed intelligent renewable energy networks; and promoting synchronized usage of heat, gas, and electricity. In addition,

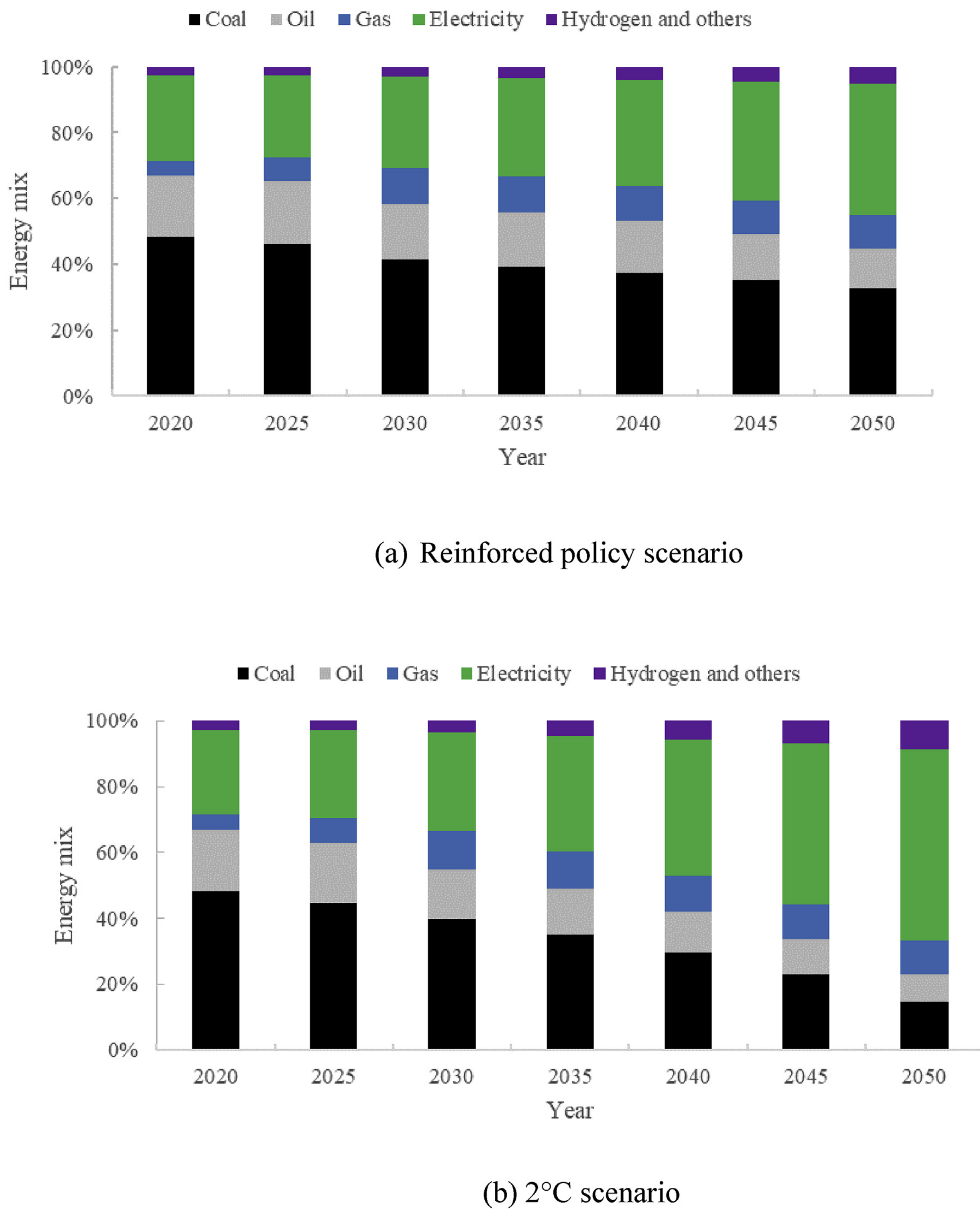


Fig. 4. End-use energy mix in the industrial sector.

Table 3
CO_2 emissions from industrial processes (unit: Gt).

	2020	2030	2040	2050
Policy scenario	1.32	1.17	1.04	0.92
Reinforced policy scenario	1.32	1.1	0.94	0.8
2 °C scenario	1.32	0.95	0.7	0.47
1.5 °C scenario	1.32	0.88	0.56	0.25

expanding commercial utilization of rural biomass resources in the fields of heating, gas, and power supply and promoting energy-saving renovation of existing buildings across the country could contribute to achieving peak carbon emissions by 2030. Under the 2 °C scenario, the total energy consumption of buildings could reduce to 713 million TCE by 2050, the electrification rate could increase from the current 28% to over 60%, and CO_2 emissions could fall to 306 Mt, as shown in Table 4, Figs. 5 and 6.

Currently, energy consumption of the transportation sector accounts for about 10% of the country's total end-use energy consumption. With the development of urbanization, it is also showing a rapid growth trend. Policy tools in this sector include coordinating the spatial layout of transportation infrastructure, promoting the intensive and efficient use of resources, optimizing the transportation structure, increasing the share of green transport, enhancing the standardization and cleanliness of green transportation equipment, improving transportation efficiency, reducing

Table 4
Building end-use energy demand and CO_2 emissions.

	2020		2030		2050	
	Energy demand (billion TCE)	Carbon emissions ($GtCO_2$)	Energy demand (billion TCE)	Carbon emission ($GtCO_2$)	Energy demand (billion TCE)	Carbon emission ($GtCO_2$)
Policy scenario	0.775	1	0.86	0.969	0.995	0.834
Reinforced policy scenario	0.775	1	0.82	0.888	0.851	0.562
2 °C scenario	0.775	1	0.716	0.65	0.713	0.306
1.5 °C scenario	0.775	1	0.692	0.565	0.621	0.081

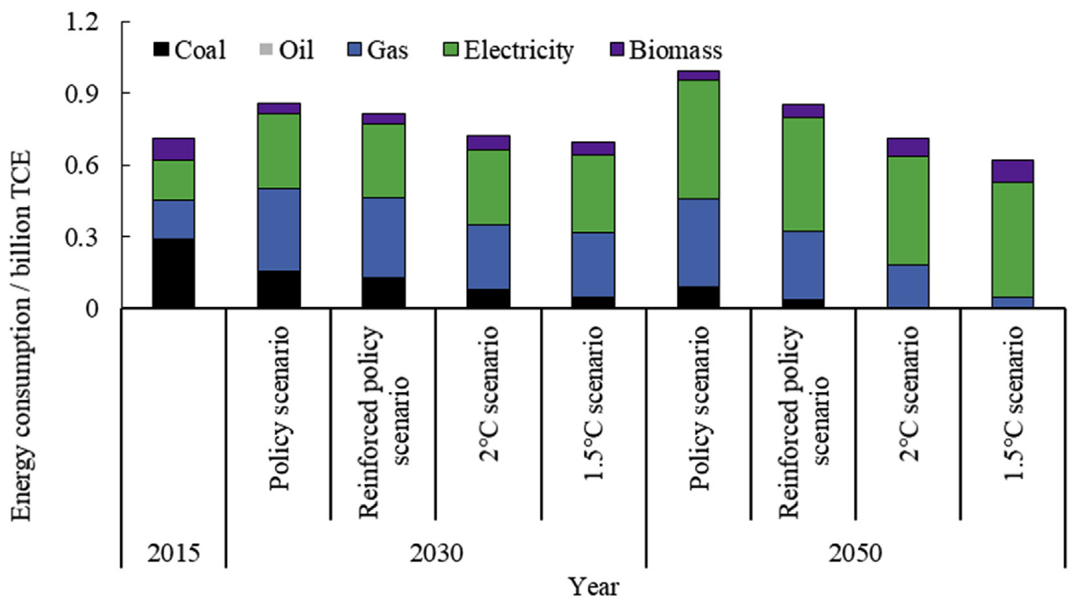


Fig. 5. Building energy consumption in 2030 and 2050 in different scenarios.

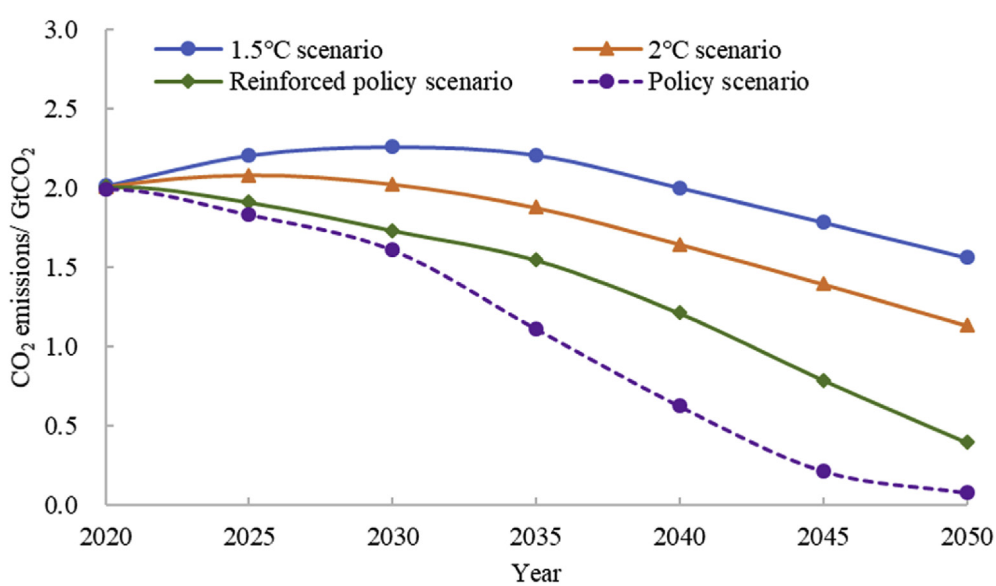


Fig. 6. Carbon emissions of the building sector (including indirect emissions) under different scenarios.

energy consumption per unit of transportation turnover, adjusting transportation mix, accelerating electrification, expanding the use of hydrogen fuel and biofuels, raising public awareness of green transport, and guiding a change in travel habits and lifestyle of the public. Under the 2 °C scenario, the electrification rate of the transportation sector could increase from 3.5% in 2015 to 25% in 2050, while carbon emissions in the transportation sector could peak around 2030 and further reduce by more than 50% in 2050 compared with the peak year (see Table 5, Figs. 7–9).

Table 5
Transportation sector end-use energy demand and CO_2 emissions.

	2020		2030		2050	
	Energy demand (billion TCE)	Carbon emissions ($GtCO_2$)	Energy demand (billion TCE)	Carbon emissions ($GtCO_2$)	Energy demand (billion TCE)	Carbon emissions ($GtCO_2$)
Policy scenario	0.514	0.99	0.599	1.155	0.585	1.109
Reinforced policy scenario	0.514	0.99	0.59	1.112	0.471	0.804
2 °C scenario	0.514	0.99	0.583	1.075	0.402	0.55
1.5 °C scenario	0.514	0.99	0.583	1.037	0.346	0.172

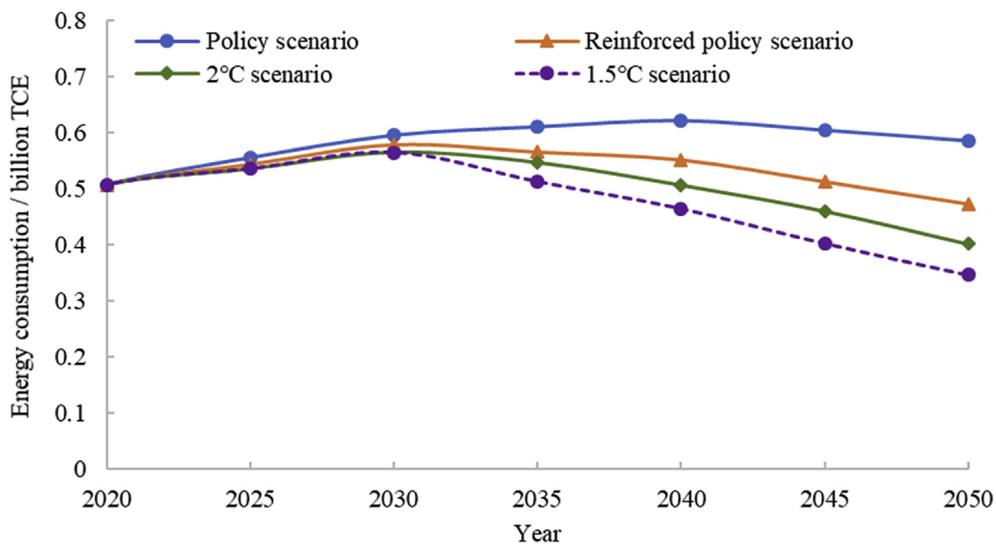


Fig. 7. Energy consumption of the transportation sector in different scenarios.

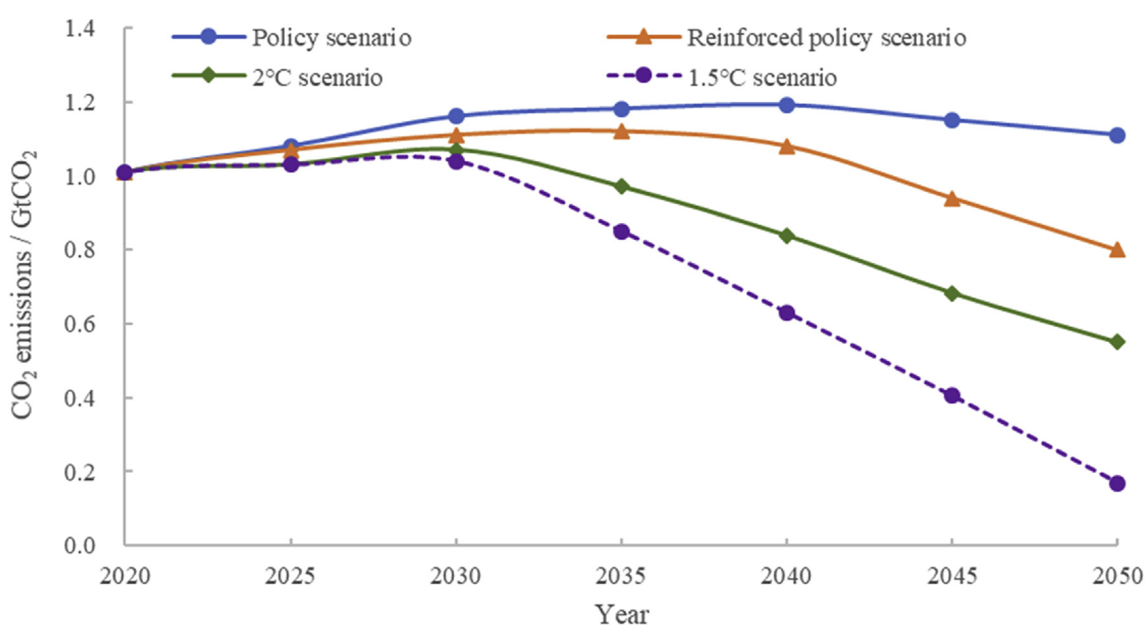


Fig. 8. CO_2 emissions from the transportation sector under different scenarios.

5. Power system transformation

Under China's long-term deep decarbonization strategy, CO_2 emissions will peak around 2030, and energy consumption will gradually enter and remain at the plateau from 2035 to 2050 under different scenarios. During the plateau period, total energy consumption tends to stabilize, and economic and social development is gradually decoupled from energy and resource consumption. Meanwhile, end-use sectors, such as industrial, transport, and building, need to achieve deep decarbonization. While energy conservation and energy efficiency keep intensifying, electrification also accelerates to replace coal, petroleum, and other fossil energy sources of direct combustion and utilization.

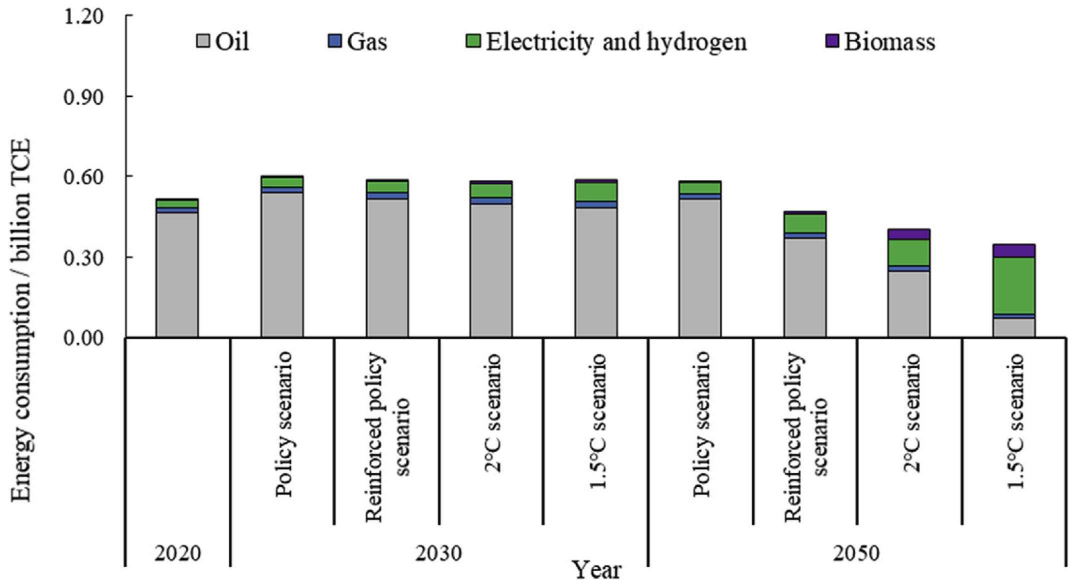


Fig. 9. Energy mix of the transportation sector in different scenarios in 2030 and 2050.

Hydrogen consumption or production using renewable and nuclear power will also help to increase the share of electricity in end-use energy consumption and the share of energy used for power generation in primary energy consumption, resulting in a faster growth rate of electricity than that of energy consumption. As a result, the demand for electricity is expected to continue to rise under all scenarios in the future. Under the 2 °C scenario, total demand will reach 13.1 trillion kilowatt hours (kWh) by 2050. Due to the significant increase of electricity substitution in end-use sectors, total demand in the 2 °C scenario will be higher than the policy scenario. Table 6 show power demand under various scenarios.

To achieve the low-carbon transition of the power system, the replacement of traditional coal and other fossil power with new and renewable power will need to expand continuously. In terms of generation fleet, under various scenarios in 2030, the total installed capacity of hydropower, wind, and solar will reach about 400 GW. By 2050, the total installed capacity of non-fossil energy will reach 5300 GW under the 2 °C scenario and account for 90.4% of the total generation (Tables 7 and 8).

The trajectory of carbon emissions in the power sector under various scenarios is shown in Fig. 10. Under the policy scenario, carbon emissions in the power sector will peak before 2030 at 4.15 billion tons yet still remain over 3 billion tons by 2050; in the 2 °C scenario, they will peak before 2025 at about 4 billion tons and then show a rapid downward trend after 2030, dropping by 2050 to about 300 million tons, or 92% lower than the peak emissions. Under the 1.5 °C scenario, greater efforts will be made to reduce emissions after 2030 and net-zero emissions will basically be achieved by 2050.

Deep decarbonization of the power system requires building a safe, reliable, and sustainable energy system based on new and renewable energy. With the high penetration of intermittent renewable energy on the grid, it is necessary to coordinate inter-regional power transmission and local distributed renewable energy smart networks, to manage daily grid balance and seasonal renewable power resources regulation and storage, and to achieve optimal dispatch of various sources, grids, and loads to develop a well-coordinated grid for a clean, low-carbon, safe, and efficient power system (see Figs. 11 and 12).

China's capacity to maintain coal and natural gas generation units in the future depends largely on the application of carbon capture and storage (CCS) and biomass energy and carbon capture and storage (BECCS) technology. CCS can capture 90% of carbon emissions of coal-fired power units, and the installation of CCS alongside coal power plants makes coal generation a relatively low-carbon generation technology. BECCS is a negative emission technology. The scale of future application of CCS technology will depend on its cost decline rate, and BECCS technology will depend further on the amount of biomass

Table 7
Generation fleet in 2050 under different scenarios (unit: GW).

	Policy scenario	Reinforced policy scenario	2 °C scenario	1.5 °C scenario
Coal	773	583	123	32
Coal with CCS	0	0	68	149
Gas	200	200	200	200
Nuclear	280	327	327	327
Hydro	410	412	414	416
Wind	1063	1387	2312	2740
Solar	893	1380	2205	2367
Biomass	0	2	6	5
BECCS	0	0	32	48
Total	3619	4289	5686	6284

Table 6
Future power demand under each scenario (unit: trillion kWh).

Sector	2020	2030				2050			
		Policy scenario	Reinforced policy scenario	2 °C scenario	1.5 °C scenario	Policy scenario	Reinforced policy scenario	2 °C scenario	1.5 °C scenario
Industrial	4.59	5.66	5.87	6.06	6.27	6.21	6.67	7.80	7.99
Building	1.87	2.60	2.56	2.51	2.59	4.06	3.87	3.68	3.92
Transport	0.22	0.29	0.37	0.42	0.56	0.32	0.55	0.79	1.59
Other sectors and loss	0.59	0.63	0.65	0.63	0.62	0.78	0.82	0.86	0.76
Total demand	7.27	9.18	9.45	9.61	10.04	11.38	11.91	13.13	14.27

Table 8
Generation by technology in 2050 under different scenarios (unit: trillion kWh).

	Policy scenario	Reinforced policy scenario	2 °C scenario	1.5 °C scenario
Coal	3.64	2.62	0.45	0.11
Coal with CCS	0	0	0.4	0.79
Gas	0.34	0.37	0.39	0.38
Nuclear	1.97	2.38	2.35	2.34
Hydro	1.44	1.48	1.47	1.48
Wind	2.51	3.06	4.87	5.75
Solar	1.48	1.98	2.96	3.11
Biomass	0	0.01	0.04	0.03
BECCS	0	0	0.19	0.29
Total	11.38	11.91	13.13	14.27

resources available in addition to the cost decline. Recent studies argue that by 2050, China still needs to retain 400–700 GW of coal power to serve the base load, system balance, and heating demand, but it needs to be retrofitted to existing units to increase their flexibility and co-generation capacity. The findings of this study are basically consistent with those results.

Under the 2 °C and the 1.5 °C scenarios, CO_2 capture and storage technology (CCS and BECCS) will play an important role. Under the 2 °C scenario, CCS will be used on a large scale in 2035, with installed capacity reaching 68 GW and carbon capture reaching 320 $MtCO_2$ in 2050; BECCS technology will be widely applied in 2040, with installed capacity reaching 32 GW and carbon capture reaching 190 $MtCO_2$ in 2050. Under the 1.5 °C scenario, large-scale application of CCS needs to start earlier (from 2030) with installed capacity reaching 149 GW, carbon capture reaching 600 $MtCO_2$ in 2050, and cumulative capture in 2040–2050 reaching 4.13 $GtCO_2$; BECCS technology will be applied on a large scale in 2040, with installed capacity reaching 48 GW and carbon capture reaching 280 $MtCO_2$ in 2050. Achieving long-term deep emission reductions, the 1.5 °C scenario will involve a greater stranded costs of early decommissioning of infrastructure than that in the 2 °C scenario (see Fig. 13).

6. Primary energy demand and carbon emissions

Based on the above analysis on end-use energy consumption and

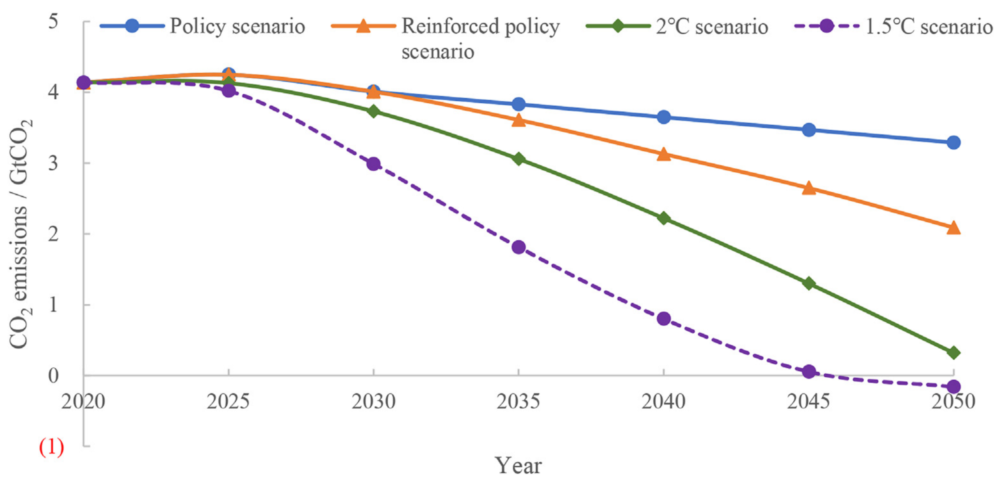


Fig. 10. CO_2 emission trajectory of the power sector under each scenario (including CCS).

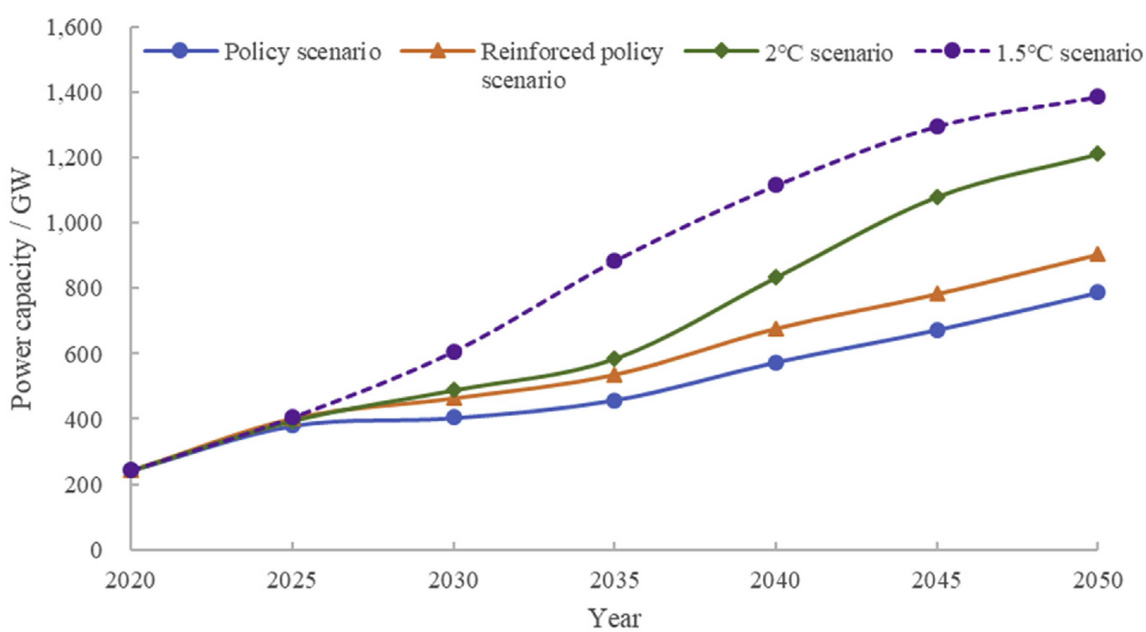


Fig. 11. Total capacity of inter-regional power distribution.

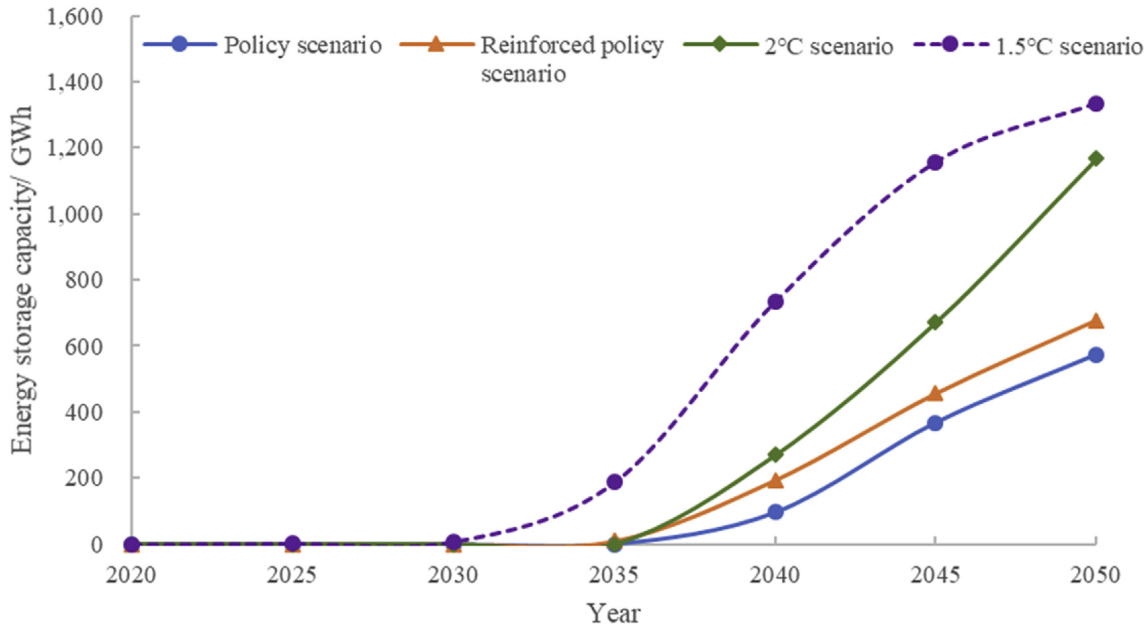


Fig. 12. Energy storage capacity demand.

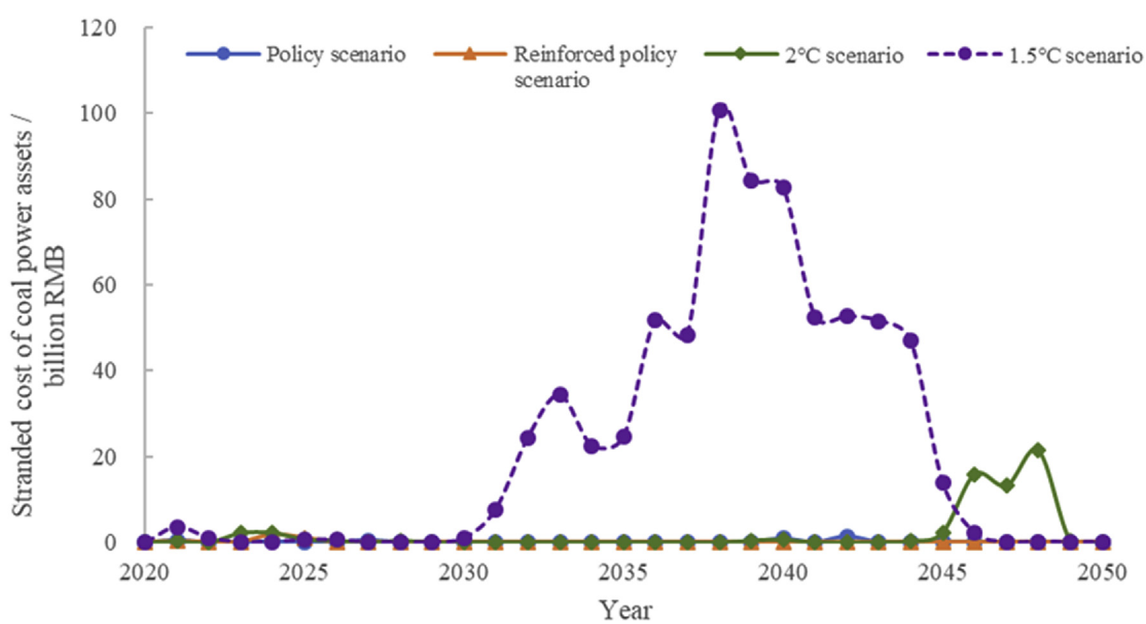


Fig. 13. Year-to-year stranded cost of coal power assets from 2018 to 2050.

power generation mix, the primary energy demand and energy-related CO_2 emissions under various scenarios are shown in Table 9.

The Primary energy demand and consumption patterns under various scenarios are shown in Figs. 14 and 15.

While continuous efforts are made to conserve energy, the energy mix upgrading is seen as the fundamental way to reduce CO_2 emissions. Under the policy scenario, energy conservation should be strengthened and the growth of total energy consumption should be controlled to

Table 9
Primary energy demand and CO_2 emissions.

	2020		2030		2050	
	Energy demand (billion TCE)	Carbon emissions ($GtCO_2$)	Energy demand (billion TCE)	Carbon emissions ($GtCO_2$)	Energy demand (billion TCE)	Carbon emissions ($GtCO_2$)
Policy scenario	4.94	10.03	6.06	11.08	6.23	9.08
Reinforced policy scenario	4.94	10.03	5.98	10.61	5.63	6.18
2 °C scenario	4.94	10.03	5.64	9.42	5.20	2.92
1.5 °C scenario	4.94	10.03	5.25	7.44	5.00	1.47

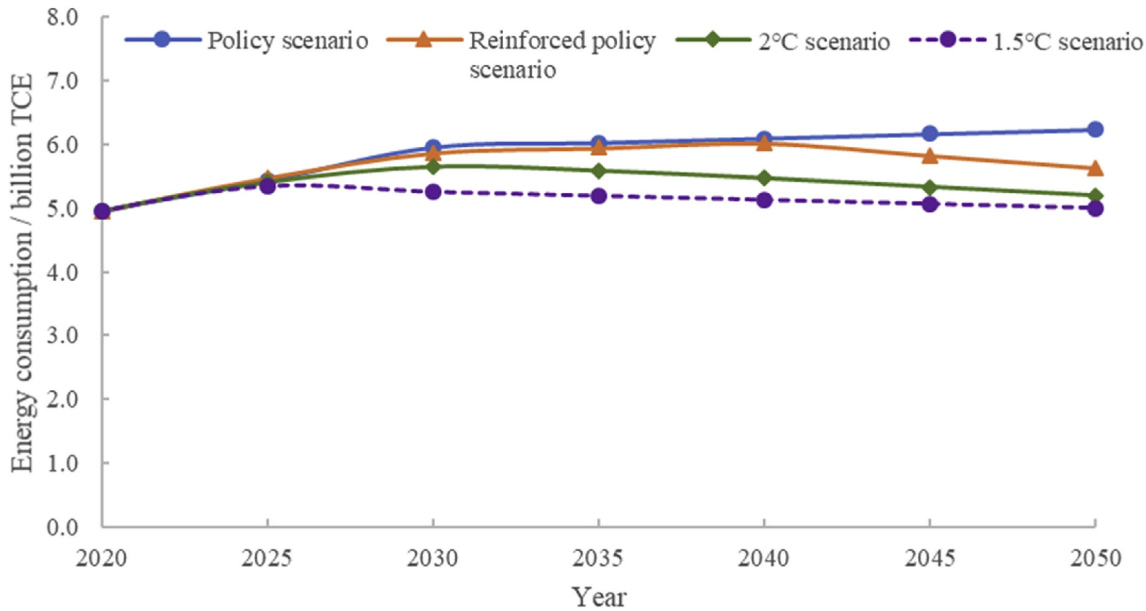


Fig. 14. Primary energy demand (billion TCE).

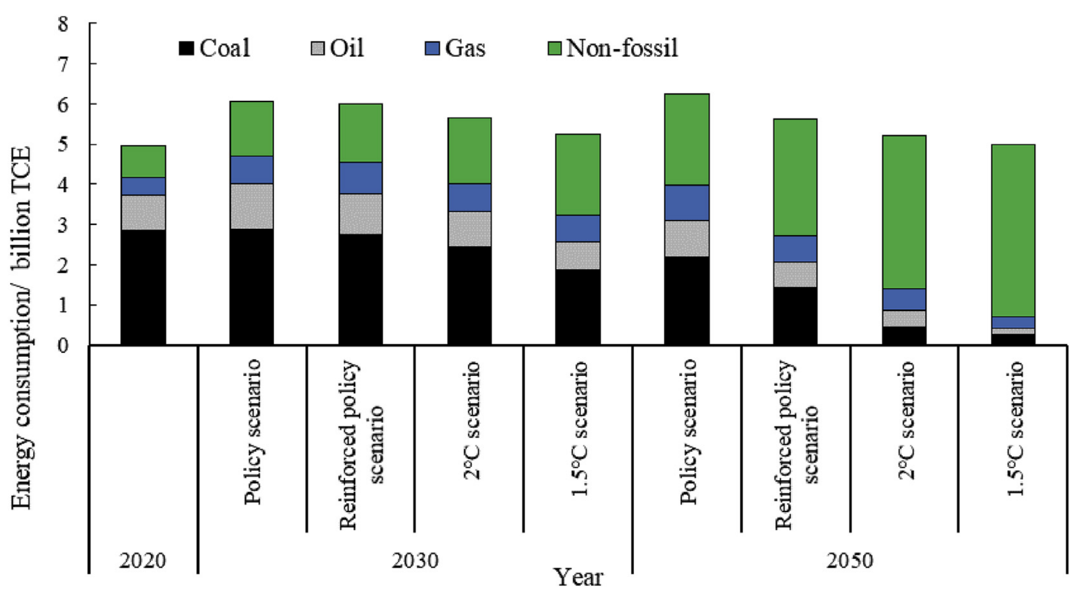


Fig. 15. Total primary energy consumption by fuel type in 2020, 2030, and 2050.

stabilize by 2050 and basically reach the peak; under the reinforced policy scenario, total energy consumption should peak around 2040 and then decline in 2050; under the 2 °C scenario, total energy consumption will basically peak around 2035 and reduce by 7.8% in 2050 from 2030; and in the 1.5 °C scenario, total energy consumption will peak around 2025. Total primary energy consumption in 2050 will reduce by 16.5% under the 2 °C scenario compared with the policy scenario or by 19.7% under the 1.5 °C scenario compared with the policy scenario.

The rate and intensity of energy mix upgrading vary even more significantly in different scenarios. The share of coal in primary energy consumption by 2030 will drop to 46% in the reinforced policy scenario and 43.2% in the 2 °C scenario, which is 1.6% and 4.4% lower than the policy scenario, respectively. The share of coal will even drop to 9.1% by 2050 in the 2 °C scenario, which is 25.8% lower than the policy scenario, while the share of non-fossil energy will increase to 73.2%, which is 36.9% higher than the policy scenario. The detailed energy consumption and CO_2 emissions of reinforced policy scenario and 2 °C scenario are showed in Table 10 and Table 11 separately.

With control and reduction of total energy consumption and especially with accelerating the energy mix decarbonization, CO_2 emissions in different scenarios will show a rapid downward trend in the future (see Fig. 16). In general, under the policy scenario the NDC target can be guaranteed, where CO_2 emissions will peak around 2030. Comparatively, CO_2 emissions will peak before 2030 in the reinforced policy scenario, before 2025 in the 2 °C scenario, or around 2020 in the 1.5 °C scenario.

Fig. 17 shows CO_2 emissions from energy consumption by sector. By 2050, the industrial sector will still be the largest emitter. As the share of electricity in end-use energy consumption will increase, under the 2 °C scenario, the direct CO_2 emissions in the industrial sector in 2050 will mainly occur in industrial processes, such as steel, chemicals, and cement manufacturing, in which emission reduction remains difficult to achieve. CO_2 emissions of the power sector will peak around 2030. As the share of non-fossil electricity in total electricity generation increases and the application of CCS and BECCS technology spreads, the power sector can

Table 10
Primary energy consumption by sector under the reinforced policy scenario (unit: billion TCE).

	2020					2030					2050				
	Coal	Oil	Gas	Non-fossil	Total	Coal	Oil	Gas	Non-fossil	Total	Coal	Oil	Gas	Non-fossil	Total
Industrial	1.05	0.41	0.10	0.06	1.62	1.07	0.44	0.28	0.08	1.88	0.67	0.25	0.21	0.11	1.23
Building	0.22	0.00	0.26	0.07	0.55	0.13	0.00	0.34	0.04	0.51	0.04	0.00	0.29	0.05	0.38
Transport	0.00	0.47	0.02	0.00	0.49	0.00	0.52	0.02	0.01	0.54	0.00	0.37	0.02	0.01	0.40
Others	0.05	0.02	0.02	0.02	0.11	0.10	0.04	0.03	0.05	0.22	0.02	0.02	0.01	0.01	0.05
Electricity	1.52	0.00	0.04	0.63	2.18	1.45	0.00	0.11	1.27	2.83	0.70	0.00	0.15	2.72	3.57
Total demand	2.84	0.89	0.43	0.78	4.94	2.75	1.00	0.78	1.45	5.98	1.42	0.64	0.67	2.90	5.63

Table 11
Primary energy consumption by sector under 2 °C scenario (unit: billion TCE).

	2020					2030					2050				
	Coal	Oil	Gas	Non-fossil	Total	Coal	Oil	Gas	Non-fossil	Total	Coal	Oil	Gas	Non-fossil	Total
Industrial	1.05	0.41	0.10	0.06	1.62	0.98	0.37	0.29	0.09	1.73	0.24	0.14	0.17	0.14	0.69
Building	0.22	0.00	0.26	0.07	0.55	0.08	0.00	0.27	0.06	0.41	0.01	0.00	0.18	0.08	0.26
Transport	0.00	0.47	0.02	0.00	0.49	0.00	0.50	0.02	0.01	0.53	0.00	0.25	0.02	0.04	0.30
Others	0.05	0.02	0.02	0.02	0.11	0.04	0.01	0.01	0.03	0.09	0.01	0.01	0.01	0.01	0.03
Electricity	1.52	0.00	0.04	0.63	2.18	1.34	0.00	0.12	1.43	2.89	0.22	0.00	0.15	3.54	3.91
Total demand	2.84	0.89	0.43	0.78	4.94	2.44	0.87	0.71	1.62	5.64	0.47	0.40	0.52	3.81	5.20

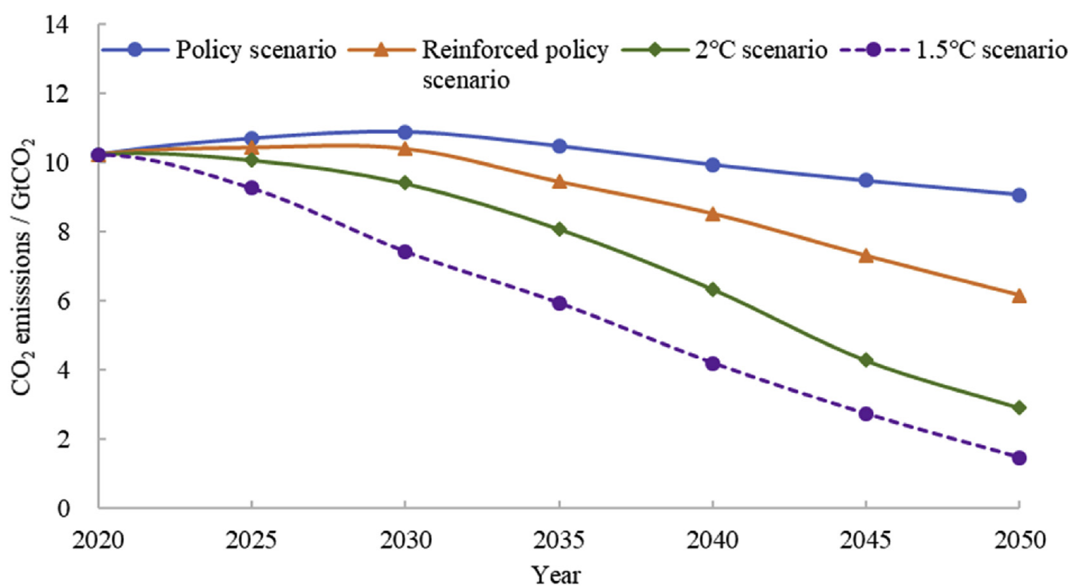


Fig. 16. CO_2 emissions from fossil fuel combustion under different scenarios.

basically achieve near-zero emissions in 2050 under the 2 °C scenario.

While ensuring sustainable economic and social development, to achieve a deep decarbonization path, it is necessary to improve policy efforts and commit significant amounts of investment. A certain cost and price have to be paid to achieve deep reduction of CO_2 emissions. Fig. 18 shows the marginal carbon price under different scenarios while Fig. 19 shows the corresponding GDP loss.

Under the 2 °C scenario, the carbon price will reach approximately 126 RMB (30 USD, constant price in 2011)/tCO_2 by 2030 and 1364 RMB (206 USD, constant price in 2011)/tCO_2 by 2050, while GDP lost will reach 0.15% and 1.38% respectively. The GDP loss will further increase by several times under the 1.5 °C scenario.

Achieving deep decarbonization in the 2 °C scenario and especially in the 1.5 °C scenario implies a major impact on improving environmental quality. In the policy scenario, $PM_{2.5}$ concentration will also reduce significantly by 2050, dropping to 14.0, 24.9, 14.6, and 14.0 μg/m^3 respectively in the whole country, in Beijing–Tianjin–Hebei and neighboring areas, in the Fenwei Plain, and in the Yangtze River Delta. However, 24% of cities across the country and more than 90% of cities in Beijing–Tianjin–Hebei and neighboring areas still fail to meet the first-level standard of 15 μg/m^3. Under the 2 °C scenario, as fossil fuel consumption and conventional pollutant emissions are effectively reduced from the source, despite the decreasing potential of terminal pollution control technologies, achieving the goal of $PM_{2.5}$ concentration meeting the 15 μg/m^3 standard by 2050 in key areas of the country would still be guaranteed. By 2030, except for around 10% of cities in Beijing–Tianjin–Hebei and neighboring areas still failing to meet the 35 μg/m^3 standard, the country overall and other major regions mostly meet the standards. By 2050, $PM_{2.5}$ concentration will drop to 8.3, 14.1, 9.6, and 7.5 μg/m^3, respectively in the whole country, in Beijing–Tianjin–Hebei and neighboring areas, in the Fenwei Plain, and in the Yangtze River Delta. By then, there will no areas with high $PM_{2.5}$ pollution left in China, most cities can achieve the target of below 15 μg/m^3, and 82% of cities can achieve an even higher standard of 10 μg/m^3.

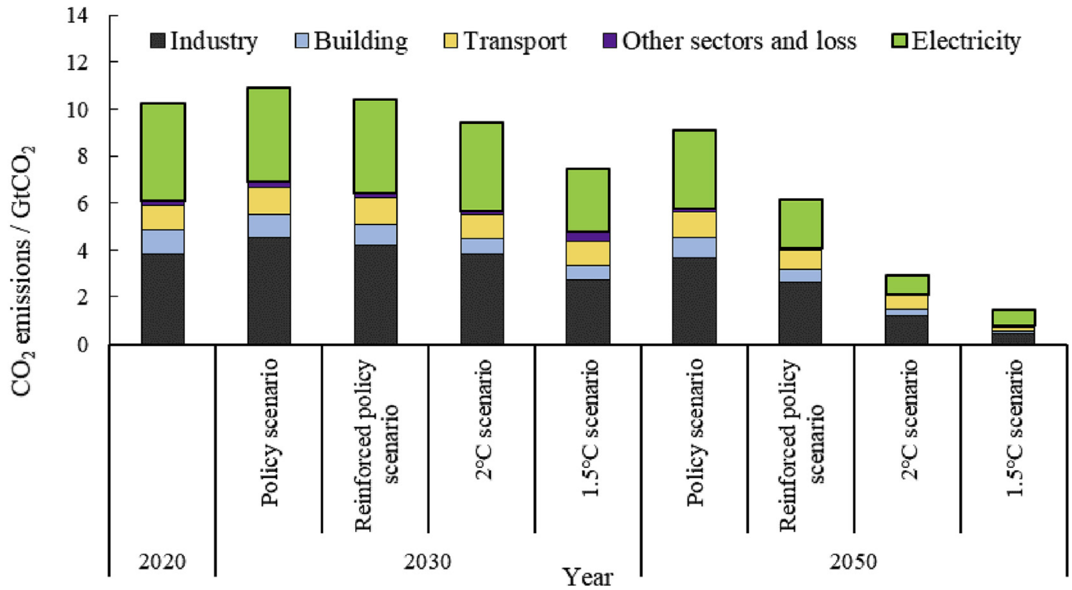


Fig. 17. CO_2 emissions by sector under different scenarios.

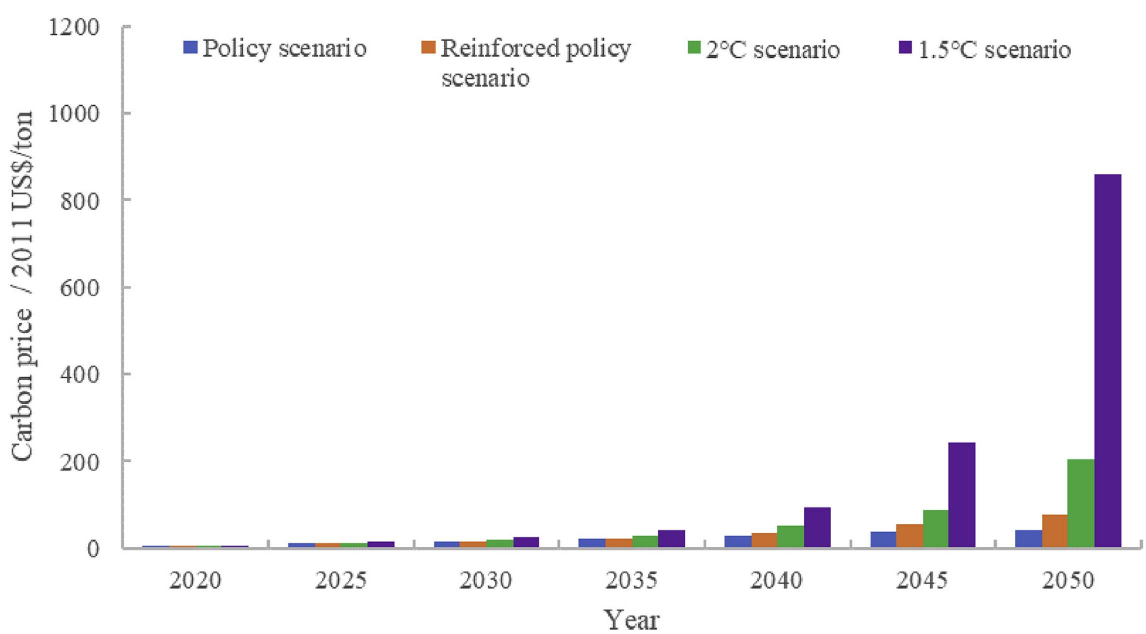


Fig. 18. Carbon price analysis under different scenarios.

7. Non-CO_2 greenhouse gas emissions

China's non-CO_2 GHG emissions in 2014 were 2 $GtCO_2e$, of which methane (CH_4) accounted for 56%, nitrous oxide (N_2O) 31%, and fluorine gases (F-gas) 12%. Non-CO_2 GHG emissions accounted for 16% of the total GHG emissions and its share is still increasing (see Fig. 20).

Coal mining gas emissions account for about 40% of the total CH_4 emissions, reaching about 540 $MtCO_2e$ in 2015. However, these emissions are estimated to drop in the future as coal mining activities decrease and coal-bed gas utilization increases. In the agricultural sector, CH_4 emissions from animal enteric fermentation and rice cultivation reached about 470 $MtCO_2e$ in 2015. These emissions are expected to continue to rise in the future and to exceed coal mining emissions to become the major source of CH_4 emissions after 2050. Fugitive emissions from oil and gas fields and landfill gas emissions are also major factors contributing to the future growth of CH_4 emissions. In the reinforced policy scenario and the 2 °C scenario, CH_4 emissions peak in 2030 (at about 1.2 $GtCO_2e$) and further drop significantly to about 800 $MtCO_2e$ in 2050, as measures are taken to reduce CH_4 emissions in the coal, oil, and gas production process, to adopt recycling and end treatment decomposition technologies, to upgrade rice planting and livestock raising, including feed food replacement, to improve waste management and disposal, etc. However, due to the non-linear and steep rise in the marginal cost of deep CH_4 emission reduction, it is still difficult to achieve near-zero emissions.

Nitrous oxide emissions mainly come from nitrogen fertilizer application, animal manure management and application, and combustion during the processing and production of adipic acid. These emissions are estimated to peak around 2020 at about 650 $MtCO_2e$ and to further significantly decrease by 2050, provided that effective measures are taken to improve the management of agricultural fertilizers, control and reduce the application of chemical fertilizers, improve farming practice, and tighten the source control and end treatment during the production

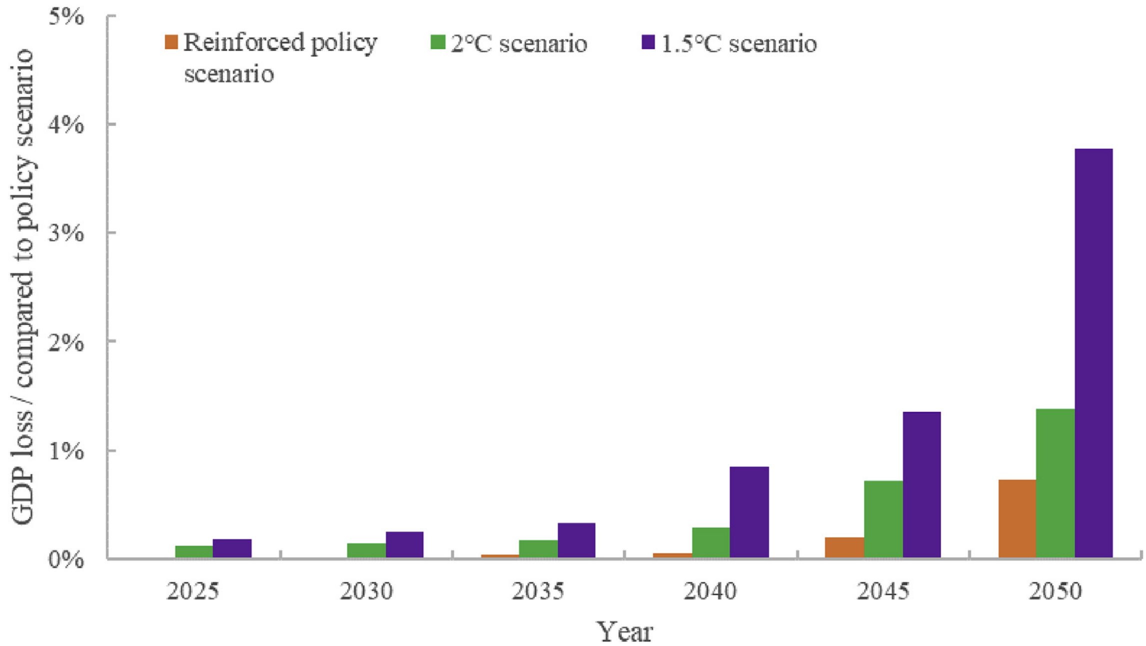


Fig. 19. GDP loss analysis under different scenarios.

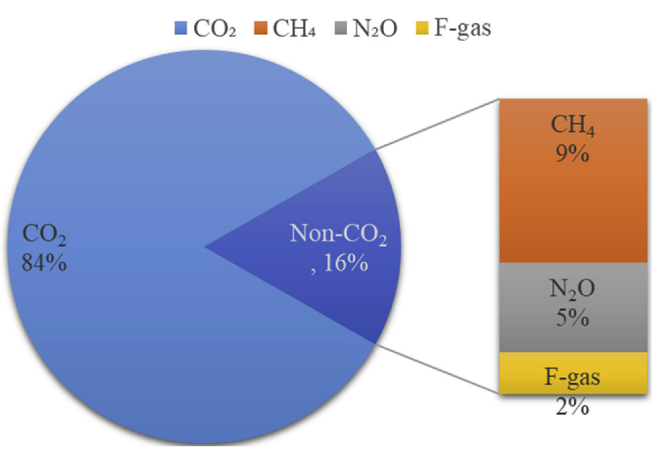


Fig. 20. Emissions by gas type in 2014.

of adipic acid.

Fluorine gas emissions mainly come from the production process of refrigerants, foaming agents, fire extinguishing agents, and chemical raw materials in many industries. These emissions may peak by 2030 at 730 $MtCO_2e$ and further drop to less than 500 $MtCO_2e$ by 2050 through the substitution of refrigerants in household, commercial, automobile, and other air-conditioning as well as the enhancement of HFC-23 by-product reduction, incineration, and resource utilization during the production process. The reduction can reach 44% under the 2 °C scenario and 60% under the 1.5 °C scenario. See Table 12 and Fig. 21 for various non-CO_2 GHG emissions under different scenarios.

Under the reinforced policy scenario and the 2 °C scenario, the emission reduction potential is fully tapped at an acceptable cost, non-CO_2 GHG emissions can peak before 2030 at 2.8 $GtCO_2e$ and around 2025 at 2.5 $GtCO_2e$, basically achieving synchronous peaking of CO_2 emissions. Because of the low cost of reducing non-CO_2 emissions during the initial period, there are many cost-effective emission reduction technologies. Currently, about one-third of the NDC reduction targets of developed countries are achieved through non-CO_2 emission reductions. China may also strengthen its non-CO_2 GHG emission reduction actions and gradually integrate them into the national NDC targets. Fig. 22 shows the non-CO_2 GHG emission reduction potential in sectors. However, for non-CO_2 GHGs, it is very difficult to achieve deep reduction and the marginal cost of emission reduction also increases steeply (see Fig. 23). As a result, after 2030, with the substantial and rapid reduction of CO_2, non-CO_2 emissions will account for an increasingly larger share of the total GHG emissions. Deep decarbonization by 2050 under the 2 °C scenario will become a challenge and priority in non-CO_2 emission reductions, and thus, requires strategic actions well in advance, including developing breakthrough technologies and policy tools. Fig. 24 shows non-CO_2 emission trends under various scenarios.

At present, it is necessary to establish and improve the measurement, accounting and statistical reporting systems for CH_4 and other non-CO_2 GHG emissions, to identify and promote cost-effective emission reduction and utilization technologies, to formulate industry and product emission standards, and to strengthen regulation and fiscal and tax incentive policies. The government should strive to integrate certified emission reductions of CH_4 and fluorine gas emission reduction projects into the voluntary carbon market as an offset mechanism, which would help to promote market-based non-CO_2 emission reductions. China should also prepare international linkages for a carbon market mechanism under the Paris Agreement, participate in cooperative emission reduction actions under the international market mechanism to promote market-based emission reduction of non-CO_2 emissions, and accelerate the construction of a monitoring, reporting, and verification (MRV) system.

Table 12
Non-CO_2 emissions in different scenarios (unit: $GtCO_2e$).

	2020	2030	2040	2050
Policy scenario	2.44	2.97	3.13	3.17
Reinforced policy scenario	2.44	2.78	2.63	2.37
2 °C scenario	2.44	2.49	2.15	1.76
1.5 °C scenario	2.44	1.94	1.59	1.27

8. Technical support

Breakthrough technical support is indispensable for pursuing long-term deep decarbonization or carbon neutralization, especially in areas where conventional emission reduction technologies or substitution

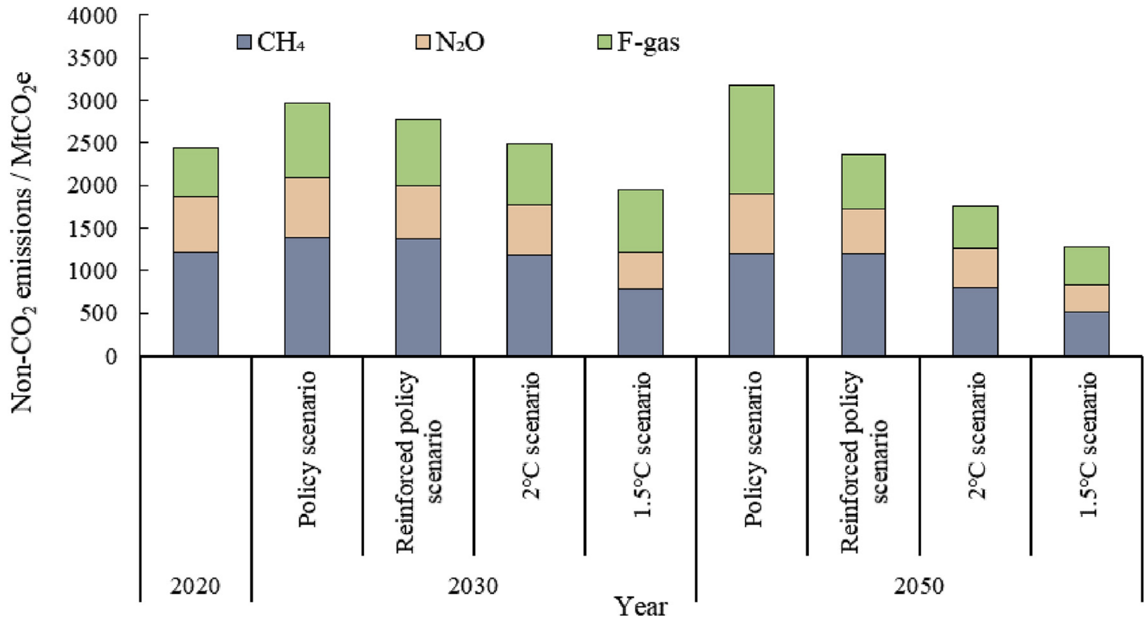


Fig. 21. Non-CO_2 emissions in different scenarios.

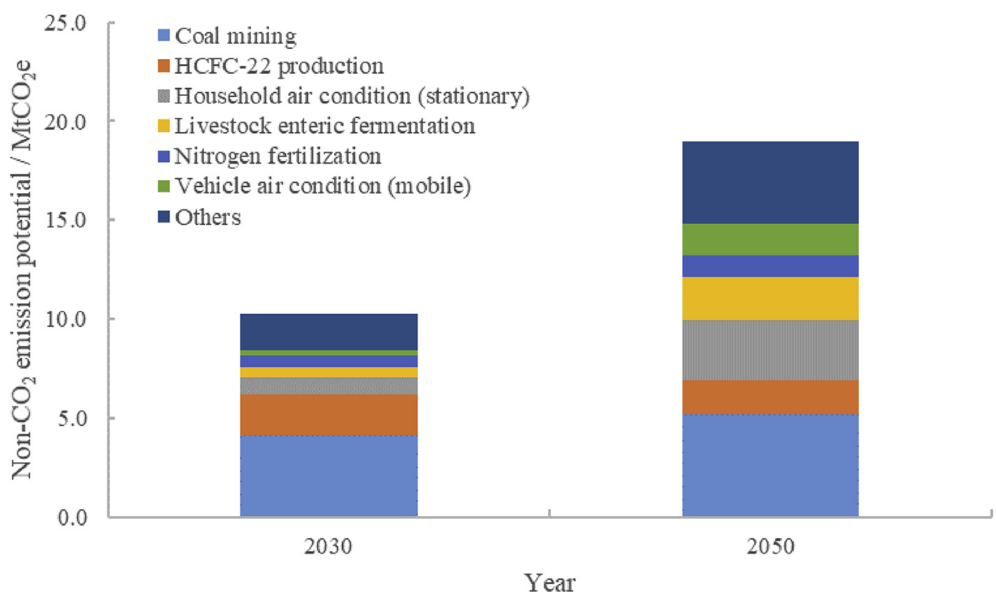


Fig. 22. China's non-CO_2 emission reduction potential in key areas.

technologies hardly serve the purpose of deep emission abatement. While further consolidating technologies of common concern (e.g., demand-side management and energy efficiency, new energy and renewable energy power generation, and heat utilization), special attention should also be paid to strategic technologies that are currently immature and costly. Those strategic technologies could play a key role in deep decarbonization. It is necessary to carry out comprehensive and systematic assessments with respect to future technical feasibility, maturity, economy, and social, environmental, and ecological impacts, to accelerate R&D and industrialization (Fig. 25).

In the future, a large proportion of intermittent renewables will be connected to the grid. The safe and stable operation of the power system will demand large-scale technical support ranging from energy storage, smart grid, and distributed renewable energy. Apart from pumped storage, electrochemical energy storage is the most attractive technology. With 6625 MW of installation globally, it is expected to become comparable to pumped storage in capacity owing to plunging costs. Hydrogen produced through electrolysis of renewable energy has also attracted attention as a means of energy storage across seasons and regions. By virtue of high load factor and stable operations, advanced nuclear power could play a basic load role in the future power system dominated by non-fossil fuels, which is conducive for safe and stable grid operations. At the same time, nuclear power has greater flexibility to adapt to grid peak shaving and combined heat and power (cogeneration). The high-temperature process heat of nuclear reactors can be used to convert nuclear energy efficiently into hydrogen energy via the thermochemical cycle, which makes possible large-scale industrial production of hydrogen energy. A smart grid can strengthen the interaction between grid-side energy storage and demand response, while global energy Internet development facilitates the coordination and optimization of development and utilization activities of renewables globally and in various regions. Both are key technologies worthy of attention to

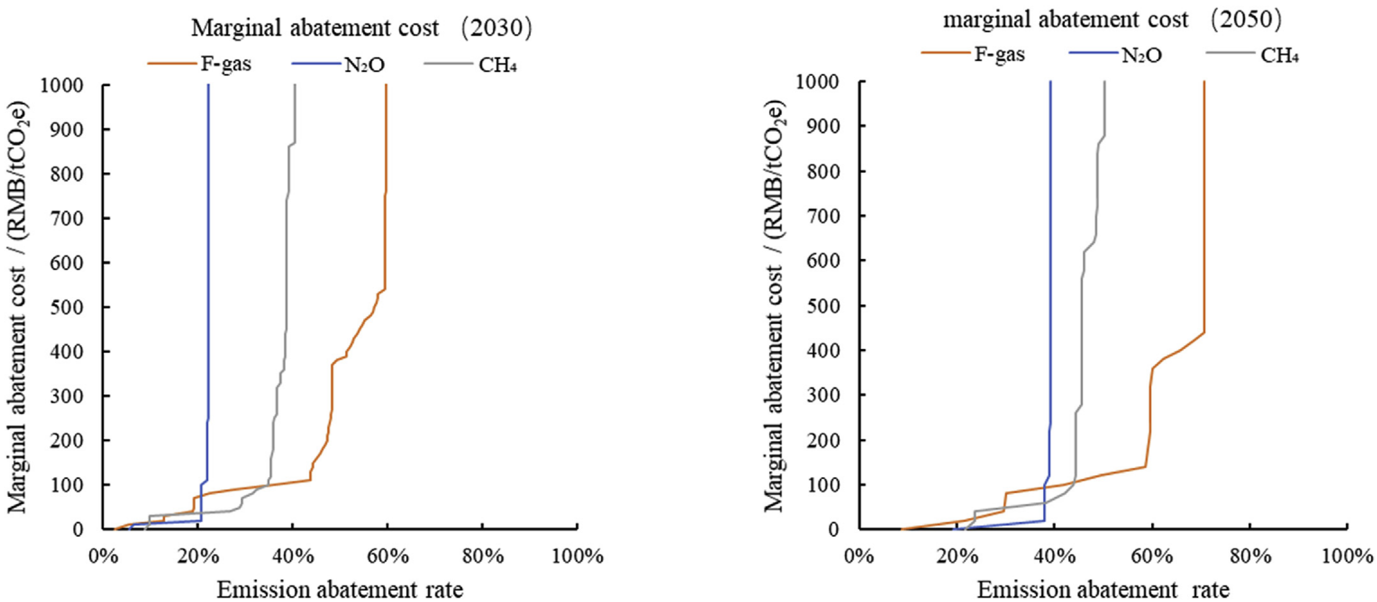


Fig. 23. Cost curve of non-CO_2 emission reduction (2030 and 2050).

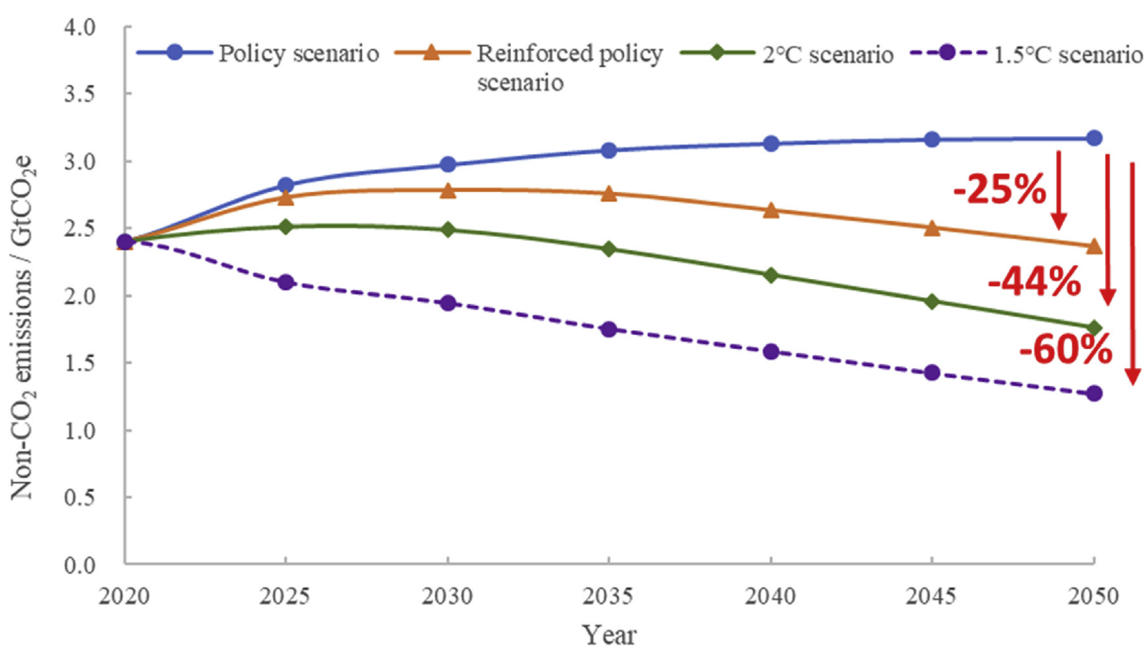


Fig. 24. Non-CO_2 emission reduction in different scenarios.

support the power system in delivering net-zero emissions.

The advancement of low-carbon technologies of the energy system complements the technological innovation and transformation of the entire society. Specifically, the various low-carbon technologies of the power system are interrelated with the energy Internet, energy big data, and artificial intelligence of the energy system, and are further related to the development of information technology, new materials, and high-end equipment industries. As shown in Fig. 26, strategic technologies in the power system, energy system, and technological innovation system support each other. The realization of deep decarbonization necessitates advanced low-carbon technologies as strategic support.

Industrial processes, such as steel and cement production, face challenges in substantially cutting CO_2 emissions. Hydrogen-based direct reduction, which replaces traditional coke, is a revolutionary technology for deep decarbonization in the production of steel, especially pig iron and crude steel. Hydrogen production with high-temperature process heat from high-temperature gas-cooled reactors can be combined with the hydrogen steelmaking process, which is very promising for large-scale industrial development. Low-carbon chemical technologies based on electricity and hydrogen energy can make important contributions to deep emission reduction. They support the technical processes of the production of petrochemical products, such as methanol, olefins, hydrocarbons, synthetic ammonia, and refined oil, by using electricity and hydrogen to reduce or replace fossil energy, such as coal and oil, in the mix of chemical raw materials. Low-carbon cement technologies based on the substitution of raw materials also have considerable potential for emission reduction, including R&D and application of alternative materials and ratio optimization of raw materials for cement production. However, these technologies are currently very costly, and thus, technical breakthroughs have yet to be made (Fig. 27).

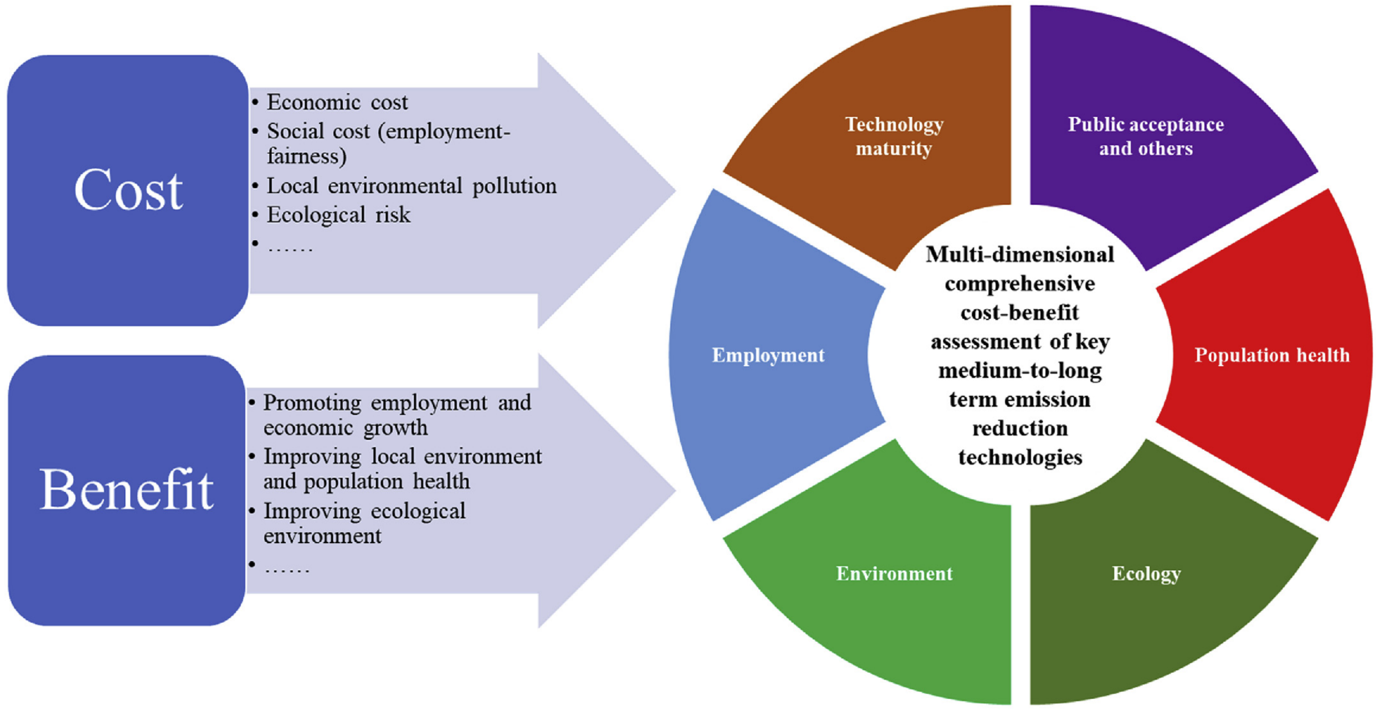


Fig. 25. Comprehensive analysis framework of key technologies for deep decarbonization.

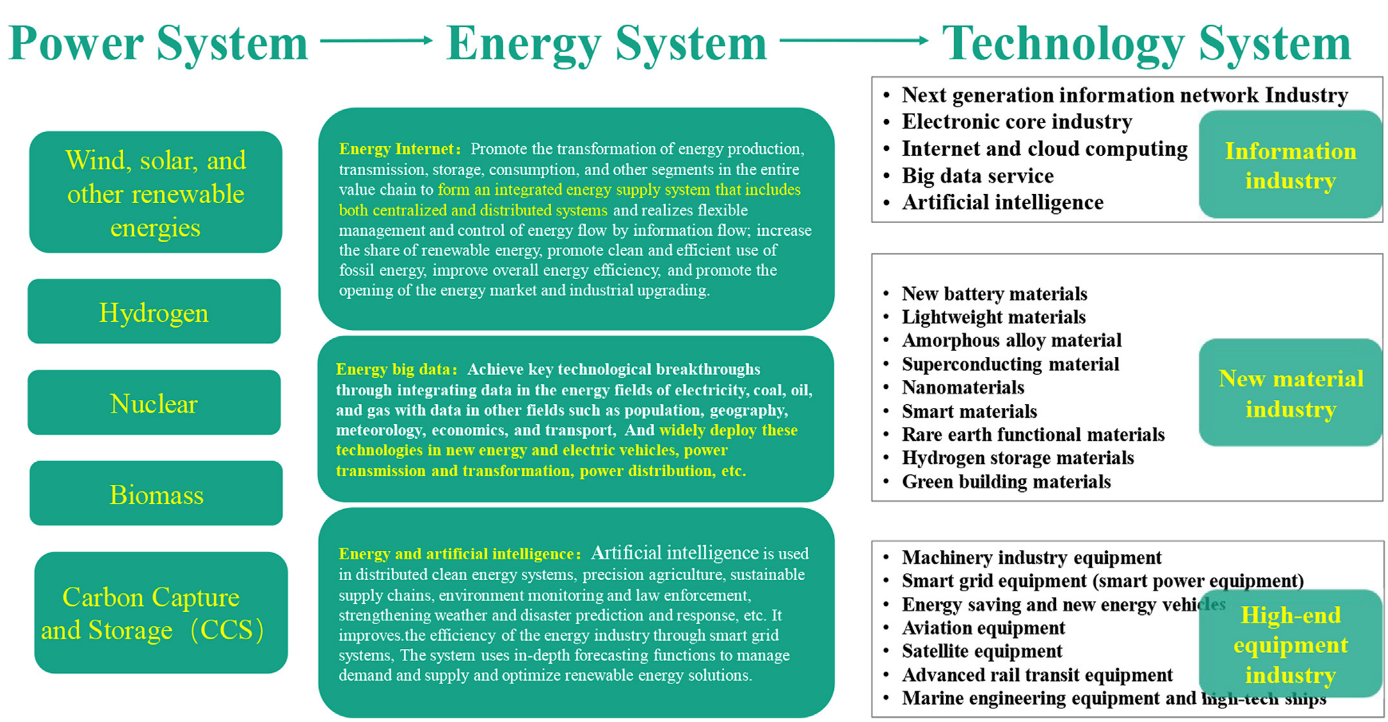


Fig. 26. Mutual support of strategic technologies in power system, energy system, and technological innovation system.

The use of electricity and hydrogen instead of fossil fuels is important for deep decarbonization in the transportation sector. It is necessary to speed up the development and promotion of electric vehicles and light-duty fuel cell vehicles. Currently, electric vehicle technology is being rapidly promoted and industrialized with the continuous decline of costs. While charging infrastructure is developing rapidly, electric vehicles are gradually approaching fuel-powered vehicles in comprehensive costs. This would greatly support deep decarbonizing of the transportation sector. The progress in hydrogen fuel cell vehicles rests on the development of the entire industrial chain and the consolidation of corresponding facilities, including hydrogen production, storage, transport, and refueling, as well as the production and management of fuel cells and car bodies. As the current fuel cell system and stack technology can meet the requirements of vehicles, fuel cell vehicles have generally reached the performance standards for commercial promotion, and fuel cell buses and trucks have entered the demonstration operation stage. Given the technological maturity and cost reduction, the prospects for development are broad.

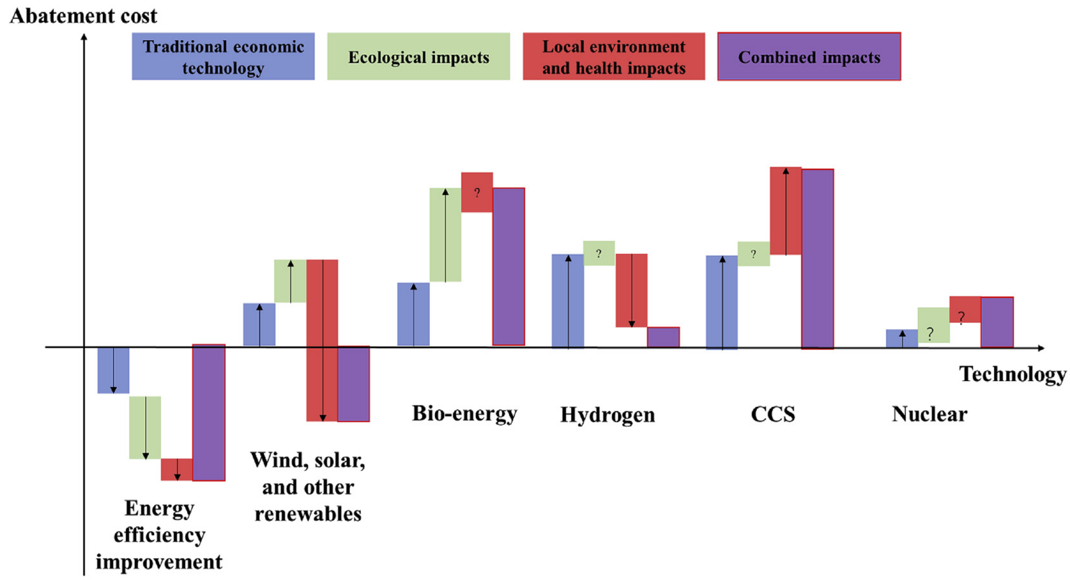


Fig. 27. Schematic diagram of abatement cost changes of China's key mid- and long-term emission reduction technologies considering ecological and health impacts.

CCS and geoengineering are important alternative technologies for deep decarbonization. With a view to deep emission reduction, CCS can be applied to fossil energy generation and the coal-chemical and petrochemical industries to decarbonize fossil energy utilization deeply. BECCS is a technique that captures and stores CO_2 emissions from biomass power generation and heat utilization to achieve negative emissions. The targets of limiting warming well below 2 °C and 1.5 °C ultimately require carbon neutrality. BECCS-based negative emissions make it possible to achieve economy-wide net-zero emissions by offsetting the remaining emissions, including CO_2 emissions of industrial production processes and non-CO_2 GHG emissions. Taking into account China's biomass resources and utilization prospects, the country is likely to achieve 0.6–1 billion tons of CO_2 negative emissions through BECCS by 2050, but currently, R&D and demonstration must be strengthened. Geoengineering generally encompasses carbon dioxide removal (CDR) and solar radiation modification (SRM). CDR directly removes CO_2 from the atmosphere or artificially increases marine and terrestrial carbon sinks to reduce CO_2 in the atmosphere. There is active R&D worldwide of various CDR techniques, and engineering demonstrations have been carried out in some cases. SRM reduces solar radiation, reaching the Earth to alleviate warming by means of stratospheric aerosol injection and albedo enhancement of the Earth's surface or atmosphere. This technology has high risks and uncertainties, and despite slow progress in R&D, is worthy of attention.

9. Investment and cost

Investment needs for driving the long-term low-carbon transition include spending on the energy supply side and in energy efficiency across end-use sectors (industry, transport, and building). Table 13 shows the projected energy investments by category under different scenarios.

Table 13
Projected cumulative energy investments by category from 2020 to 2050 (trillion RMB).

	Energy Supply	Industry	Building	Transport	Total
Policy scenario	53.71	0.00	6.29	10.51	70.51
Reinforced policy scenario	77.89	0.39	7.42	13.99	99.69
2 °C scenario	99.07	2.66	7.94	17.57	127.24
1.5 °C scenario	137.66	7.18	7.88	21.66	174.38

The cumulative energy investment needs on the supply side (including power generation, electricity transmission, distribution and storage, extraction, and conversion of fuels) from 2020 to 2050 will climb from 53.7 trillion RMB in the policy scenario, to 99.1 trillion RMB in the 2 °C scenario, and to 137.7 trillion RMB in the 1.5 °C scenario. The total cumulative energy investment needs under the 2 °C scenario is approximately 127 trillion RMB, while that required under the 1.5 °C scenario is more than 174 trillion RMB. To achieve the goal of deep decarbonization in the middle of this century, it is necessary to establish and perfect the investment and financing mechanism and capital guarantee measures.

Under various scenarios, the costs of energy and power supply will be driven up by energy transition in the near term, but tend to shrink in the long run. The annual average power supply cost, in RMB per kWh, of electricity produced in the policy scenario shows a downward trend. In the reinforced policy scenario, they are relatively stable with a slight increase over a long period of time, but will plummet after 2028. In both the 2 °C and the 1.5 °C scenarios, the average power supply cost will first rise and then fall, peaking at around 2028 and 2033, at a level 1.40 times and 1.41 times that of 2018, respectively. In the long term, power supply costs will still decrease. In 2050, they will decline to 69%, 66%, 75%, and 90% of that of 2018 in the policy, reinforced policy, 2 °C, and 1.5 °C scenarios, respectively. The costs to supply power in 2 °C and 1.5 °C scenarios are higher than those of the other two scenarios, mainly because of higher fixed investments, operation and maintenance costs, and power transmission costs, as shown in Figs. 28 and 29.

In the long term, as the total energy consumption reaches its peak, the total energy expenditures will show a downward trend under most of the scenarios (Table 14).

10. Mid- and long-term low-carbon development pathways

For long-term low-carbon development pathways, it is necessary not only to bear in mind the goal of deep decarbonization to keep warming well below 2 °C and pursue efforts for below 1.5 °C, but also to take current economic, social, environmental, and climate targets fully into account. Overall planning and deployment are needed to solve existing urgent problems.

For the implementation and enhancement of NDCs to 2030, current actions need to be intensified and aligned with deep decarbonization pathways toward the goal of limiting warming below 2 °C and pursuing efforts for below 1.5 °C. Based on the current specific situation of economic transition and energy reform, the policy scenario for NDC

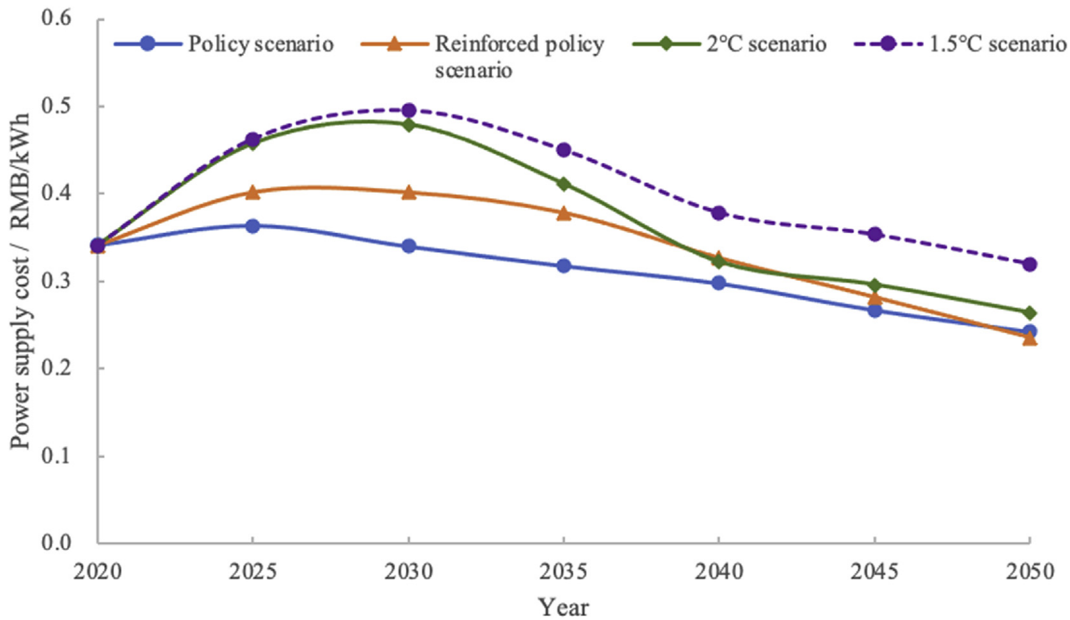


Fig. 28. Trends in power supply costs under different scenarios.

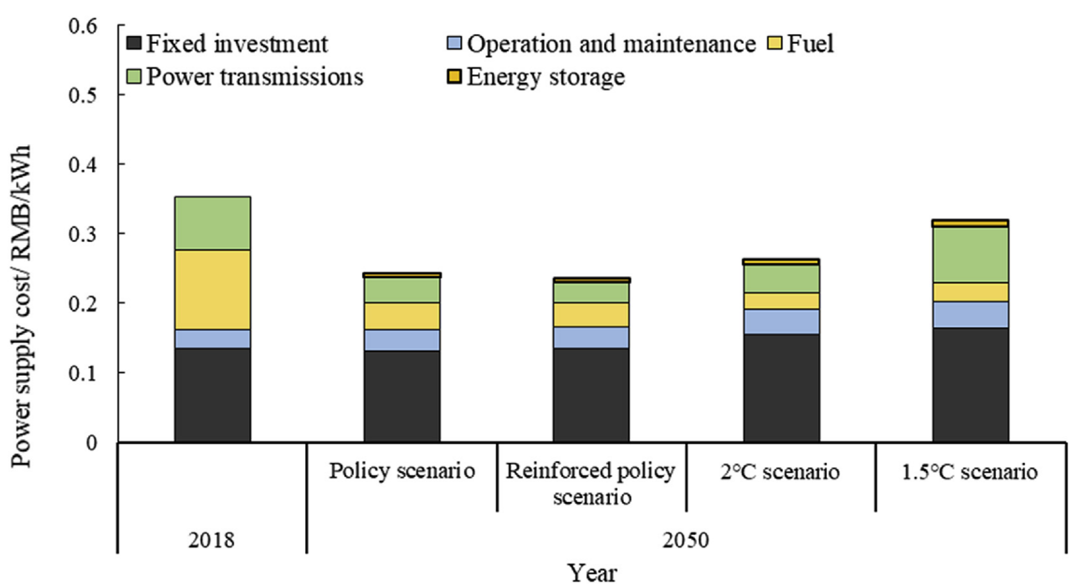


Fig. 29. Composition of power supply costs in 2050.

Table 14
Total energy expenditures (unit: trillion RMB).

	2020	2030	2050
Policy scenario	9.1	11.7	11.3
Reinforced policy scenario	9.1	12.5	10.7
2 °C scenario	9.1	13.3	12.2
1.5 °C scenario	9.1	13.1	13.5

implementation will be strengthened by upgrading policies and actions to gradually align with the 2 °C scenario and even 1.5 °C scenario, with a view to deep decarbonization by mid-century. Such a pathway entails more rapid energy reform and economic transition in the post-2030 period, especially after 2035, and puts more pressure on future low-carbon transition.

Future economic development and energy transition face greater uncertainties owing to the impacts of the COVID-19 pandemic on the global industrial chain and supply and demand. At present, based on the "six stabilities" and "six guarantees," China is upholding a new vision of development, accelerating industrial transformation and upgrading and high-quality development, and endeavoring to develop the digital economy and high-tech industries. As the focus of economic growth has shifted from scale and speed to quality and efficiency, the GDP growth rate overall will gradually slow. By 2035, the first-stage goal will be achieved, that is, realizing socialist modernization. Assuming that, if GDP were to double from the 2020 level, and per capita GDP were to be 20,000 U.S. dollars at current constant prices, the annual GDP growth rate in the next 15 years would be about 4.8%. During the 14th Five-Year Plan period, the rate may be slower than in the previous period, but it is still likely to exceed 5%. During the next two five-year plan periods, the rate will stay at around 4.8% and 4.4%, respectively.

By adopting intensified mitigation measures, carbon intensity (CO_2 emissions per unit of GDP) will be reduced by about 20% in each of the

14th and 15th Five-Year Plan periods. CO_2 emissions will enter a plateau period by 2025, peak before 2030, and start to decline thereafter. In 2030, carbon intensity can be cut by 65–70% compared with the level in 2005, and the share of non-fossil energy in primary energy consumption will be about 25%, achieving the NDC targets ahead of schedule and in excess, as shown in Table 15.

In this pathway, energy intensity (energy consumption per unit of GDP) will be reduced at an annual rate of about 3% between 2020 and 2030. However, due to changes in the energy mix, the annual decline of CO_2 emissions per unit of energy consumption will be on the rise, up from 1.16% in the 13th Five-Year Plan period to 1.38% in the 14th Five-Year Plan period and 1.59% in the 15th Five-Year Plan period. As a result, the annual decline of carbon intensity will reach 4.5% or more during the 15th Five-Year Plan period, supporting the peak of CO_2 emissions before 2030.

While vigorously saving energy and optimizing the energy mix, fossil fuels will be increasingly replaced by electricity in end-use sectors. The share of power generation in primary energy consumption will keep increasing, which provides a chance for the rapid development of renewable electricity. By 2030, the share of electricity in final energy consumption will climb from about 25% to more than 30%; the share of non-fossil electricity in total electricity will reach about 50%; and the share of power generation in primary energy consumption will expand from the current 45% to more than 50%. Improving the electrification of final energy consumption is an important measure to trim CO_2 emissions.

Considering the 2 °C pathway to 2050, the global temperature rise will be below 2 °C, CO_2 emissions in 2050 will be 70% lower than in 2010, and the average CO_2 emissions per capita in that time will be less than 1.5 tons. To achieve the 2 °C pathway by mid-century, it is necessary to further step up mitigation efforts after 2030 based on the reinforced scenario for transitioning to the emission reduction pathway in the 2 °C scenario. The aim is to achieve a significant reduction in CO_2 emissions in 2035 compared to the peak year, and to realize emission reductions compatible with the 2 °C goal by 2050. This forms the recommended scenario in this study (Fig. 30), which is called the 2 °C target oriented low-carbon development path (2 °C target path).

Primary energy consumption will enter a plateau period around 2030 and reach a peak around 2035 in the 2 °C target path. By 2050, energy consumption will drop by 13% from 2030. Promoting economic transition and improving energy efficiency will still play an important role. The energy consumption mix will also speed up significantly after 2030. The share of coal in primary energy consumption will fall to 45% by 2030 and below 10% by 2050, while the share of non-fossil fuels in primary energy consumption will increase to 25% by 2030 and 73% by 2050. Non-fossil electricity will contribute to about 90% of the total electricity production (see Fig. 31). CO_2 intensity per unit of energy consumption will decrease by 68%. A deeply decarbonized energy system with new energy and renewable energy as the mainstay will be basically formed. CO_2 emissions from the energy system will be cut by 72.1% in 2050 compared to 2030, of which about 14% can be attributed to smaller energy consumption and 86% to the low-carbon energy mix (see Table 16). Therefore, following the decoupling of economic growth from energy consumption, expediting the deep decarbonization process of energy system will play a decisive role in pursuing net-zero emissions by 2050.

Table 15
Analysis of energy consumption and CO_2 emissions in scenarios of implementing and strengthening NDC targets to 2030.

		2005	2010	2015	2020	2025	2030
Annual GDP growth rate (%)			11.3	7.9	5.9	5.3	4.8
5-year decline in energy consumption per unit of GDP (%)			19.1	18.5	14.3	14.0	14.0
Energy consumption (billion TCE)		2.61	3.61	4.34	4.94	5.5	5.98
Energy consumption structure	Coal (%)	72.4	69.2	63.7	57.0	51.0	45.0
	Oil (%)	17.8	17.4	18.3	18.5	18.0	17.0
	Natural gas (%)	2.4	4	5.9	8.5	11.0	13.0
	Non-fossil fuel (%)	7.4	9.4	12.1	16.0	20.0	25.0
CO_2 emissions per unit of energy consumption (kg CO_2/kgce)		2.32	2.25	2.16	2.03	1.90	1.75
CO_2 emissions ($GtCO_2$)		6.06	8.13	9.37	10.03	10.45	10.46
5-year decline in CO_2 emissions per unit of GDP (%)			21.5	21.2	19.7	19.4	20.6
Decline from the 2005 level (%)					50.3	60.0	68.3

Under the dual effect of energy saving and energy substitution, CO_2 emissions related to energy consumption will decline rapidly. By 2050, electricity will represent 55% of the final energy consumption, while the share of fossil fuels will fall drastically; direct CO_2 emissions from the industrial and power sectors will still be the main contributor. Among them, direct CO_2 emissions from the power sector in 2050 will reduce 80% from the level in 2020 due to decarbonization of the energy mix, which provides more low carbon electricity for end-use sectors. CO_2 emissions from the energy system will shrink to 2.92 billion tons.

CCS and BECCS will play an important role in long-term deep CO_2 emission reduction. To 2050, up to 510 $MtCO_2$ emissions from the power system will be captured and stored, net CO_2 emissions from the energy system will be reduced to 2.41 Gt, and CO_2 emissions from industrial production processes will drop from 940 Mt in 2030 to 470 Mt in 2050. The annual carbon sinks from agriculture and from land-use, land-use change, and forest (LULUCF) will be about 700 $MtCO_2e$ per year. As such, the total CO_2 emissions in 2050 will be 2.18 Gt, down 80%, from 2030. The average CO_2 emissions per capita will be about 1.5 tons, which will meet the global emission reduction pathway under 2 °C (see Tables 17 and 18 as well as Fig. 32).

In pursuit of deep decarbonization without compromising sustainable socio-economic development, GDP in 2050 will be 3.5 times the 2020 level. Energy consumption will peak around 2035 and fall thereafter, as new and renewable energy will maintain the momentum of rapid growth. There will be a quicker decline in CO_2 emissions per unit of energy consumption. With the realization of absolute CO_2 emission reduction before 2030 to decouple GDP growth from CO_2 emissions, carbon intensity decline will pick up pace after 2030, and the annual rate will exceed 10% after 2040 (Fig. 32), to which energy mix changes contribute an increasing share.

The deep reduction of all GHG emissions in the 2 °C target path in 2050 covers CO_2 emissions from the energy system, CO_2 emissions from industrial processes, and other non-CO_2 GHG emissions, and needs to take into account CO_2 emissions captured and stored by means of CCS and BECCS and carbon sinks added by agroforestry and forests. By 2050, up to 700 million tons of carbon sinks will be created by agroforestry and LULUCF each year under the 2 °C target path, and 510 million tons stored by applying CCS and BECCS technologies. It is more difficult to trim non-CO_2 GHG emissions because so far, there is no such measure with acceptable cost. Excluding carbon sinks and CCS, non-CO_2 gases will account for as high as 34% of GHG emissions by 2050, much higher than the current proportion of 16%. In other words, the reduction of non-CO_2 GHG emissions will become more important. Future GHG emissions are shown in Table 19 and Fig. 33. By 2050, net GHG emissions will be cut by more than 70% from the 2030 level. In the 2 °C target path, GHG emissions will be 8.36 billion tCO_2e or 68% less than the 12.3 billion tCO_2e in the policy scenario.

At present, more and more countries and regions are adopting carbon neutrality as a long-term development strategy and vision, and are striving for a low-carbon transition of their economies and societies driven by the 1.5 °C warming goal. China has adopted a two-step strategy of socialist modernization. Before 2030, China must try to find room for emission reduction in economic development, and use emission

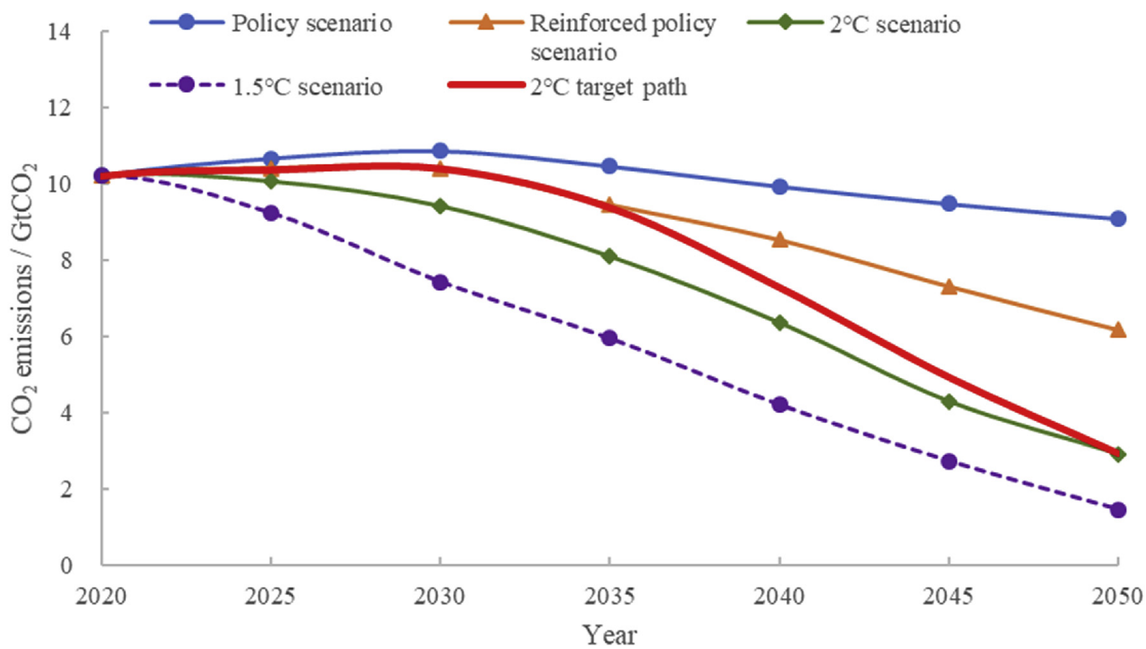


Fig. 30. CO_2 emissions in different scenarios and 2 °C target path.

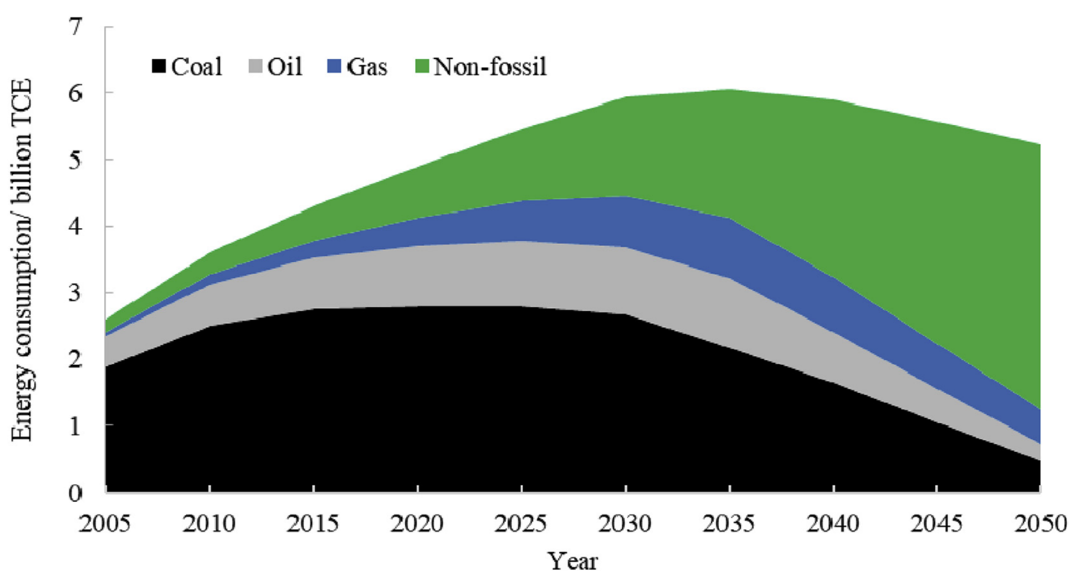


Fig. 31. Mix of primary energy in the 2 °C target path.

Table 16
Energy consumption and CO_2 emissions in the 2 °C target path.

		2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Annual GDP growth rate (%)			11.3	7.9	5.9	5.3	4.8	4.4	4.0	3.6	3.2
GDP index		1	1.71	2.50	3.33	4.31	5.45	6.75	8.22	9.81	11.48
Energy consumption (billion TCE)		2.61	3.61	4.34	4.94	5.5	5.98	6.06	5.89	5.58	5.2
Energy mix	Coal (%)	72.4	69.2	64	57	51	45	36	28	19	9.1
	Oil (%)	17.8	17.4	18.1	18.5	18	17	17	13	9	7.7
	Natural gas (%)	2.4	4	5.9	8.5	11	13	15	14	12	10
	Non-fossil fuels (%)	7.4	9.4	12	16	20	25	32	45	60	73.2
CO_2 emissions per unit of energy consumption (kg CO_2/kgce)		2.32	2.25	2.16	2.03	1.90	1.75	1.55	1.24	0.88	0.56
Annual decline of CO_2 emissions per unit of energy consumption (%)			0.58	0.83	1.27	1.30	1.59	2.46	4.38	6.50	8.62
CO_2 emissions ($GtCO_2$)		6.06	8.13	9.38	10.03	10.45	10.46	9.38	7.29	4.93	2.92
Annual decline of energy consumption per unit of GDP (%)			4.15	3.82	3.09	2.97	2.97	3.96	4.39	4.53	4.44
Annual decline of CO_2 emissions per unit of GDP (%)			4.72	4.62	4.33	4.23	4.57	6.32	8.58	10.74	12.74
Decline from the 2005 level (%)			21.5	38.0	50.3	60.0	68.3	77.1	85.4	91.7	95.8

Table 17
Energy consumption and CO_2 emissions by sector in 2 °C target path.

Final sectors	2020		2030		2050	
	Energy consumption (million TCE)	CO_2 emissions ($MtCO_2$)	Energy consumption (million TCE)	CO_2 emissions ($MtCO_2$)	Energy consumption (million TCE)	CO_2 emissions ($MtCO_2$)
Industrial	1610	3770	1880	4150	690	1190
Building	550	1000	510	880	260	310
Transport	490	990	540	1090	300	550
Electricity	2170	4060	2830	3950	3920	830
Other sectors	120	210	220	380	30	40
Total	4940	10,030	5980	10,460	5200	2920

Table 18
CO_2 emissions in total and by sector in 2 °C target path (unit: $GtCO_2$).

	2020	2030	2050
CO_2 emissions from energy consumption	10.03	10.46	2.92
CO_2 emissions from industrial production processes	1.32	0.94	0.47
CO_2 emissions stored by CCS/BECCS	0.0	0.0	−0.51
Carbon sinks	−0.58	−0.61	−0.70
Total	10.77	10.79	2.18

reduction to promote higher-quality economic and social development. Based on the prospective peaking of CO_2 emissions before 2030, China should further increase the speed and intensity of energy reform and economic transition, and strive to achieve net-zero CO_2 emissions and deep reduction in other GHG emissions by 2050, paving the way for early realization of net-zero GHG emissions. To achieve this scenario, it is necessary to change to decarbonization pathway of the 1.5 °C scenario as soon as possible, in a greater and faster manner than under the long-term low-carbon scenario, which is called 1.5 °C target oriented low-carbon development path (1.5 °C target path), as shown in Fig. 34.

To pursue 1.5 °C target path in 2050, the most important element is to raise more rapidly the share of non-fossil fuels in primary energy consumption while limiting total energy consumption, as shown in Fig. 35.

To achieve the deep emission reduction pathway in the 1.5 °C target path, efforts to increase carbon sink in agriculture and forestry and to reduce non-CO_2 GHG emissions are essential. By 2050, with the contribution of 780 $MtCO_2e$ of carbon sinks from agriculture and LULUCF and 880 $MtCO_2$ emissions stored by CCS (BECCS), economy-wide CO_2 emissions will be cut to about 60 Mt, which is basically "net zero". By then, there will still be 1.33 $GtCO_2e$ of non-CO_2 emissions due to the lack of cost-effective technical support for mitigation. Total GHG emissions are about 90% lower than the peak year, as shown in Table 20 and Fig. 36.

To move from the 2 °C target path to the 1.5 °C target path by 2050, additional mitigation efforts by various sectors are required, as shown in Fig. 37. Moreover, zero-carbon and negative-carbon technologies, such as CCS/BECCS, are essential for net-zero emissions, and non-CO_2 emission reduction technologies need to be further deployed in advance, so as to contribute to the early realization of net-zero GHG emissions.

11. Strategy highlights and policy support

China has launched a national strategy to address climate change, developing a comprehensive policy system covering a wide range of sectors. Since the 11th Five-Year Plan period, binding targets for energy

Table 19
GHG emissions in the 2 °C target path (unit: $GtCO_2e$).

	2020	2030	2050
CO_2 emissions from energy consumption	10.03	10.46	2.92
CO_2 emissions from industrial processes	1.32	0.94	0.47
Non-CO_2 GHG emissions	2.44	2.78	1.76
Forest carbon sinks	−0.58	−0.61	−0.70
CCS+BECCS	0	0	−0.51
Net emissions	13.21	13.57	3.94

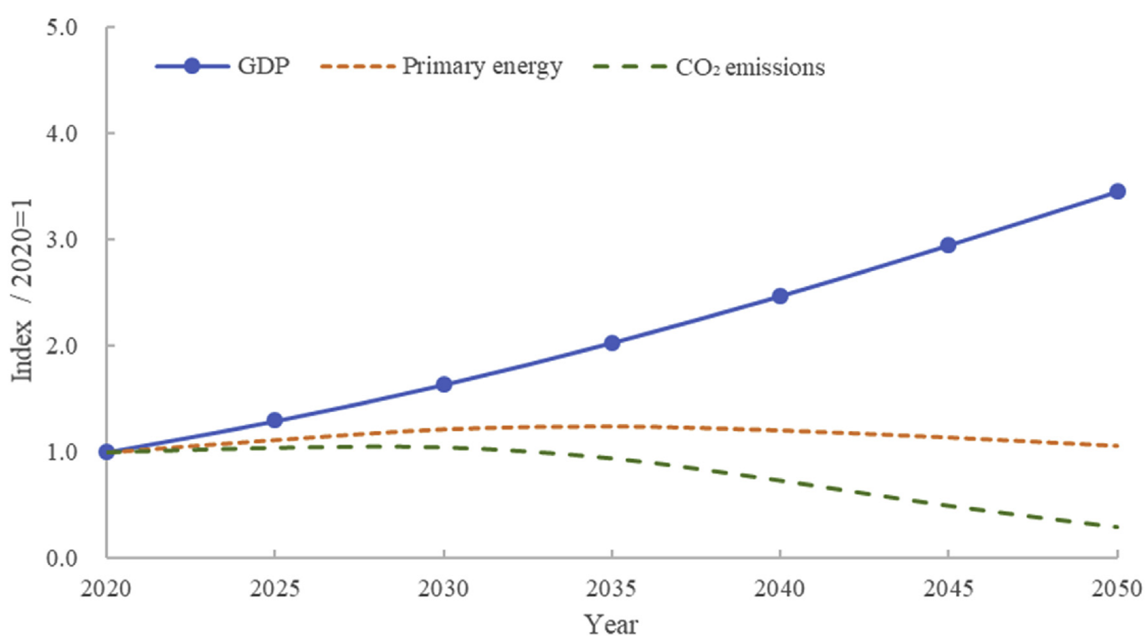


Fig. 32. Indexes of GDP, primary energy consumption and CO_2 emissions (2020 = 1).

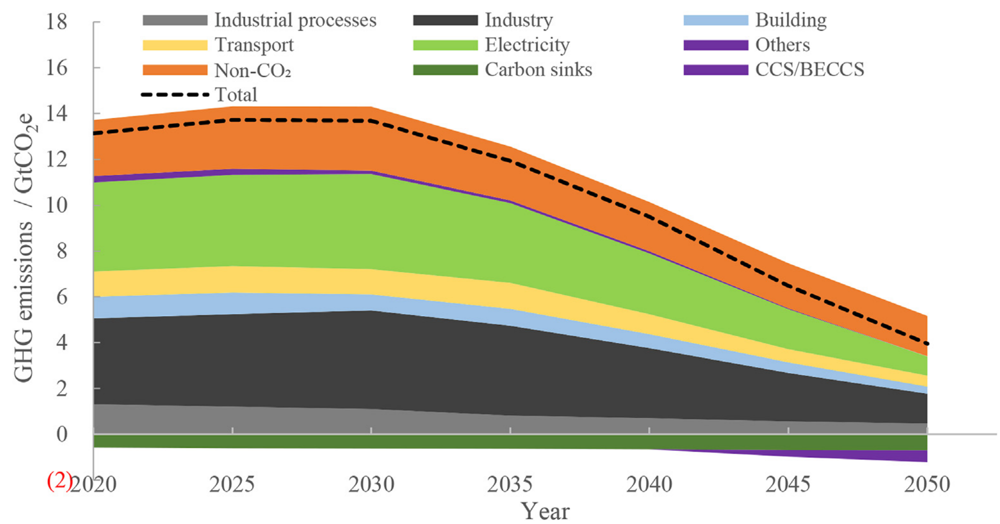


Fig. 33. GHG emissions by sector in the 2 °C target path.

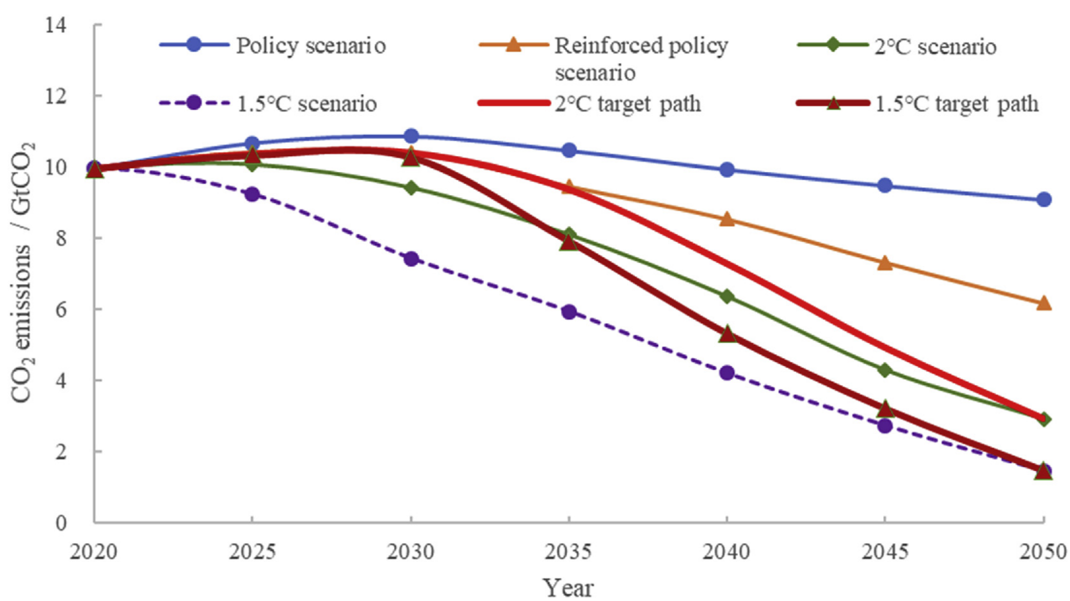


Fig. 34. Comparison of CO_2 emissions in 2050 in 1.5 °C target path and other scenarios.

conservation and carbon reduction have been set in every five-year plan, and assigned to provinces and cities, as a part of a tightened target-oriented system of responsibility for governments at all levels. Meanwhile, fiscal and tax policy support systems have been put in place, while development of a carbon emission trading scheme has advanced. Government regulatory measures are being combined with market mechanisms to promote the implementation of China's national climate change strategy.

Addressing climate change involves all areas of the economy, society, and environment. Therefore, the climate change strategy must be aligned with the national overall development strategy, and integrated into the strategies of various fields and sectors of economic and social development, so as to create a win–win pattern of collaborative governance in economic, social, environmental, and climate fields. China's long-term low-carbon development strategy to 2050 focuses on development to support the goal of building a modern socialist country that is prosperous, strong, democratic, culturally advanced, harmonious, and beautiful. At the same time, China is stepping up efforts to build an ecological civilization by taking the path of green, low-carbon, and circular development, with the aim of promoting harmony between humans and nature as well as sustainable development. Specifically, it is moving toward deep decarbonization compatible with the goal of keeping global warming well below 2 °C (Fig. 38).

From the perspective of national macro strategy, China's climate change strategy and policy support should highlight the following aspects.

(1) **China should explicitly set addressing climate change as a national strategy, and incorporate pathways to deep decarbonization for limiting global warming well below 2°C or pursuing effort to 1.5°C into its mid- and long-term overall development goals and strategies.** Tackling climate change is consistent with China's fundamental national policy of conserving resources and protecting the environment in terms of objectives and policy orientation. Green, low-carbon, and circular development represents an important objective of and pathway to China's socialist modernization. It embodies the core content of developing ecological civilization and the responsibility of a major country to protect the Earth's ecological security for the common interests of all humankind. Therefore, it is necessary to conduct

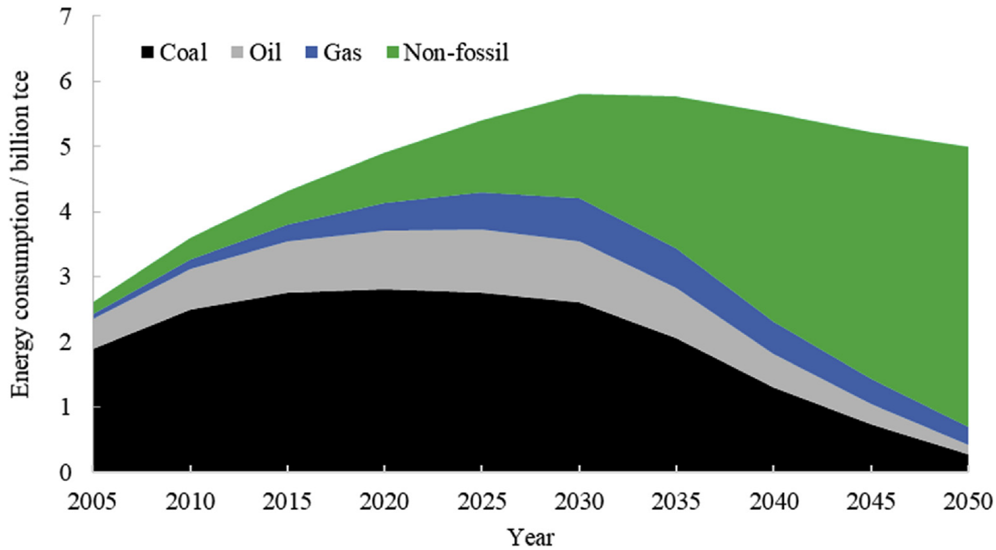


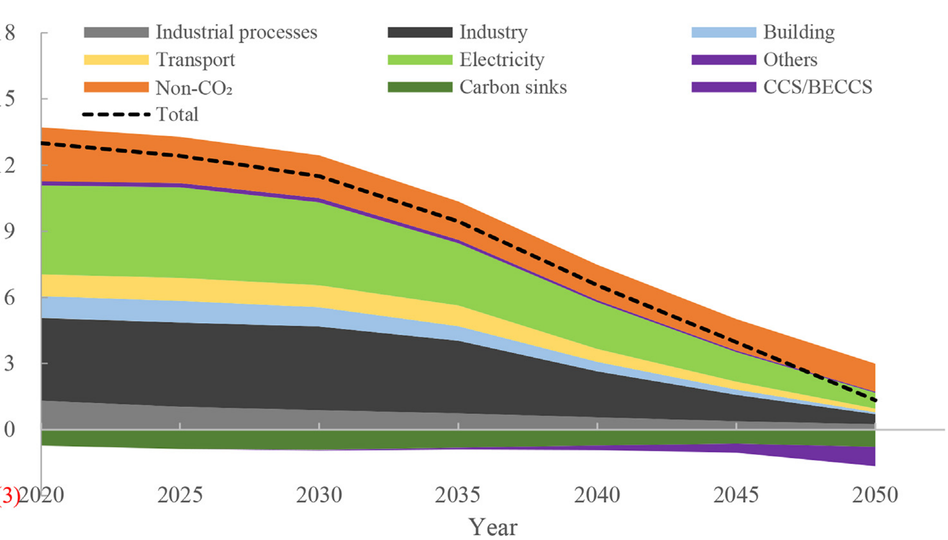
Fig. 35. Primary energy consumption and composition in 1.5 °C target path.

Table 20
GHG emissions in 1.5 °C target path (unit: $GtCO_2e$).

	2020	2030	2050
CO_2 emissions from energy consumption	10.03	10.31	1.47
CO_2 emissions from industrial processes	1.32	0.88	0.25
Non-CO_2 GHG emissions	2.44	2.65	1.27
Forest carbon sinks	−0.72	−0.91	−0.78
CCS+BECCS	0.0	−0.03	−0.88
Net emissions	13.07	12.90	1.33

overall planning and advancement toward the goals of keeping global warming well below 2 °C and building a strong modern country by 2050. First, the NDC implementation and enhancement to 2030 should be incorporated into the strategic planning and key tasks of the first stage of building a modern socialist country. Actions and measures should be implemented to fundamentally improve domestic environmental quality and fulfill international emission reduction commitments, known as "double attainments," which would drive high-quality economic development. Second, the economy-wide deep reduction of all GHG emissions by 2050 should be reflected in the overall goal and strategies of the second stage. In developing China, a green, low-carbon, and circular industrial system with a near-zero-emission energy system dominated by new energy and renewable energy should be fostered. Energy and resource efficiency should be raised to an internationally advanced level. A major national strategy is addressing climate change. Low-carbon, climate-resilient development advocated by the Paris Agreement represents a critical strategic choice for China to follow and lead global trends in energy reform and economic transition, and in so doing, it could sharpen its competitive edges in economic, trade, and technological fields as well as improve its international influence and competitiveness. Governments and leaders at all levels should enhance the sense of responsibility, mission, and urgency in coping with climate change, aim to achieve consensus and understanding, and scale up efforts.

(2) **China should uphold a new vision for development and promote industrial restructuring for a transition to a green, low-carbon, and circular economy.** China must stick to the path of a new type of industrialization, improve the economic structure, promote industrial transformation and upgrading, promote high-tech industries and advanced manufacturing, develop the digital



(3)

Fig. 36. GHG emissions and their composition in the 1.5 °C target path.

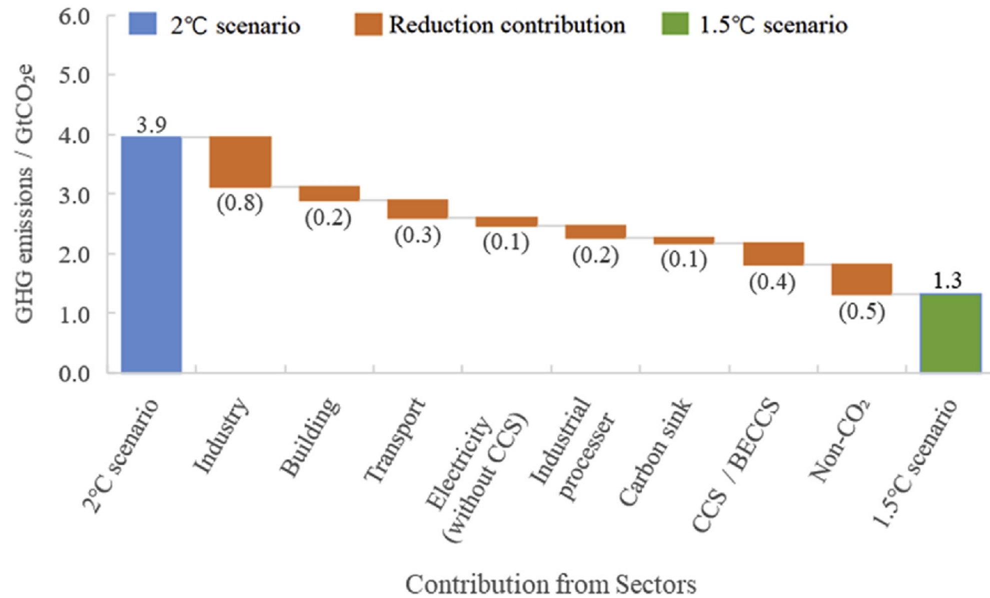


Fig. 37. Emission reductions by sector in the transition from 2 °C target path to 1.5 °C target path in 2050.

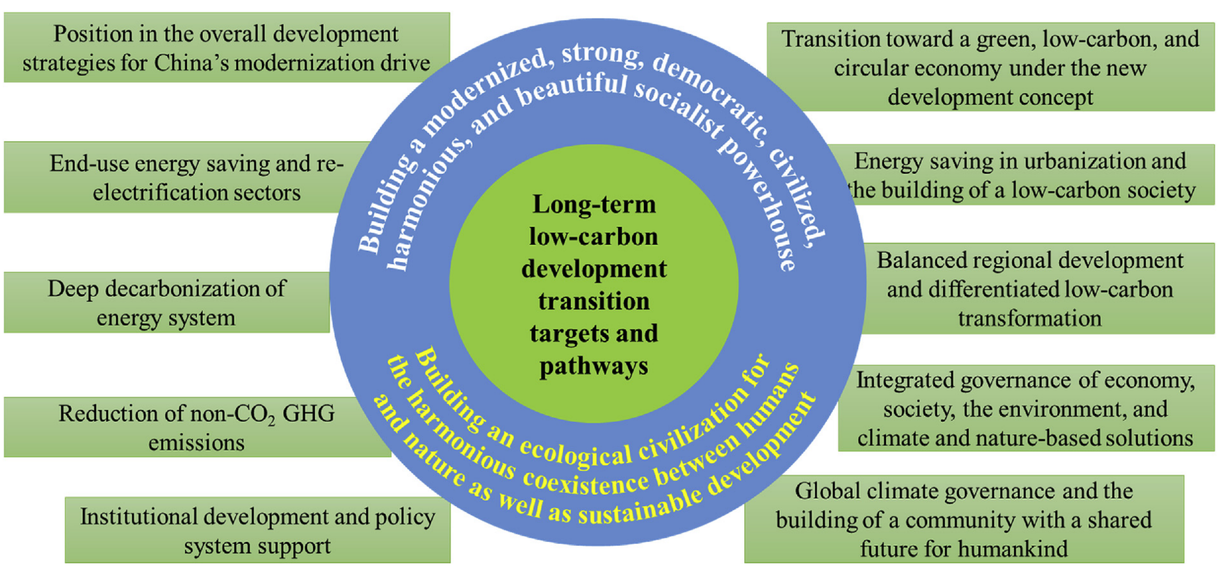


Fig. 38. Strategic framework for long-term low-carbon transition.

economy, strictly limit the expansion of energy-intensive and high-emission industries, eliminate backward production capacity, reduce the proportion of heavy and chemical industries, and increase the value-added rate of manufactured products. At present, structural measures associated with industrial and product restructuring contributes about two-thirds of the decline in energy intensity, while technical measures, such as energy efficiency improvement, contribute one-third. Structural energy conservation through the economic growth mode change and industrial transformation and upgrading will continue to play an important part in reducing energy intensity and improving energy efficiency and output for a long time to come. At the same time, China must develop a circular economy that uses resources more efficiently. China currently lags far behind developed countries in material resource efficiency. The country is targeting a multiplication of resources utilization efficiency in 2035 with the aim of reaching the world's advanced level in 2050. Resource saving and recycling will be instrumental in protecting the ecological environment and trimming energy consumption and CO_2 emissions. In addition, the structure of export products in foreign trade will be changed to cut embodied energy consumption and CO_2 emissions, by raising the proportion of services and prioritizing manufactured products at the high end of the value chain. In 2018, the CO_2 emissions embodied in exports accounted for approximately 15.3% of China's total emissions. The proportion of net embodied CO_2 emissions still reached 10.5% after offsetting those embodied in imports and exports. Given this, a decline in net transfer of energy and carbon emissions embodied in import and export trade will be crucial for reducing CO_2 emissions and achieving low-carbon transition in China. In summary, staying committed to the new vision of development characterized by innovation-driven green growth, and building a green, low-carbon, and circular industrial system are the fundamental measures and the only way to improve energy and resource efficiency and to reduce CO_2 emissions.

(3) **China should strengthen energy conservation and efficiency improvement of end-use sectors, as well as accelerate the substitution of electricity and hydrogen for direct combustion and utilization of fossil energy.** China should push for an energy consumption revolution by strengthening energy use management and energy efficiency improvement in the industrial, building, transportation, and other end-use sectors. The industrial sector should strengthen technological upgrades to eliminate backward production capacity, promote advanced energy-saving technologies, and consolidate energy-saving technology standards with energy use cap and CO_2 emission quota systems. Industrial parks operating as a circular economy should be developed to promote energy and materials saving in the industrial chain. The building sector should apply advanced energy efficiency standards, speed up energy saving and metered heating renovation of existing buildings, and implement an energy use quota system for public buildings. The transportation sector should optimize the structure and modes of transport, raise fuel consumption standards, and improve transportation efficiency. Increasing the proportion of green travel in public transport could effectively reduce energy demand in transport. In the 2 °C scenario, the total final energy demand for the industrial, construction, and transportation sectors will be reduced by 20% by 2050 compared with 2020. At the same time, China will scale up the substitution of electricity for direct consumption of fossil energy. The industrial sector should push forward re-electrification by accelerating the replacement of fossil energy in manufacturing processes. The building sector should expand the use of electricity for heat supply and heating through the development of distributed renewable energy systems. Electric vehicles should be greatly encouraged, while fuel-powered vehicles should be restricted and gradually phased out. By increasing the proportion of electricity in the final energy consumption, fossil energy consumption and CO_2 emissions would be substantially curtailed. The proportion of electricity in the final energy consumption was about 23% in 2018, and is projected to rise to more than 55% in 2050 under the 2 °C scenario and to 70% under the 1.5 °C scenario. China should also promote the application of hydrogen in the production of steel and chemical raw materials, and achieve breakthroughs in innovative low-carbon technologies. The large-scale application of hydrogen fuel cells in buildings and homes, as well as the large-scale application of fuel cell vehicles, would constitute important contributions to in-depth emission reduction of "hard to abate" sectors and fields. Developing a circular economy with higher resource efficiency is an important strategic choice for achieving a low-carbon transition. Resource reduction, reuse, and recycling would enable access to large numbers of higher value-added and more sustainable products and services with less resource consumption and fewer emissions to the environment. China is striving to multiply the productivity of major resources by 2035 and to reach the world's most advanced level in resource efficiency by 2050.

(4) **China should speed up the decarbonization of its energy mix and ensure clean, safe, and economical energy supply.** A low-carbon energy mix is a key measure to reduce CO_2 emissions without undermining energy supply. It is necessary to build an energy system that mainly consists of new energy and renewable energy for sustainable deep decarbonization, and to integrate large-scale renewable energy into the power system. Under the 2 °C scenario, non-fossil energy will account for approximately 25% of primary energy consumption in 2030 and over 70% in 2050. And the electricity from non-fossil fuel will account for nearly 90% of total electricity production. Under the 1.5 °C scenario, the process of decarbonization of the energy system will accelerate further, with net-zero emissions in the energy system achieved in 2050, a share of non-fossil fuel in primary energy consumption of more than 85%, and a share of electricity from non-fossil fuels of more than 90% of total electricity production. At the same time, China should develop energy storage, hydrogen energy, smart grid, and CCS and BECCS technologies, and aim to build a near-zero-emissions energy system dominated by new and renewable energy by 2050. Doing so would control and reduce conventional pollution from the source, which is essential for fundamental improvement of environmental quality and compliance with air quality standards. In addition, replacing oil and natural gas imports with local renewable resources offers a basic way to ensure energy supply security and to develop advanced energy technologies and international competitiveness of industries.

(5) **China should push forward the reduction of non-CO_2 GHG emissions, and take measures to reduce economy-wide GHG emissions.** China's current NDC targets mainly focus on CO_2 emissions from energy activities. The Paris Agreement requires developing countries to move toward economy-wide GHG emission reduction or limitation targets taking into account different national circumstances. Non-CO_2 GHGs accounted for about 16% of China's total GHG emissions in 2014, of which CH_4 accounted for 56%. Therefore, China must gradually incorporate non-CO_2 GHGs into NDC targets and action plans, set up a corresponding MRV system, and implement economy-wide GHG mitigation measures. As the costs of initial emission reduction are relatively low, it is possible for non-CO_2 GHG emissions to peak simultaneously with CO_2 emissions by 2030, and the peak non-CO_2 GHG emissions could be controlled below 2.8 billion tCO_2e. However, the marginal costs for achieving deep decarbonization would increase steeply. By 2050, with a substantial reduction of CO_2 emissions in the energy system, non-CO_2 GHGs will take up a larger portion of total GHG emissions, and become a difficult and key area for deep decarbonization. Under the 2 °C target path, non-CO_2 GHG emissions will decrease more than 40% compared to the reinforced policy scenario in 2050, and under the 1.5 °C target path, by about 60%. At present, China should explore a long-term deep decarbonization strategy for non-CO_2 GHGs, and strengthen the R&D and application of ground-breaking technologies, with a view to achieve economy-wide net-zero GHG emissions and carbon neutrality as soon as possible.

(6) **China should attach importance to urban energy conservation to drive the change of consumption patterns and the construction of a low-carbon society.** Urbanization requires coordination in many aspects, such as urban layout, infrastructure construction, transportation mode, building structure and energy efficiency standards, as well as energy supply and consumption patterns. Urban energy conservation should be combined with the construction of smart cities to optimize resource allocation and improve efficiency, so as to develop smart low-carbon cities. At the same time, the public should be encouraged to establish diligent and thrifty consumption patterns and civilized and simple lifestyles, which would help to build a low-carbon society. Media coverage and information dissemination should be improved to enhance public awareness of climate change and encourage extensive engagement and active action by the public and grassroots groups. Such change in consumption patterns would trigger adjustments of production patterns and product mix. They would provide important guidance for reducing the energy demands of the whole society and achieving the goal of deep decarbonization.

(7) **China should promote coordinated and balanced regional development and a differentiated low-carbon transition in line with local conditions.** In China's vast territory, there are large regional development disparities and big differences in natural resource endowments. In this context, China has different strategic positioning and industrial layout for different regions. A differentiated and inclusive low-carbon transition should be promoted taking into account local characteristics. The more

developed provinces and cities in the eastern coastal areas should strictly control fossil energy consumption, their CO_2 emissions should peak, and they should achieve near-zero emissions by the mid-century. Taking advantage of their abundant renewable energy resources, the central and western regions should take steps toward a low-carbon transition while supplying renewable power at large scale to the central and eastern regions. The southwestern regions, which possess rich renewable energy resources, should take the lead in establishing demonstration cities committed to 100% renewable energy, while some provinces and cities should take the lead in ensuring that CO_2 emissions peak. The old industrial bases and resource-based cities in northeast China should speed up green and low-carbon industrial transition. Key ecological function areas should delineate ecological red lines, restrict the development of energy-intensive and high-carbon projects, and establish an exit mechanism for incompatible industries. Low-carbon industries could be developed according to local conditions to realize inclusive low-carbon transition. In terms of industrial layout, energy-intensive heavy and chemical industries and electricity-consuming infrastructure, such as data centers, could be deployed to priority areas rich in renewable energy resources in the northwest and southwest to facilitate local consumption of renewable power. Special attention should be paid to the needs of poor groups in marginal rural areas for better production and living conditions as well as clean and high-quality energy supply. Distributed renewable energy should be deployed according to local conditions. In addition, China should include certified emission reductions as an offset mechanism in national or provincial carbon markets to promote the sustainable development of impoverished areas.

(8) **China should harmonize measures for economic development, environmental protection, climate change, and biodiversity improvement and it should implement nature-based solutions.** In line with the law of nature, nature-based solutions should be adopted to enhance the service functions and climate resilience of ecosystems through protection, restoration, improvement, and upgraded management. The carbon storage capacity of forests, grasslands, wetlands, and agricultural land should be enhanced, so as to increase carbon sinks while reducing carbon sources. This would bring synergistic effects, such as new economic growth and job opportunities, water, soil and air quality improvement, food safety improvement, and biodiversity conservation. Such efforts are guided by the vision of ecological civilization that prioritizes ecology and promotes harmony between humans and nature. Nature-based solutions respect the environment, rely on the enhancement of natural ecosystems, and offer an important way to tackle the global climate crisis and promote coordinated governance and sustainable development of the economy, society, environment, and climate change. The implementation of these measures should be guided by Chinese President Xi's' thought on ecological civilization and placed within the framework of system construction for ecological civilization, so as to achieve multiple targets, such as ecological protection and climate change and biodiversity conservation while improving the functions of natural ecosystems. To this end, climate change adaptation and mitigation should be integrated into various policies for resource conservation and environmental protection, to support comprehensive management of ecosystems, including mountains, rivers, forests, farmlands, lakes, and grasslands. A variety of ecological projects should be implemented for carbon source reduction and sequestration, such as afforestation, protection of natural forests, return of farmlands to forests and grasslands, sheltered forest system construction, comprehensive control of desertification, and water and soil conservation. Nature-based solutions are of great significance for achieving carbon neutrality in the future. By 2050, China's agroforestry carbon sinks are expected to increase by about 700 million tCO_2e annually, which would significantly offset the remaining emissions in "hard to abate" sectors, such as industrial processes and land use, land-use change and forestry.

(9) **China should improve the institutional arrangement for addressing climate change and form a policy system, investment and financing mechanism, and market system that ensure long-term low-carbon development.** The institutional framework for addressing climate change is an important part of the system for developing an ecological civilization. First, laws on climate change should be established to ensure, in legislative form, the realization of long-term strategic goals and measures to deal with climate change. It is also necessary to strengthen and improve the policy system that supports long-term low-carbon development. The government should scale up financial support and tax incentives, and establish an investment and financing mechanism that favors a low-carbon transition. The investment of enterprises, the financial sector, and private capital should be guided by green investment project guidelines, green credit mechanism, green asset-backed securities and green bonds, and green credit incentive and guarantee mechanisms. To advance and improve a unified national carbon market, the coverage of industries should be gradually expanded, and the proportion of auctions in allowances should be raised. Thus, regulatory measures are combined with market mechanisms to ensure the realization of national emission reduction targets. At the same time, China must foster a technological innovation system that facilitates substantial emission reduction, press ahead with innovation and industrialization of advanced low-carbon technologies, and make forward-looking arrangements for the development and demonstration of strategic technologies for long-term deep decarbonization in "hard to abate" sectors. Doing so would create sound institutional, policy, and market environments for China's long-term low-carbon development and transition.

(10) **China should promote global climate governance and international cooperation, and advance the construction of a global ecological civilization and community with a shared future for humankind.** Taking a driving seat in international cooperation to tackle climate change, China has become an important participant, contributor, and torchbearer in the global endeavor for global ecological civilization. Guided by Xi's thoughts on global ecological civilization and a community with a shared future for humankind, China should stay committed to the construction of a global governance system that is fair, equitable, and provides win–win solutions through cooperation, and that promotes the full, balanced, and effective implementation of the Paris Agreement in accordance with the principles of the UNFCCC. China's successful practices of energy reform and economic transition toward green, low-carbon, circular, and high-quality development would provide the world, especially developing countries, with lessons and solutions. China should actively promote international cooperation on climate change, especially South–South cooperation in the Belt and Road Initiative. This would enhance policy guidance for a low-carbon transition, and improve green investment and financing as well as low-carbon technology transfer to green the Belt and Road Initiative. At the same time, China should encourage exchange and cooperation with developed countries at the national, local, and city levels, as well as among enterprises, non-governmental organizations, and research institutions. China is striving to be a pioneer in tackling climate change and a successful example of building a community with a shared future for humankind.

12. Global climate governance and international cooperation

The UNFCCC, the most basic and fundamental legal document for global climate governance, set the goals and principles for the world to tackle climate change. The Paris Agreement follows these goals and principles in the UNFCCC and determines detailed goals and schemes for the world to address climate change after 2020, a new milestone in the global fight against climate change. As the world enters the phase of comprehensive implementation of the Paris Agreement, the principles set by the UNFCCC and reaffirmed in the Paris Agreement, namely, the principles of equity and common but differentiated responsibilities, respective capabilities, and consideration for specific needs and special circumstances of different countries, should be upheld to promote implementation of all elements of the Paris Agreement in a comprehensive, balanced, and effective manner. In these efforts, China will continue to play an active leading role.

The coronavirus pandemic is a public crisis facing the globe at present that will profoundly affect and reshape world political, economic, and trade patterns and aggravate turbulence; the changes are profound and have not occurred for a century. Global climate change is a long-term ecological crisis for the Earth that the entire world faces. It is the largest threat to the survival and development of humankind. After the pandemic, the process of world cooperation in combating climate change will face great uncertainties and will definitely become the most important and pressing issue of general concern within the international community. The priority of countries in tackling economic recession against the backdrop of the current pandemic is to help companies, safeguard people's livelihood, and address weak links in the industrial chain. For economic recovery after the pandemic, major world powers will attach more importance to safeguarding national economic security, developing emerging industries, and finding new growth points, and leading the strategic trends of world economic reforms. The previous prioritized position of addressing climate change and low-carbon transformation will be affected. However, the international community has been ardently advocating a green economic recovery. UN Secretary-General Guterres has publicly appealed for climate actions to be stressed in economic recovery measures and that we should do things right for the future. He said that countries should join hands for higher-quality recovery and work together to respond to the deeper crisis of climate change. Transnational corporations and various business and financial sectors are also studying measures for green economic recovery and seeking business opportunities in this regard. Although the actions and intensity of the world's tackling of climate change and low-carbon transformation may abate at present and in the short run, the long-term trend will not change, and will become even more pressing. The international community has already achieved universal consensus to facilitate the post-pandemic realization of a green recovery and low-carbon transition, and the fight against climate change and a green, low-carbon transition is set to become the predominating path of economic reform and development after the pandemic.

The Paris Agreement has set the climate change objective of holding the global average temperature increase to below 2 °C and even below 1.5 °C. It is urgent for emission reduction paths to be achieved; limiting global warming within 2 °C requires global net-zero emissions of GHGs during the second half of the century (around 2060–2070), that is, carbon neutrality. The ultimate objective of keeping the average temperature increase below 1.5 °C demands that the world realizes carbon neutrality in the middle of the century (around 2050). In current climate negotiations, developed countries, such as the those constituting the EU, have strongly endorsed the 1.5 °C mitigation goal and in the EU Green Deal, proposed the goal of net-zero emissions by 2050. Up to now, over 120 countries have set the goal or vision of achieving carbon neutrality by 2050, including some developing countries, such as Chile and Ethiopia, some small island countries, and even some least developed countries. In addition, many countries and cities have set the aim of achieving 100% renewable energy within the 2030–2050 period, and have proposed timetables for phasing out coal, coal power, and fossil fuel vehicles. Willingness to take actions for deep decarbonization around the world during and after the pandemic may weaken during the short term, but the situation and trend of low-carbon transformation for energy and the economy will only become more pressing in the long term.

The EU Green Deal aims to build Europe into a prosperous, modern, carbon-neutral, and economically competitive continent by 2050. It is also the long-term strategic deployment of the EU to coordinate its own prosperous development and response to climate change, and the strategic choice to improve its economic competitiveness and international leadership in the world, so that Europe can establish a role as a leader in economic transformation and global governance. While implementing enhanced reduction measures, the EU has also proposed a border carbon adjustment mechanism to protect the competitiveness of local companies, and plans to impose carbon tariffs on certain industries or products, or force them to purchase EU carbon quotas. Such unilateralism does not accord with the principles of the UNFCCC, nor does it conform to the emission reduction mechanism under the Paris Agreement. This behavior amounts to a transfer of emission reduction responsibilities and costs to other countries, especially developing countries, which would only cause new trade disputes and exacerbate unrest during the profound changes of the transition. It would add more uncertainties to global economic development and trade, and disrupt the cooperation process under the Paris Agreement of countries in the world.

The target of restricting global warming to below 2 °C and preferably to below 1.5 °C in the Paris Agreement is the political consensus and common vision reached by governments based on the scientific evaluation of the IPCC, and is a hard-won achievement from protracted climate negotiations. Now in the stage of comprehensive implementation of the Paris Agreement, the key lies in enhanced practical actions of the parties to promote full, balanced, and effective implementation of all clauses of the Paris Agreement. Meanwhile, the overall realization of global net-zero emissions does not mean that all countries can achieve this goal at the same time synchronously. Developed countries should take the lead in reaching net-zero emissions early, and then vigorously develop carbon sink technologies and technologies to recover CO_2 from the atmosphere. By achieving large quantities of negative emissions, these countries could help to achieve more equitable sustainable development by leaving space for developing countries to emit CO_2 and time for them to transform their economies. Emerging developing powers, including China, would generally take more time to achieve carbon neutrality than developed countries.

China advocates a new form of global governance featuring mutual respect, fairness, justice, and win–win cooperation. Addressing climate change as an opportunity for the sustainable development of countries could promote mutually beneficial cooperation and common development of all parties. This would help to extend the areas and space that countries are willing to cooperate in, expand shared interests, turn climate negotiations from a zero-sum game to win–win cooperation, and promote the development of a human community of common destiny. China has demonstrated a new leadership and guiding role in climate governance philosophy and cooperation models, which is different to that of the US and European countries, and is gaining increasing recognition worldwide.

The basic divide between the developing and the developed camps in climate negotiations will continue for a long time. In the current negotiations, developed countries have become increasingly open about their intent and actions to weaken the principle of common but differentiated responsibilities. They have given mitigation undue emphasis, while ignored comprehensive, balanced, and effective implementation of other factors in the Paris Agreement, such as adaptation, capital, technology, and capacity building. The Paris Agreement and negotiations for its implementation rules have been undermined by the lack of consideration for the interests and demands of developing countries and the absence of constructiveness and flexibility in negotiations, together with the tendency toward unilateralism and protectionism of some developed countries. China, always insistent on the strategic positioning of developing countries, has been safeguarding and expanding strategic backing and internal solidarity of developing countries, and upholding proper appeals of developing countries and their right to realize fair sustainable development. Meanwhile, China has strengthened communication and consultation with developed countries and has become an active participant, contributor, and torchbearer in the global fight against climate change. In the complicated international relations era after the pandemic, China must consolidate and strengthen its role as a leader for the common benefit of all humanity. First, China should cooperate with India and other emerging powers and like-minded developing countries to adhere to the principle of common but differentiated responsibilities, and for practical cooperation and common actions with countries and blocs of different types and in different development phases. Second, China needs to enhance the domestic policy orientation of green, low-carbon, and circular development and strengthen measures and actions against climate change, so that the NDCs for 2030 can be implemented and enhanced. This would boost China's status as a large power that actively shoulders its international responsibilities. Such an initiative would help to foster a positive image for China. In the long run, while realizing the goal of building the nation as a great modern socialist country by the middle of the century, China should also realize deep decarbonization pathways fitted to the 2 °C global warming limit goal, which would enable it to follow and lead reform trends in world energy and economic low carbonization. By doing so, China would make new contributions to global ecological safety and human progress, and boost its international competitiveness and influence.

The global fight against climate change has promoted low-carbon transformation of energy and economies around the world. Chinese President Xi's thoughts on ecological civilization play an important guiding role for China in the realization of global low-carbon development transformation. China has long prioritized the concept and practice of ecology alongside green, low-carbon, and circular development, and offers Chinese insights and approaches to global low-carbon development transformation. China has been proactively promoting international cooperation on climate change, especially South–South cooperation in the Belt and Road Initiative. By promoting inclusiveness and mutual learning with countries along the Belt and Road, China hopes to embark on a climate-friendly low-carbon economic development path together with these countries. In summary, Xi's thoughts on ecological civilization and the concept of a community with a shared future for humankind should be the guiding philosophy for China in promoting and leading global climate governance and cooperation process.

13. Conclusions and policy recommendations

Based on the analysis of this study, we provide the following recommendations for China's formulation of goals and pathways for its long-term low-carbon development strategies.

(1) **China should formulate and implement long-term low-carbon development strategies, as it follows global trends in social and economic reforms.** Global climate change is the greatest threat facing the sustainable development of human society at present. Protecting the ecological safety of the Earth and cooperating to handle the challenge of climate change has become the universal consensus of the international community. The key to addressing climate change is to mitigate anthropogenic GHG emissions, mainly CO_2 from the consumption of fossil fuels. This has driven revolutionary reforms of energy systems and the low-carbon transformation of economic development patterns around the world. Advanced energy and deep decarbonization technologies have become hotspots in the world's scientific and technological innovations. Furthermore, the advanced technologies over which big powers would certainly compete for capabilities in energy and economic low-carbon transformation have become a reflection of a country's economic, trade, and technological competitiveness. The establishment and formation of a clean, low-carbon, safe, and efficient energy system and a green, low-carbon, and circular economic system have become an important feature of modern energy and economic systems. The goals, scenarios, and implementation paths of China's mid- and long-term low-carbon development must, on the one hand, be based on the country's national conditions, capabilities, and modernization process with a view to ensuring the realization of China's goals for socialist modernization in the new era, and on the other hand, be oriented toward the long-term emission reduction goal of controlling global warming below 2 °C and pursing effort to 1.5 °C set in the Paris Agreement. Doing so would enable China to undertake its international responsibilities and contributions for the ecological safety of the Earth and the common cause of humankind in tandem with its growing composite national strength and international influence. Meanwhile, developed countries must show differentiated responsibilities and processes. These goals and visions could be achieved through long-term hard efforts and would allow China to build a good image in the international community and boost its competitiveness and influence.

(2) **The long-term low-carbon development strategy is a goal-oriented comprehensive development strategy.** With development as its core, the strategy can, while ensuring sustainable economic and social development, allow China to transition to green, low-carbon, circular, and sustainable development and achieve harmony between people and nature. Therefore, China's long-term low-carbon development strategies should follow deep decarbonization pathways fitted to the goals of limiting global warming to a 2 °C increase and even 1.5 °C. The long-term low-carbon transformation development strategies are oriented toward both the goal of building a great socialist country and the long-term goal of global emission reduction in tackling climate change. Goals and visions for economic development, social fairness and prosperity, conservation and efficient utilization of resources, environmental protection, addressing climate change, and all other aspects should be coordinated comprehensively for synergistic and integrated governance. By doing so, these strategies would become an important part of the overall goals and strategies of China's socialist modernization in the new era, and be incorporated into overall development strategies and deployment. China's domestic and international imperatives can be coordinated to rejuvenate the Chinese nation, while enabling China to contribute in new ways to global ecological civilization and to building a community with a shared future for humankind.

(3) **The mid- and long-term low-carbon development strategies must achieve coordination of the "two stages."** The 19th National Congress of the Communist Party of the People's Republic of China put forward goals and basic policies for realizing socialist modernization in the new era. It comprehensively analyzed international and domestic situations and China's development conditions, and made arrangements and deployments for the two stages. In the first stage of 2020–2035, to realize socialist modernization, China needs to reach the goal of a fundamental improvement in the domestic ecologic environment as well as its international emission reduction commitments. High-quality economic and social development must be promoted, while technological and industrial bases, policy support, and market environment must be provided for the realization of deep decarbonization in 2050. In the second stage of 2035–2050, on the path to building a great socialist modern and beautiful China, goal orientation under the emission reduction pathways for the 2 °C global warming limit should be stressed while China should take the initiative in assuming international responsibilities consistent with its ever-increasing composite national strength and international influence. From the viewpoints of improving international competitiveness, influence, and leadership in low-carbon transformation, China should strengthen efforts in emission reduction

and achieve the deep decarbonization goals of near-zero emissions by 2050. This would help China to be a great socialist modern country of world-leading comprehensive national strength and international influence and become a torchbearer.

(4) **The goals and transition pathways for long-term low-carbon development strategies in 2050 should be clarified.** The deep emission reduction pathways for achieving the 2 °C target path by 2050 requires the realization of near-zero CO_2 emissions. Net CO_2 emissions need to be reduced to about 2 billion tons, which is equivalent to a world average of 1–1.5 tons of per capita emissions by then and about an 80% reduction compared to peak CO_2 emissions in around 2030. Non-carbon-dioxide GHG emissions would also peak together with CO_2 emissions. Emission reduction efforts should be continuously strengthened. By 2050, all GHG emissions should be reduced by 70% from their peak emissions. Total energy consumption should also peak in around 2035. By 2050, non-fossil fuels should account for more than 70% of primary energy consumption, and non-fossil fuel power for about 90% of total power generation, basically forming a near-zero carbon emission energy system mainly featuring new energy and renewable energy. The safety of energy supply is fundamentally guaranteed, and the discharge of conventional pollutants is controlled from the source. Total GDP in 2050 will increase by more than 10 times compared with 2005. Energy intensity per unit of GDP will be over 80% lower than 2005, and CO_2 intensity over 95%, realizing the decoupling of sustainable economic and social development from CO_2 emissions. To achieve the 1.5 °C target path, the world needs to achieve net-zero CO_2 emissions by 2050 and deep reduction of other GHGs. Based on this goal, China further needs to strengthen and facilitate emission reduction of all GHGs on an economic scale. By 2050, net-zero CO_2 emissions should be reached, and all GHG emissions should be reduced by about 90%. After 2050, China needs to strengthen emission reduction of non-carbon-dioxide GHGs and increase carbon sinks. BECCS, CDR, and other negative emission measures must be taken to achieve net-zero emissions of all GHGs at the earliest time possible. This would require more arduous efforts and larger-scale investments, and incur greater costs.

(5) **Implement and strengthen NDCs for 2030.** Since China began to adopt its national strategy for addressing climate change, it has made significant progress in energy conservation and carbon emission reduction. The self-imposed external reduction targets pledged for 2020 have been achieved ahead of schedule and even exceeded, laying the foundation for the implementation and strengthening of the NDCs for 2030. China is aiming to work toward the goals for the first stage of modernization by 2035, namely, the basic realization of modernization. If we assume that China's GDP will double over the next 15 years, and per capita GDP is USD 20,000 in real terms, then the average annual GDP growth rate in the next 15 years is expected to be about 4.8%. Average annual GDP growth during the 14th Five-Year Plan period may slow down compared with that of the 13th Five-Year Plan period, but is still expected to exceed 5%. The average annual GDP growth rate from 2020 to 2030 will remain at about 5%, and energy intensity per unit of GDP will continue to decrease at a relatively high rate of 14–15%. Total energy consumption in 2030 can be controlled below 6 billion tons of coal equivalent, ensuring sustained economic growth while achieving the goal of total energy consumption control set in the Energy Production and Consumption Revolution Strategy (2016–2030). New energy and renewable energy will continue to grow rapidly. While meeting the growing total energy demand, the development potential of renewable energy will be further released, and its proportion will rise significantly, reaching about 25% in 2030. The proportion of primary energy in power generation will be raised from the current 45% to about 50%, which is in line with the 50% target of non-fossil fuel power in total power demand for 2030 defined in the Energy Production and Consumption Revolution Strategy (2016–2030). This has the dual effect of energy saving and energy substitution. By 2030, CO_2 emissions per unit of GDP could drop by 65–70% from the 2005 level. Installed capacity of hydropower, wind power, and solar power by then will reach about 500 million kilowatts respectively, becoming new economic growth points and creating new fields of employment. Based on this, CO_2 emissions are calculated to enter the peak plateau by 2025 and reach a stable peak before 2030. According to National Plan for Major Ecosystem Conservation and Restoration (2021–2035), forest stock volume will reach 21 billion m^3 by 2030, an increase of 5.5–6 billion m^3 over that of 2005. All items in the NDC target for 2030 have the potential and possibility to be achieved ahead of schedule and to be exceeded. The 2030 NDC targets should be further enhanced and updated, which would strongly guide the post-epidemic economic green recovery and high-quality development, respond to the concerns of the international community, and lead the process of global climate governance cooperation.

(6) **China's goals and policy measures for addressing climate change should be strengthened in the 14th Five-Year Plan.** China is the first country in the world to have contained the COVID-19 pandemic and achieved economic recovery. The global spotlight is on how to reflect the concept of green and low-carbon development in the 14th Five-Year Plan and how to strengthen indexes and policy orientation for energy-saving and carbon reduction. They are also expected to become the "weathervane" for the world's realization of post-pandemic high-quality, sustainable, and green recovery. Under the expectation that the average annual GDP growth rate will continue to exceed 5% during the 14th Five-Year Plan, the drop of energy intensity per unit of GDP could be maintained at 14–15%, while total energy consumption at the end of the period could be controlled to within 5.5 billion tons of coal equivalent. Currently, wind power, solar power, and other renewable energy sources are competitive with coal power in terms of generation costs, and in the 14th Five-Year Plan period, annual non-fossil fuel growth can be maintained at about 7%, the average growth rate during the 13th Five-Year Plan period. There is great potential for the development of corresponding energy storage systems and smart grids. By 2025, non-fossil fuels will account for 20% of primary energy. With the rapid development of new energy and renewable energy, new power demand during the 14th Five-Year Plan can be met mainly by increasing power supply from non-fossil fuels to effectively curb the rebound of coal power supply and coal consumption. Except for the needs of improving weak links in specific cases, such as peak load regulation and regional heat supply, newly built coal power stations must be strictly controlled during the 14th Five-Year Plan. The dual effect of energy saving and energy substitution could help to reduce CO_2 intensity per unit of GDP by 19–20%, and the total CO_2 emissions by the end of the period will be less than 10.5 billion tons.

The 14th Five-Year Plan should continue the energy-saving and CO_2 emission reduction indexes of the 12th and 13th Five-Year Plans. In particular, the binding indexes for the reduction of CO_2 intensity per unit of GDP should still be included and stressed, because they are the representative indexes for China to fulfill its self-imposed emission reduction commitments under the Paris Agreement, based on which the country can implement and realize the phased NDC arrangements of a reduction of 60–65% in CO_2 emissions per unit of GDP in 2030 compared to that of 2005. A special plan for addressing climate change during the 14th Five-Year Plan period should also be formulated, clarifying phased goals, main tasks, policies, and actions. China should also carry out regional and industrial CO_2 emission peaking actions, and encourage more developed provinces and cities along the east coast and high energy-consuming and high-carbon emission industries to set goals for early peaking.

(7) **Step up institution building for addressing climate change.** Institution building for addressing climate change is the fundamental guarantee for China to realize its long-term low-carbon emission development strategy, and is also an important part of institution building for ecological civilization. China should establish and form a sound supporting policy system and implementation mechanisms, including laws and regulations, and fiscal, taxation, and financial policies. China should also deepen reforms, improve energy price mechanisms and carbon cap-and-trade systems, and form a technological innovation system that supports low-carbon transformation.

Legislation to address climate change should be enhanced to ensure the implementation of climate change strategies, mechanisms, and policy systems and the realization of long-term emission reduction goals in legal form. Fiscal, taxation, and financial policy systems that support long-term low-carbon development should be strengthened and improved, and governments should increase financial input and tax incentives to form investment and financing mechanisms that support low-carbon transformation. Construction of a national carbon emission trading market should be accelerated so that market mechanisms can play a fundamental role in advancing low-carbon transformation of energy and the economy. By combining market mechanisms with regulatory government measures, China can achieve national emission reduction targets, yielding an effective institutional tool for hedging and countering border adjustment measures of developed countries. We should continue to deepen reforms and strengthen the government's leading role in implementing low-carbon transformation development strategies. A target-oriented accountability system for energy savings and carbon reduction should be implemented among all levels of governments, and energy-saving and carbon reduction indexes should be included in national and local five-year plans. China needs to place more efforts in building institutions and policy support systems for technological innovation and advanced technology industrialization. Scientific and technological innovation systems should be adopted to support R&D and the industrialized development of advanced technologies and to place advanced technologies and industries in a leading position with competitive advantages.

(8) **China should take a proactive role in responding to the new situation of global climate governance after the COVID-19 pandemic.** The world economy has been hit hard by the coronavirus pandemic, after which the US has been trying to lead the reconstruction of the world economic order. Coping with climate change would be an important area of competition among major powers. China has already exhibited increasing influence and coordination capabilities in the field of climate change, and the international community also expects China to further assume a leadership and play a “bridging” role. While China–US relations continue to deteriorate, there are still opportunities for negotiating and cooperating with the US in the field of climate change. Actively participating in and advancing global climate governance would help consolidate the strategic backing of developing countries. China should continue along the path of multilateralism and should expand its diplomatic advantages in the field of climate change, striving to resolve any challenges or pressures. In the complex and uncertain post-pandemic international context, China must actively promote global climate governance and cooperation, and should foster institution building of global climate governance featuring fairness, justice, and win–win cooperation. China should uphold principles of equity, common but differentiated responsibilities, and respective capabilities, and should carry out exchanges and communications with countries and blocs with different national conditions and in different development phases. Comprehensive, balanced, and effective implementation of all factors and clauses in the Paris Agreement, such as mitigation, adaptation, capital, technology, capacity building, and transparency, should be ensured. At the 26th session of the Conference of the Parties (COP 26) to the UNFCCC, China should work hard to promote a conclusion in the negotiations concerning Article 6 of the Paris Agreement and comprehensive adoption of its implementation rules. China should also strengthen South–South cooperation in addressing climate change, and promote practical cooperation actions of the international community, striving to make the field of climate change a pioneering and successful example of Chinese President Xi's thoughts on building global ecological civilization and building a community with a shared future for humankind.

In conclusion, faced with a complex domestic and international situation at present, it is necessary for China to maintain its strategic focus. Following President Xi's instructions to “build a good external image and promote domestic development” in addressing climate change, China needs to coordinate domestic and international aspects, and short-term and long-term aspects. Two documents are due to be submitted to the UNFCCC Secretariat this year, namely, a report on the implementation and update of NDCs for 2030 and a long-term low GHGs emission development strategy by the middle of the century, and the 14th Five-Year Plan is under preparation. In these plans, China will clarify its ambitious goals, policies, and measures for energy-saving and CO_2 emission reduction in different stages. On the domestic front, China will promote industrial transformation and upgrading and high-quality development, and create a coordinated and win–win scenario for economic development, energy security, environmental protection, and addressing climate change. On the international stage, China should consolidate and expand its diplomatic advantages in tackling climate change, respond to the general concerns of the international community, and lessen pressures on other countries to reduce emissions and raise funds, thereby building a reputation as a great power taking responsibility for a shared vision of the world.

Acknowledgment

Thanks for the support of the Special Fund for Global Green Development and Climate Change of Tsinghua University Education Foundation and the Energy Foundation.