How to understand carbon neutrality in the context of climate change? With special reference to China

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ABSTRACT
Understanding the scientific goals and practical processes of carbon neutrality is a hot topic of current interest to both academic and practical communities. A scientific and correct understanding of carbon neutrality is an important prerequisite for mankind to deal with climate change and is of great significance to promote the smooth implementation of carbon neutral related policies. Firstly, this paper describes the scientific connotation and practical significance of carbon neutrality from three aspects: the concept of carbon neutrality, the object of carbon removal, and carbon neutrality in macro and micro perspectives. Then, starting from the current characteristics of global carbon emissions, this paper summarizes the main progress, specific implementation measures, policies, resources, technologies, markets and major problems faced by countries in the current global carbon neutrality process. Finally, this paper describes China’s carbon neutrality goals and roadmap, summarizes the challenges facing China’s carbon neutrality implementation, and proposes key measures to advance the carbon neutrality process in the future. That is to promote the efficient and clean use of coal, accelerate the replacement of clean energy, enhance the role of natural gas as a bridge in the low-carbon transformation, vigorously develop the “green hydrogen” industry and its industrial chain, increase the application and promotion of CO2 burial and storage, develop carbon conversion and forest carbon sinks, and establish a market mechanism to control carbon emissions.

1 Introduction
Climate change is the most serious non-traditional security issue facing the world today, seriously threatening the survival and development of human society (IPCC Climate Change, 2014; IPCC SR1.5, 2018; IPCC SREX, 2012), and there is a large gap between the current international emission reduction commitments and the achievement of the long-term goals set out in the Paris Agreement (Bonoli et al., 2021; Chirico et al., 2019; Madaleno & Moutinho, 2021). Climate change has already altered the geographic distribution, seasonal activity, migration patterns, and biodiversity of many biological species (IPCC Climate Change, 2014). Species in some terrestrial regions are pushing an average of 17 km and 11 m per decade to polar regions and high altitudes, respectively (IPCC SREX, 2012). Climate change causes ocean acidification, which affects marine ecology, such as coral death and damage to fisheries. Climate change has a predominantly negative impact on global food production. Climate change has led to average yield reductions of 1.9% and 1.2% per decade for wheat and maize, respectively (IPCC SR1.5, 2018). Changes in precipitation and melting snow and ice have altered hydrological systems, affecting water quantity and quality and leading to a lack of freshwater resources. About 1/3 of the world’s 200 major rivers have experienced significant reductions in runoff since the mid-20th century (Bonoli et al., 2021). Therefore, if the vision of carbon neutrality is not realized by effectively promoting greenhouse gas emission reduction, the further increase of global warming will lead to a more serious climate crisis (Campos-Seijo, 2020; Chi et al., 2021).

Since 1880, the global average surface temperature has increased by 0.85°C, with two-thirds of that increase occurring since 1975 (Chi et al., 2021). Along with rising surface temperatures, global sea level has risen by 19 cm and polar ice reserves have declined at an accelerated rate, averaging 362 billion tons per year over the past five years (Campos-Seijo, 2020). With the further development of global warming, human society is facing
increasingly severe climate catastrophe risks (Gil & Bernardo, 2020; Schreyer et al., 2020; Yamori & Goltz, 2021). In recent years, the frequency, breadth and depth of climate catastrophes in many regions of the world have been increasing, and the hazards and impacts on socio-economic systems have further increased (Griffiths & Sovacool, 2020). At the same time, the cross-regional nature of climate catastrophes has become increasingly evident, the multi-causal nature and complexity of catastrophes have increased, and the uncertainty and randomness of their occurrence have been enhanced (Kong, 2020; Kong et al., 2018; Shi, 2019). As a result, climate catastrophe risks have caused great damage to natural ecosystems and socio-economic systems (Kong & Sun, 2021).

In particular, climate catastrophes have had many significant impacts on key areas such as regional water resources, food production, habitat, ecology, human health and major projects (Lee et al., 2021; Monjardino et al., 2021; Fa Ubert et al., 2020). If humans do not succeed in controlling the global average temperature rise to 1.5°C, it will bring catastrophic consequences, such as habitat loss, coral extinction, ice cap melting, sea level rise, etc (Abbasi, 2021; IPCC SR1.5, 2018; Tester et al., 2020). Climate catastrophes will also increase further dramatically, which will seriously threaten human survival and development, and will also bring more damage to global economic development (Kawashima et al., 2021). According to a report released by the World Bank in 2015, 100 million people will fall back into poverty by 2030 due to climate impacts if no measures are taken to address climate change (IPCC SR1.5, 2018). Disaster preparedness, infrastructure and adaptive capacity vary greatly from country to country in the face of climate catastrophes (Li et al., 2020). The poorest developing countries and the poor are the greatest victims of climate change and climate catastrophe risks, which also relate to the global sustainable development issues of fighting hunger, fighting poverty and maintaining social stability (Amo & Ganiu, 2020).

In 2018, the United Nations Intergovernmental Panel on Climate Change released the Special Report on Global Warming of 1.5°C, which stated that the global warming is 0.2 ± 0.1°C per decade and has already warmed by 1°C, and according to this trend, the warming will reach 1.5°C in 2030–2052 (IPCC SR1.5, 2018). The serious shortfall in countries’ voluntary contributions and emission reduction commitments is expected to result in a global temperature increase of 2.9–3.4°C by 2100, which will be devastating to human society (Salvia et al., 2021). According to the World Meteorological Organization’s Statement on the State of the Global Climate 2019, the global average temperature for 2019 is 1.1°C above pre-industrial levels, second only to the record high temperatures set in 2016, and the hottest decade on record from 2010 to 2019 (International Monetary Fund. World Economic Outlook, 2020a, 2020b; International Monetary Fund. World Economic Outlook Update, 2020). According to the Emissions Gap Report 2020 released by the United Nations Environment Programme, global greenhouse gas emissions have increased by an average of 1.4% per year since 2010, and global greenhouse gas emissions (including those caused by land use change) are expected to reach a record high of 59.1 billion tons of CO₂ equivalent in 2019, with global temperatures expected to rise by more than 3°C by the end of the 21st century (State Council of China, 2021). By the end of the 21st century, the global temperature is expected to rise by more than 3°C, requiring countries to strengthen climate protection actions (United Nations International Strategy for Disaster Reduction (UNISDR), 2019). The Paris Agreement proposes to limit the global average temperature increase to 2°C by 2100 compared to the industrial era, and to strive to limit the temperature increase to 1.5°C (IPCC SR1.5, 2018). Global greenhouse gas emissions will peak as soon as possible and achieve net zero global emissions by the second half of the 21st century (Kamei et al., 2020). From China’s point of view, the Central Economic Work Conference of the Chinese government in 2020 clearly put forward that the work of carbon peaking and carbon neutrality should be done in 2021, and strive to reach the peak by 2030, and strive to achieve carbon neutrality by 2060. Carbon neutrality is becoming an irreversible global trend (State Council of China, 2021).

In the context of profound development of global climate change, how to comprehensively understand the scientific connotation and practical significance of carbon neutrality? What are the current characteristics of global carbon emissions, the main progress of carbon neutrality and the challenges faced? As the world’s largest emitter of greenhouse gases, how does the Chinese government design a roadmap for achieving carbon neutrality? What efforts should the Chinese government make to achieve the goal of carbon neutrality? These questions are both scientific issues of current academic concerns and policy issues and concrete operational issues of carbon emission reduction for the practical community. This is because the formulation and implementation of carbon neutral policies need to be based on a proper understanding of the meaning of carbon neutrality in the context of current climate change. For China, the implementation of carbon neutrality needs to be based on international experience.
In order to answer the above questions, this paper presents the current scientific connotation and practical significance of carbon neutrality from three aspects: the scientific connotation of carbon neutrality, the type of atmospheric carbon to be eliminated under the carbon neutrality goal, and the macro-level and micro-level carbon neutrality studies. The paper describes the current characteristics of global carbon emissions, the main progress of global carbon neutrality and the main technical measures in achieving carbon neutrality. The paper then describes the main challenges of global carbon neutrality in terms of policy, resource, technology, market and energy structure. The paper then describes the characteristics of the four main ways of carbon substitution, carbon reduction, carbon sequestration and carbon recycling to achieve global carbon neutrality. Finally, this paper elaborates the goal and roadmap of China's carbon neutrality from the path of its implementation, analyzes the challenges facing China's carbon neutrality, and proposes key measures to achieve China's carbon neutrality (Figure 1).

2 Scientific connotation and practical significance of carbon neutrality

2.1 Scientific connotation of carbon neutrality

Carbon neutrality is a business concept developed by Future Forests of in 1997, which focuses on the pathway to carbon neutrality from an energy technology perspective in areas such as transportation and travel, home life and personal behavior, by purchasing certified carbon credits to offset carbon emissions (Leblois et al., 2020). The British Standards Institute further defines carbon neutrality at the product level as the production process of the subject product or service that does not result in a net increase in greenhouse gas emissions to the atmosphere (Nam, 2017). Generally, carbon neutrality is a voluntary act, in which individuals and companies take carbon compensations and carbon offsets in order to build up their public image when they feel the climate change or due to environmental awareness or moral considerations, by calculating the carbon emissions directly or indirectly caused and the economic costs.

Figure 1. Logical framework of understanding of carbon neutrality.
required to offset them, by contributing to reforestation, or by purchasing carbon credits through carbon trading to offset the carbon emissions produced during production and consumption (Cutter, 2016; Krammer et al., 2013). According to the IPCC’s Special Report on Global Warming of 1.5°C, carbon neutrality means that an organization’s CO₂ emissions in a year are offset by CO₂ elimination measures and technologies such as reforestation, energy conservation and emission reduction, thus reaching a balance, or net zero CO₂ emissions (IPCC SR1.5, 2018). The goal is to achieve carbon neutrality by reducing global CO₂ emissions by approximately 45% by 2030 compared to 2010, and reaching near-zero emissions by 2050 (Madaleno & Moutinho, 2021). The goals set out in the Paris Agreement call for parties to the United Nations Framework Convention on Climate Change to make immediate and explicit nationally owned contributions to mitigate climate change, peak carbon emissions as early as possible, achieve carbon neutrality in the second half of the 21st century, and hold the global surface temperature increase to 2°C or less by the end of the 21st century relative to pre-industrial times. Not only that but the parties will also make efforts to achieve the temperature control target of 1.5°C (IPCC SR1.5, 2018). In essence, carbon neutrality requires a dynamic balance between carbon emissions caused by human activities and the earth’s carbon cycle as the goal, the orderly replacement of fossil energy by new carbon-free energy sources as the way, economic and industrial policies, energy technologies, etc. as the content, and the exploration of the minimal impact of human activity footprints on the natural environment development (Chi et al., 2021). In terms of technology connotation, carbon neutral includes the whole process of CO₂ emission, capture, utilization, storage and removal caused by human production and life and its related technology system (IPCC SREX, 2012). Overall, the Carbon neutrality is also a fundamental measure for humans to protect the ecological environment, helping to preserve biodiversity and ecosystems and avoid more species extinction (Campos-Seijo, 2020).

### 2.2 Carbon removal objects under carbon neutrality target

Carbon is one of the major elements in living matter, an important component of organic matter, and is stored in the Earth’s atmosphere, terrestrial ecosphere, oceansphere and lithosphere in the form of CO₂, organic matter and inorganic matter (Gil & Bernardo, 2020). Elemental carbon is cycled through the Earth’s atmosphere, terrestrial ecosphere, oceansphere and lithosphere by means of carbon fixation and carbon release. Carbon fixation refers to the absorption of CO₂ by photosynthesis of plants, dissolution of atmospheric CO₂ by seawater, absorption of CO₂ by saline soils in arid areas, formation of rocks containing carbon elements, and conversion of CO₂ into chemicals or fuels using artificial techniques. Carbon is released mainly from respiration of plants and animals, consumption of fossil fuels, and decomposition of rocks containing elemental carbon (Schreyer et al., 2020). In this paper, CO₂ that is fixed or available in the atmosphere is defined as “gray carbon”; CO₂ that cannot be fixed or available and remains in the atmosphere. Since the industrialization of human society, the consumption of fossil fuels has increased dramatically, and the carbon from fossil energy sources in the lithosphere has been released into the atmosphere, resulting in the increasing concentration of CO₂ in the atmosphere and the disruption of the balance of the Earth’s carbon cycle, resulting in the increasing content of CO₂ in the atmosphere (Yamori & Goltz, 2021). Therefore, the main purpose of carbon neutralization is to reduce the content of CO₂ in the atmosphere, gradually restore the balance of the carbon cycle of the green earth, protect the ecological environment on which human beings depend for survival, and build a livable earth.

### 2.3 Carbon neutrality in macro and micro perspective

In this paper, the macro level refers to the development approach underlying the socio-economic and energy structures, which refers to the widely adopted carbon neutral approach in the economic development pattern and the value of carbon neutrality to the overall socio-economic development. At the micro level, more emphasis is placed on the ways in which individuals can effectively participate in the process of carbon neutrality. The aggregation at the micro level leads directly to a reflection of the pattern of carbon neutrality in the process of achieving carbon neutrality at the macro level.

At the macro level, carbon neutrality emphasizes the transformation of economic and energy structures, accelerating the application of low-carbon and zero carbon technology innovation, focusing on energy conservation and energy efficiency, accelerating the application of renewable energy, expanding the construction of forests and carbon sinks, and promoting the balance of global greenhouse gas emissions and absorption. As a result, carbon neutrality accelerates the low-carbon green transformation of energy systems and brings new economic growth points to the world. According
to the Energy Transition 2050 report published by the International Renewable Energy Agency, carbon neutrality could generate an additional 2.4% of global GDP growth and an additional 7 million energy sector jobs (State Council of China, 2021).

At the micro level, the Theory of Planned Behavior, a classic theory of psychology, emphasizes that attitudes, subjective norms and perceived behavioral control are the three main influences on the triggers of environmental protection and carbon neutrality behavior. Academic microsurvey results indicate that individual consumer awareness of climate and environmental issues, incentives to engage in environmental protection behaviors, and interpersonal influences on environmental behavior are the main factors triggering carbon neutrality behavior. Willingness to pay for carbon neutrality is closely related to behavioral attitudes, education, environmental awareness, and perceived level of climate change, and demographic characteristics, with higher willingness to pay among young and educated people. Individuals’ sense of moral obligation and climate responsibility are the main drivers of willingness to pay, and behavioral attitudes, social norms, personal norms and behavioral controls also influence willingness to pay for carbon neutrality.

In general, the top-down macroscopic research focuses on the total target and the energy sector, and designs carbon neutrality realization paths in terms of energy conservation, energy efficiency, renewable energy development, and increasing forest carbon sinks, etc. Insufficient research has been conducted on the specific implementation measures of the overall target and the implementation mechanisms of micro entities. The bottom-up microscopic perspective focuses on the carbon neutrality pathways and measures of enterprises or individuals, which has the advantage of promoting actions by emitters, but lacks analysis and evaluation of the overall environmental effects of carbon neutrality actions. At present, there is a trend of fragmentation between the two, which is highlighted by the lack of micro foundation for macro research and the lack of macro vision for micro research.

3 Understanding global carbon emissions characteristics and global carbon neutrality

3.1 Current characteristics of global carbon emissions

According to the International Energy Agency, global energy related CO₂ emissions in 2019 are unchanged from 2018 (33.3 billion tons in 2018), with the top 5 carbon emitting countries being China, the United States, India, Russia, and Japan, with carbon emissions of 9.8 billion tons, 4.8 billion tons, 2.3 billion tons, 1.50 billion tons, and 1.1 billion tons s, respectively (Salvia et al., 2021). Carbon emissions in Asia come mainly from China, India and Japan, in the Americas from the United States, Canada and Brazil, in Europe from Russia, Germany and the United Kingdom, in Africa from South Africa, Egypt and Algeria, and in Oceania from Australia. Fossil fuel consumption is the main source of increased CO₂ emissions. Coal consumption has been the No.1 source of CO₂ emissions since 2003. Coal, oil, and natural gas consumption accounted for 45%, 43%, and 22% of total CO₂ emissions, respectively, in 2019 (Abbasi, 2021). The power sector is the largest carbon emitter, accounting for 38% of total emissions, followed by the transportation, industrial, and construction sectors, accounting for 24%, 23%, and 9% of total emissions, respectively (Yamori & Goltz, 2021). From the 1970s to the present, global carbon emissions have basically shown a positive correlation with global economic development, and both carbon emissions and per capita emissions have increased significantly with global economic development (Chi et al., 2021). In terms of total emissions and growth rate, global carbon emissions and total economic volume show a synchronous upward trend, but the growth rate has slowed down in recent years (Lee et al., 2021). The reason for the simultaneous growth of total economic volume and carbon emissions is that economic growth increases the demand for energy such as electricity and oil in various economic sectors, and the use of fossil energy such as electricity production, oil, and natural gas all produce large amounts of carbon emissions (Campos-Seijo, 2020). The economic recession, on the other hand, has seen a decline in energy use and a similar phased decline in carbon emissions, such as the 2008 economic crisis and the 2020 COVID-19 epidemic, which both brought about a phased decline in carbon emissions (State Council of China, 2021). In 2018, global carbon emissions reached their highest value to date at 34.05 billion tons, three times the level in 1965 (Shi, 2019). In terms of growth rate, with climate issues gradually becoming a global consensus and countries taking measures to control carbon emissions, the growth rate of carbon emissions began to slow down. In terms of per capita carbon emissions, global per capita carbon emissions and global carbon emissions basically show the same trend of change, gradually increasing amidst fluctuations. 2018, global per capita carbon emissions grew to 4.42 tons per person, an increase of 20% from 1971 (Shi, 2019). In terms of emission sources, electricity and heat production activities, manufacturing industries and construction and transportation are the most important sources of carbon emissions, and it is foreseeable that these areas
are the key points for future emission reduction. Electricity and heat production activities are the main sources of carbon emissions worldwide. The power supply industry still uses the burning of fossil fuels such as coal, oil and natural gas as the most important way to generate electricity, and the heating industry also uses the burning of fossil fuels as the main way to supply heat, and the burning of fossil fuels brings a large amount of carbon emissions. In 2018, the global carbon emissions generated by major electricity and heat production activities reached 13.98 billion tons, accounting for 41.7% of global carbon emissions in that year (State Council of China, 2021). The transportation industry is the second largest source of carbon emissions globally. Currently, land transportation, aviation and navigation still use fuel oil as the most important source of power, and the high demand for fuel oil also brings a lot of carbon emissions. The manufacturing and construction industries are another important source of carbon emissions. Steel smelting, chemical manufacturing, mining, construction and other industries have high demand for energy, and the decomposition of raw materials during the production process also brings carbon emissions (Chi et al., 2021).

3.2 Key advances in global carbon neutrality implementation

As of May 2021, 28 countries worldwide have achieved or committed to carbon neutrality targets. Among them, the Republic of Suriname and Bhutan have already achieved carbon neutrality (State Council of China, 2021). Six countries (Sweden, the UK, France, Denmark, New Zealand and Hungary) have passed legislation committing to carbon neutrality. Six countries and territories (the European Union, Canada, South Korea, Spain, Chile and Fiji) are in the process of developing relevant legislation. Fourteen countries (Finland, Orly, Iceland, Japan, Germany, Switzerland, Norway, Ireland, South Africa, Portugal, Costa Rica, Slovenia, the Marshall Islands and China) have committed to becoming carbon neutrality (Nam, 2017). The year 2050 is the main global timeline for achieving carbon neutrality, and Finland is committed to achieving carbon neutrality as early as 2035, in addition to the 2 countries that have already achieved it (Leblois et al., 2020). Austria and Iceland have committed to be carbon neutral by 2040. Ten countries, including Japan, Germany and Switzerland, have committed to becoming carbon neutrality by 2050 (Salvia et al., 2021). The Chinese government has formally committed to achieving carbon neutrality by 2060 (State Council of China, 2021). In addition, 99 other countries around the world are discussing carbon neutrality targets, with Uruguay proposing a target of 2030 and the rest aiming for 2050 (State Council of China, 2021).

The two countries that have achieved carbon neutrality are characterized by small land area and extremely high forest cover, with the Republic of Suriname having 80% forest cover and Bhutan having 72% forest cover (Yamori & Goltz, 2021). The European Union is the most active in the carbon neutrality process and wants to build the first carbon neutrality continent (Chi et al., 2021). In December 2019, the European Commission officially released the European Green Deal, which spells out Europe’s course of action toward a climate neutrality circular economy, proposing a 50% to 55% reduction in greenhouse gas emissions from 1990 levels by 2030 and a net zero emissions target by 2050 (Bonoli et al., 2021). In December 2020, the Japanese government launched the Green Growth Strategy, which is seen as a schedule to achieve Japan’s carbon neutrality goal by 2050 (Madaleno & Moutinho, 2021). From the countries that have committed to carbon neutrality so far, except for the European Union and Japan, which have released specific roadmaps for carbon neutrality, the rest of the countries’ carbon neutrality routes are still under further development.

3.3 Key measures in the implementation of global carbon neutrality

Firstly, phase out the coal generation program. With the exception of Germany, the European Union countries that have committed to carbon neutrality have fewer coal resources and smaller land areas, and have all withdrawn from coal power generation. The German government has officially announced that it will completely withdraw from coal power generation by 2040 (Zhang et al., 2021). Countries that are rich in coal resources or have a high percentage of coal generation consumption (such as Australia) have not yet determined plans to withdraw from coal generation (Kirikkaleli & Adebayo, 2021a).

Secondly, accelerate the application and promotion of solar energy, wind energy, hydrogen and other new energy industries. Photovoltaic power generation will become the number one source of electricity in the European Union and Japan, and offshore wind power has seen explosive growth. Offshore wind power in the European Union and Japan is expected to grow more than 25 times by 2050 (Friedlingstein et al., 2020; Kirikkaleli & Adebayo, 2021b; Qin et al., 2021). In terms of hydrogen energy, the European Union focuses on green hydrogen preparation, Japan comprehensively
develops the hydrogen energy industry chain, and South Korea has legislated on hydrogen energy to expand the application of hydrogen energy to transportation, metallurgy, power generation and other fields (Zhang et al., 2021).

Thirdly, develop carbon sequestration and carbon conversion technologies. Germany will restart its CO₂ capture and storage project, while making use of its abundant natural gas pipeline facilities and vigorously developing electricity to gas technology to convert CO₂ into methane for pipeline transportation. Japan will develop carbon recovery and resource utilization technologies to achieve a price comparable to conventional jet fuel for CO₂ recovery to fuel by 2030, and a price comparable to existing plastic products for CO₂ to plastic by 2050 (Khan et al., 2021; Koonadh et al., 2020, 2021).

Fourthly, develop a carbon pricing mechanism to increase the cost of carbon emissions. In 2005, the European Union started to implement the Emissions Trading System, which is the world’s first multinational carbon emissions trading system. The trading system adopts the rule of total control and trading, which is based on limiting the total amount of greenhouse gas emissions, and trading carbon emissions through the purchase and sale of administrative permits. The trading system also sets limits for each member country by setting limits and trading schemes, decomposes emission reduction targets to enterprises, and specifies emission reduction caps to force emission reduction.

4 Key challenges in the global carbon neutrality process

Carbon neutrality has become a global consensus to address global climate change, but in the process of implementation, it still faces challenges in politics, resources, technology, market, energy structure and other aspects.

Firstly, the realization of carbon neutrality faces challenges at the policy level. Achieving carbon neutrality is a global goal that requires the cooperation of all countries in the world, and the permanent members of the United Nations should take the lead in setting a carbon neutrality goal, but two permanent members, the United States and Russia, have not yet committed to achieving carbon neutrality. India, one of the top 5 global carbon emitters, has not yet committed to a carbon neutrality time frame (Schreyer et al., 2020). The Paris Agreement was initially signed by Angola, Iran, Iraq, South Sudan, Turkey, and Yemen, but without formal legislative ratification. Another 99 countries are discussing carbon neutrality targets, and the adoption of carbon neutrality targets is still up in the air (State Council of China, 2021).

Secondly, the realization of carbon neutrality faces challenges at the resource level. The substitution of fossil fuels by new energy sources is a fundamental measure to achieve carbon neutrality. There are spatial and temporal differences in the global distribution of new energy sources such as solar and wind, which pose challenges for the development of new energy scales. Global solar energy resources are mainly concentrated between the Earth’s Tropic of Cancer, with the Sahara region in northern Africa being the most abundant, while the eastern and southern parts of the African continent, Australia and northwestern China are also solar resource rich areas. Wind energy resources are mainly distributed in East Asia, Southeast Asia, Central Asia, America between 30°N-30°S, as well as northern and eastern China, Mongolia, northeast Australia, sub Saharan Africa and other regions (IPCC SREX, 2012). There are obvious regional and seasonal differences in the global land solar and wind energy resources.

Thirdly, the realization of carbon neutrality faces challenges at the technical level. The maturity of new energy technologies determines the speed of the carbon neutrality process. The overall price of solar, wind and other new energy generation is still higher than that of coal generation, with poor peak to valley stability and peaking technology requiring further innovation. It is difficult to electrify heavy industries and long distance transportation, etc. Hydrogen fuel cells are the optimal choice, but some of the key technologies are still in the demonstration or prototype stage and have not yet been promoted and industrialized on a large scale. Compared with traditional fossil energy hydrogen production (gray hydrogen), the cost of renewable energy hydrogen production (green hydrogen) is higher, and the supporting CO₂ capture and storage technology is still in the demonstration stage. Although low-carbon technology transfer has significant emission reduction and warming control effects, developed countries’ commitments to provide financial and low-carbon technology assistance to developing countries have yet to materialize.

Fourthly, the realization of carbon neutrality faces challenges at the market level. The promotion and application of new energy sources in the carbon neutrality process depends on the cost advantage and ease of application. At present, although the cost of new energy is decreasing year by year, it still lacks competitiveness compared to fossil energy. In particular, the cost advantage of fossil energy has had a negative impact on the new energy transition in 2020 due to the plunge
in global crude oil prices. New energy supporting equipment is not perfect, the application is not convenient, such as electric vehicle charging piles are not yet popular, the number of hydrogen refueling stations is small and other issues increase the cost of using new energy vehicles.

Fifthly, the realization of carbon neutrality faces challenges at the energy structure level. The global energy consumption structure is still dominated by fossil energy, and the proportion of new energy is low. Global energy consumption in 2019 is 14.4 billion tons of oil equivalent, of which coal accounts for 27%, oil for 33%, natural gas for 24% and new energy for 16% (Kamei et al., 2020). In the process of achieving carbon neutrality, the proportion of high carbon fossil energy consumption, such as coal and oil, should be significantly reduced and the proportion of new energy sources should be increased. At present, the proportion of fossil energy consumption is still high, which poses a challenge for energy transition.

5 Four pathways to the global carbon neutrality goal

In the current practice of addressing climate change, adaptation and mitigation are two strategies to address climate change. The key to carbon neutrality is to achieve net zero carbon emissions, which requires us to adopt carbon reduction technology measures from the perspective of mitigation and adaptation in the process of achieving carbon neutrality. Therefore, from the technically operable level in practice, the countermeasures to reduce carbon emissions and achieve carbon neutrality can be divided into four main pathways: carbon substitution, carbon reduction, carbon sequestration, and carbon recycling. Carbon substitution mainly includes substitution with electricity, substitution with heat and substitution with hydrogen, etc. Electricity substitution is the use of hydropower, photo-electricity, wind power and other “green power” to replace thermal power, heat substitution refers to the use of solar thermal, geothermal and other alternatives to fossil fuel heating, hydrogen substitution refers to the use of green hydrogen instead of gray hydrogen.

Carbon reduction mainly includes energy saving and energy efficiency improvement. In the construction industry, we are focusing on improving the energy efficiency of electrical appliances and equipment, adding solar photovoltaics to houses, developing new materials such as cement and steel, and reducing the implicit carbon emissions of cement and steel. In the transportation industry, the main focus is on reducing CO2 emissions at the source by using more efficient power systems and lighter materials.

Carbon sequestration refers to the collection of CO2 produced by large thermal power plants, steel mills, chemical plants, etc., transporting it to a suitable place and using technical means to sequester it from the atmosphere for a long time. Geological storage is the main form of carbon storage, and the storage sites are mainly oil and gas reservoirs, deep underground brackish water formations and abandoned coal mines. In the future, after the oil and gas fields have been extracted, the use of existing surface and underground facilities for CO2 storage may be the main cause of the initiative to reduce the amount of CO2 in the atmosphere through technology.

The carbon recycling includes artificial carbon conversion and forest carbon sinks as well as other natural systems (Friedlingstein et al., 2020; Qin et al., 2021). Artificial carbon conversion refers to the use of chemical or biological means to convert CO2 into useful chemicals or fuels, including the synthesis of methanol from CO2 and the preparation of CO or light hydrocarbon products by electrocatalytic reduction of CO2. Forest carbon sink means that plants absorb CO2 from the atmosphere through photosynthesis and fix it in the vegetation and soil, reducing the concentration of CO2 in the atmosphere and playing the role of reusable gray carbon. Other natural systems such as oceans and wetlands can also absorb carbon dioxide from the atmosphere (Qin et al., 2021).

For the above four major carbon neutrality practice pathways, based on the maturity of technology or the competitiveness with the price of conventional fossil energy, it is predicted that the CO2 emission reduction rate under the global carbon neutrality target in 2020–2050 will be relatively slow, mainly because the price advantage of new energy has not yet emerged and failed to achieve large-scale application, and the carbon sequestration technology has not yet matured (Khan et al., 2021). It is expected that by 2030–2050, with the maturity of related technologies, the cost of new energy can compete with fossil energy, new energy projects will be rapidly promoted and landed, and CO2 emissions will drop significantly (Koondhar et al., 2020). The carbon sequestration technology will reach the application requirements and make the main contribution to carbon neutrality (Koondhar et al., 2021). Carbon substitution will become the backbone of the carbon neutrality process, and is projected to contribute 47% of global carbon neutrality by 2050, with carbon reduction, carbon sequestration and carbon recycling contributing 21%, 15% and 17% respectively (State Council of China, 2021).
6 Implementation path for China’s carbon neutrality target

6.1 China’s carbon neutrality target and roadmap

The Chinese government is committed to achieving carbon neutrality and is actively promoting the process through the development of policies. The Chinese government and leaders have repeatedly made clear their carbon reduction targets and requirements. At the Copenhagen Climate Conference in 2009, the Chinese government stated that by 2020, it would achieve the goal of reducing CO₂ emissions per unit of GDP by 40%–45% compared to 2005, that non-fossil energy would account for 15% of primary energy consumption, and that forest stock would increase by 1.3 billion cubic meters compared to 2005 (Kong, 2020). At the 2015 Paris Climate Conference, the Chinese government proposed that by 2030, CO₂ emissions should be reduced by 60%–65% relative to 2005 and aim to reach the peak, non-fossil energy should account for 20% of primary energy consumption, and forest stock should increase by 4.5 billion cubic meters compared to 2005 (Chi et al., 2021). In September 2020, Chinese President Xi Jinping proposed at the 75th General Debate of the UN General Assembly that China will increase its autonomous national contribution, adopt stronger policies and measures, strive to peak CO₂ emissions by 2030, and work towards achieving carbon neutrality by 2060 (Chi et al., 2021; Kong & Sun, 2021). At the UN Climate Ambition Summit in December 2020, China further proposed that by 2030, China’s CO₂ emissions per unit of GDP will drop by more than 65% compared to 2005, the share of non-fossil energy in primary energy consumption will reach about 25%, forest stock will increase by 6 billion cubic meters compared to 2005, and the total installed capacity of wind and solar power will reach more than 1.2 billion kilowatts. On 24 October 2021, the Chinese government issued the “Opinions on the Complete and Accurate Implementation of the New Development Concept for Carbon Neutrality” (State Council of China, 2021). These carbon emission reduction measures and requirements provide important strategic guidelines for China to build a carbon neutrality country. In December 2020, the Chinese government released a white paper entitled “China’s Energy Development in a New Era”, which comprehensively describes the main policies and major initiatives of China’s energy security development strategy in the new era and new stage. The report “Study on China’s Long-Term Low-carbon Development Strategy and Transformation Pathway” released in October 2020 by Tsinghua Institute for Climate Change and Sustainable Development of Tsinghua University, which is headed by Xie Zhenhua, China’s Special Representative for Climate Change Affairs, states that China’s CO₂ emissions are expected to enter a peak plateau period around 2025, and strive to achieve a stable peak by 2030, with peak CO₂ emissions from fossil energy consumption controlled to within 11 billion tons, and by 2035 CO₂ emissions will drop significantly from the peak year. The report projects China’s carbon emissions in 2060 in three scenarios: low, medium and high emissions, according to the degree of reduction of peak CO₂ emissions (Kong & Sun, 2021). In the low scenario, China’s CO₂ emissions are reduced to 40% of the peak and to 4.4 billion tons; in the medium scenario, China’s CO₂ emissions are reduced to 30% of the peak and to 3.3 billion tons; and in the high scenario, China’s CO₂ emissions are reduced to 20% of the peak and to 2.20 billion tons [30,144]. The remaining CO₂ emissions are mainly absorbed through CO₂ sequestration and utilization, forest carbon sinks, etc. Carbon neutrality technologies such as CO₂ storage and utilization and forest carbon sinks are in greater demand under the medium and high scenarios, and investment in these areas should be strengthened. By the end of 2019, China’s carbon emissions intensity has been reduced by about 48.1% compared to 2005, and the share of non-fossil energy in primary energy consumption has reached 15.3%, fulfilling China’s foreign commitments by 2020 ahead of schedule and laying a solid foundation for 100% implementation of the country’s autonomous contribution and efforts to achieve the carbon peak target and carbon neutrality vision (State Council of China, 2021). China plans to move from carbon peaking to carbon neutrality in about 30 years (Friedlingstein et al., 2020). Thus, China is on the path to achieving carbon neutrality.

6.2 Challenges to achieving China’s carbon neutrality goal

Compared with other countries, China will face many challenges on the road to carbon neutrality, such as large carbon emissions, fossil based energy consumption, and a short buffer time from carbon peak to carbon neutrality. China is the world’s largest emitter of CO₂, accounting for 29.4% of total global emissions in 2019, more than the United States (14.4%), India (6.9%) and Russia (4.5%) combined (Zhang et al., 2021). At present, China’s energy consumption is still dominated by coal, oil, natural gas and other fossil energy, especially the proportion of coal accounted for
more than half. In 2019, China’s total energy consumption will be 7.08 billion tons of oil equivalent, with coal accounting for 58% and oil for 19% (State Council of China, 2021). At present, China’s manufacturing industry is still in the middle and low end of the international industrial value chain, with high energy and material consumption, low value added rate, and the difficult task of economic restructuring and industrial upgrading. The energy consumption per unit of GDP is still high, 1.5 times the world average and 2–3 times that of developed countries, and the task of establishing a green and low-carbon economic system is arduous (Khan et al., 2021; Kong & Sun, 2021). China has gone from carbon peak to carbon neutrality in just 30 years, i.e. it needs to decline rapidly after reaching carbon peak to become carbon neutrality. The European Union has committed to a 60–70 year buffer time from peak carbon to carbon neutrality, which is twice as long as that of China. To achieve carbon neutrality, a large amount of green and low-carbon investment is needed (Kirikkaleli & Adebayo, 2021a). In view of China’s national conditions, China cannot copy the carbon neutrality model of other countries and needs to develop a carbon neutrality implementation route that is in line with China’s resource endowment and national conditions, especially to mobilize social capital through the financial system to achieve it (Zhang et al., 2021).

### 6.3 Key measures to achieve carbon neutrality in China

#### 6.3.1 Promote the efficient and clean use of coal

China is rich in coal resources, and coal resources are important industrial raw materials. Vigorously promote the efficient and clean use of coal, can effectively control CO₂ emissions, but also can play the main role of coal to ensure national energy security. Efficient and clean utilization of coal includes safe, efficient and green mining of coal, pollution control and purification in coal combustion, new clean coal combustion, advanced coal-fired power generation and clean and efficient conversion of coal. Underground coal gasification is an important way of clean utilization, which can fundamentally change the mining and utilization of deep coal, and reduce the negative impact of coal mining and Application on the environment. The Chinese government is working hard to realize the gasification of China’s land coal resources at a depth of 1,000–3,000 m. It is estimated that these coal resources will produce 272–332 trillion cubic meters of methane, hydrogen and other gases after gasification (Kong, 2020). About 50% of China’s total coal consumption is used for power generation. Solving the problem of clean and efficient coal-fired power generation is the top priority of efficient and clean utilization of coal. Modern coal chemical industry mainly focuses on clean energy and fine chemical industry, including coal to gas, coal to oil, coal to chemicals, etc (Friedlingstein et al., 2020).

#### 6.3.2 Accelerate the replacement of clean energy use

Accelerating the implementation of clean energy substitution, optimizing the energy structure and building a clean, low-carbon, safe and efficient energy system is an important step for China to achieve carbon neutrality (Koondhar et al., 2020). Rely on technological innovation to further reduce the cost of solar and wind power generation, the use of wind power—photovoltaic—energy storage coupling mode instead of thermal power, play the rapid response of energy storage technology, two-way regulation, energy buffer advantage, improve the regulation capacity of new energy systems and online stability. The use of solar thermal—geothermal coupling mode to replace coal-fired heating energy, play the respective advantages of solar thermal and geothermal, the formation of complementary heating energy (Leblois et al., 2020).

#### 6.3.3 Enhance the role of natural gas as a bridge in the low-carbon transition

Natural gas is a low-carbon clean energy source that bridges the energy transition from high-carbon to zero carbon and contributes positively to achieving carbon neutrality. In the context of achieving carbon neutrality targets, China’s natural gas demand is growing strongly and is expected to grow rapidly to a potential 650–700 billion cubic meters by 2035 (State Council of China, 2021). The Chinese government urgently needs to build multiple tens of bcm natural gas production bases focusing on the Sichuan Basin, Ordos Basin and Tarim Basin to promote increased production of conventional natural gas. There is an urgent need to focus on breaking through the exploration and development of unconventional natural gas, improving the industrial policy system, and promoting the development and utilization of shale gas and coal bed methane (Khan et al., 2021).

#### 6.3.4 Develop the green hydrogen industry and its industrial chain

China needs to accelerate the building of a hydrogen energy industry, just like the coal and oil and gas industries. China has a strong demand for hydrogen energy, but hydrogen is still mainly produced from fossil fuels (i.e. grey hydrogen). The use of green hydrogen to
replace gray hydrogen can effectively reduce CO₂ emissions (Qin et al., 2021). According to the forecast of China Hydrogen Energy Alliance, China will be in the middle of hydrogen energy market development in 2030, and the average annual demand of hydrogen will reach 35 million tons, accounting for 5% of the terminal energy consumption; in 2050, the average annual demand of hydrogen will reach 60 million tons, and green hydrogen will account for 70% of the source of hydrogen, accounting for at least 5% of the terminal energy consumption, which can reduce about 700 million tons of CO₂ (State Council of China, 2021). In addition, it is urgent to accelerate the overall development of the industrial chain of hydrogen storage, hydrogen transportation, hydrogen fuel cells and hydrogen refueling stations, and deepen the integration with the oil and gas industry. Using the existing infrastructure such as natural gas pipeline network and gas stations, oil and gas companies can play their innate advantages in the nodes of the industrial chain such as hydrogen production and hydrogen refueling, and realize the joint construction of four stations of “oil, gas, hydrogen and electricity” to promote the high quality development of the hydrogen industrial system (Kirikkaleli & Adebayo, 2021b).

### 6.3.5 Increase the application and promotion of CO₂ burial and storage

CO₂ burial and storage can achieve large-scale CO₂ emission reduction, and is a supporting technology for the clean use of fossil energy (Koondhar et al., 2021). China’s coal based resource endowment determines that it must increase the application and promotion of CO₂ burial and storage, play its role in the carbon neutrality process, and promote the efficient and clean use of coal. In the future, the Chinese government can use the depleted oil and gas fields after the extraction of oil and gas to form artificial CO₂ gas fields to bury and store CO₂. At present, the Chinese government has carried out CO₂ oil drive technology in Jilin oilfield, Xinjiang oilfield and Daqing oilfield, resulting in an annual output of over 1 million tons of oil drive, making a new breakthrough in CO₂ oil drive technology. China’s offshore CO₂ seabed geological storage potential is large, with a total storage capacity of about 2.5 trillion tons. The preliminary prediction of CO₂ effective storage in deep saline reservoir and oil reservoir in Ordos Basin of China is 13.3 billion tons and 1.91 billion tons respectively, and the effective storage of CO₂ in oil and gas reservoir, deep saline reservoir and coal seam in Tuha Basin is 4.4 billion tons. The sorption and sequestration of CO₂ from coal seams in the Qinshui Basin in China is predicted to be up to 128 billion tons, with sorption accounting for more than 96% of this amount (State Council of China, 2021). In addition, CO₂ oil and gas drive can not only realize CO₂ burial, but also improve oil and gas recovery rate. In the future, the finished oil and gas fields can be built into artificial CO₂ gas field burial and storage demonstration bases in large oil and gas areas in China, such as Songliao, Bohai Bay, Ordos and Daqing.

### 6.3.6 Develop carbon conversion and forest carbon sink

The Chinese government can develop carbon conversion, converting CO₂ into chemical products or fuels. The “Liquid Sunshine” technology proposed by the Dalian Institute of Chemistry and Physics of the Chinese Academy of Sciences reacts “green hydrogen” with CO₂ to make methanol, and the production of 1 ton of methanol can fix 1.375 tons of CO₂ (State Council of China, 2021). China’s methanol production capacity is about 80 million tons, mainly made from natural gas and coal, if all methanol is produced by "Liquid Sunshine" technology, hundreds of millions of tons of CO₂ can be fixed. There is an urgent need to vigorously develop forest carbon sinks, and important forest areas in southwest and north-east China have a large capacity for carbon sinks. The average annual carbon sequestration capacity of terrestrial vegetation in China from 2010 to 2016 is about 1.1 billion tons, which is equivalent to about 45% of China’s annual carbon emissions during this period (Kong & Sun, 2021). Afforestation can play a beneficial role in the process of carbon neutrality in China (Kirikkaleli & Adebayo, 2021a).

### 6.3.7 Establish a market mechanism to control carbon emissions

There is an urgent need to establish a national carbon emissions trading market and use market mechanisms to control carbon emissions (Kirikkaleli & Adebayo, 2021a). Establishing a carbon market and increasing the cost of fossil carbon utilization is conducive to reducing fossil energy consumption at source and lowering CO₂ and air pollutant emissions. China’s current carbon emissions trading market is still in the early stage of construction, and it is necessary to further improve the supporting rules of the carbon emissions trading market, implement relevant infrastructure construction, clarify the behavior standards and norms of carbon trading related parties, and improve the national carbon emissions trading market system (Khan et al., 2021).

### 7 Summary

Global warming is a consequence of human activities that cause climate change on Earth. Carbon is the natural resources that consist of the element carbon, such as oil,
coal, wood, etc. More carbon is consumed and more CO\textsubscript{2}, which causes global warming, is produced. Global warming is also affecting people’s lifestyles and causing more and more problems. The ecological environment is a matter of human survival and sustainable development, and requires the solidarity and cooperation of all countries to jointly address the challenges (Kirikkaleli & Adebayo, 2021a, 2021b; Zhang et al., 2021).

The international community working together to achieve carbon neutrality is probably the largest international agreement ever reached in human history and is a positive sign for the development of the international community. Human society has wasted too much time in realizing the seriousness of global warming and in taking the necessary steps to address the problem, since the first transnational scientific assessment to express a consensus on the issue was published in 1992. It is time for the human community to do all it can to take action not only to curb carbon emissions but also to find a solution to the energy crisis. In the short time since 1850, humans have used up nearly half of the fossil fuels that took hundreds of millions of years to form. It is clear that current fossil energy consumption is unsustainable (Khan et al., 2021; State Council of China, 2021). Therefore, human society should actively seek solutions to the energy crisis. Carbon neutrality will be the solution to this crisis and the first step towards a sustainable future where human beings and nature can coexist in harmony (Koonadh et al., 2021).

Carbon neutrality is the consensus reached by mankind to address global climate change, and countries around the world are actively committed to achieving the goal of carbon neutrality (Kirikkaleli & Adebayo, 2021b). The concept of carbon neutrality has been gradually accepted by all walks of life, driven by the leading enterprises in various industries and the media, and the public’s attention to global climate change has been increasing. In order to understand the current global and Chinese carbon neutrality related progress, this paper elaborates the scientific connotation of carbon neutrality, relevant progress and challenges in the global carbon neutrality process, and further elaborates China’s roadmap to achieve carbon neutrality, the challenges it faces to carry out and potential measures, which is a reference value for a comprehensive understanding of China’s pathway under the carbon neutrality goal.

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**Data availability statement**

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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**Public interest statement**

A comprehensive understanding of the scientific objectives and practical process of carbon neutralization is a hot topic in the current academic and practical circles. This paper expounds the scientific connotation and practical significance of carbon neutralization from three aspects: the concept of carbon neutralization, the object of carbon removal, and carbon neutralization from macro and micro perspectives. Starting from the characteristics of current global carbon emissions, this paper summarizes the main progress, specific implementation measures, policies, resources, technology, market and main problems faced by various countries in the current global carbon neutralization process. This paper introduces China’s carbon neutralization goal and road map, summarizes the challenges faced by China’s implementation of carbon neutralization, and puts forward the key measures to promote the process of carbon neutralization in the future. This paper has a certain reference value for the public to understand China’s carbon neutralization process.

**Funding**

This research was funded by National Key Research and Development Program of China (2018YFE0109600) and the Beijing Social Science Foundation Project (19JDGLA008).

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