Chapter 1
Introduction

In 2015, 195 countries and regions signed on to the Paris Agreement, which laid the institutional framework for global cooperation on climate change after 2020. The Paris Agreement becomes effective when 55 Parties representing at least 55% of global emissions join the Agreement, a criteria met on October 5, 2016. Officially taking effect on Nov 4 2016,[1] the Agreement established a long-term temperature goal to combat climate change: keeping the global temperature rise (hereafter increase) this century well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase even further to 1.5°C. To achieve this temperature goal, the Parties aim to reach global peaking of greenhouse gas emissions (GHGs) as soon as possible and achieve net zero emission of greenhouse gases in the second half of this century. By 2020, parties are expected to communicate or update their 2030 NDCs as well as their mid-century, long-term low greenhouse gas emission development strategies to the UNFCCC secretariat. As of the end of 2019, 195 parties have signed on to the Agreement; 187 parties have ratified or accepted the Agreement; 184 parties have submitted their first NDCs and two have updated their NDCs. In addition, 14 other parties have submitted their long-term low-emission development strategies.[2]

China's 19th Party Congress laid out the overarching goal and masterplan of achieving socialist modernization by 2050. Targets and strategies for addressing climate change that align with the country's blueprint for development should be studied and formulated. China, like all nations that have signed the Paris Agreement, is obliged to submit a mid-century, long-term low greenhouse gas emission development strategy. The research on China's Long-term Low-carbon Development Strategies and Pathways emerged out of this context. The project centers around two areas: (1) given the condition of limiting global temperature increase within 2°C and

[1] The Paris Agreement was open for signature from April 22, 2016, to April 21, 2017 and, like the Kyoto Protocol, would only enter into force when 55 parties accounting for at least 55 percent of global greenhouse gas emissions ratified it.

[2] https://unfccc.int/process/the-paris-agreement/long-term-strategies.

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developing China into a great modern socialist country, the pathways of China's low-carbon transition to 2050 from aspects of funding, technology, policy required; and (2) examining the feasibility for China to deliver carbon neutrality by 2050 under the 1.5°C target, and evaluating the corresponding technical pathways, costs, obstacles and socioeconomic impact.

1.1 Global Climate Change Impact and Response

1.1.1 The Global Impact of Climate Change

Climate change refers to a rise in the average global temperature, extreme weather and other climate anomalies caused by increasing CO_2 and other greenhouse gases in the atmosphere caused by human activities, such as the burning of fossil fuels and deforestation, as well as natural changes in the environment. The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The Intergovernmental Panel on Climate Change (IPCC) believes that human activities in the industrial age have contributed to climate change in two main ways: first, the use of fossil fuels has led to increasing atmospheric concentrations of CO_2, aerosols and other pollutants, resulting in an increase in the levels of heat-trapping greenhouse gases in the atmosphere as well as pollution; and second, changes in land use and land cover affect global climate via reflections between the land surface and the atmosphere. These reflections modify near-surface energy, moisture, and momentum fluxes via changes in albedo and surface roughness, among others. According to the IPCC Fifth Assessment Report, "it is extremely likely (95 percent confidence) that human influence on climate caused more than half of the observed increase in global average surface temperature from 1951 to 2010" [1].

According to the World Meteorological Organization (WMO) bulletin, the physical signs and socio-economic impacts of climate change are accelerating as record greenhouse gas concentrations drive global temperatures towards increasingly dangerous levels. Atmospheric CO_2 levels have risen from 357 ppm in 1994 to 405 ppm in 2017. The warming trend in the global climate system continues. Global mean warming reached 1°C above pre-industrial levels in 2018, and the previous five years from 2014 to 2018 were the warmest years in the modern record of meteorological observation. In addition, other obvious signs of climate change, including sea level rise, warming ocean water, ocean acidification, melting glaciers and ice sheets continue to emerge while extreme weather and climate events such as tropical storms, floods, heavy precipitation, heat waves, droughts, cold waves and snow storms have wrought havoc across continents (Fig. 1.1) [2].

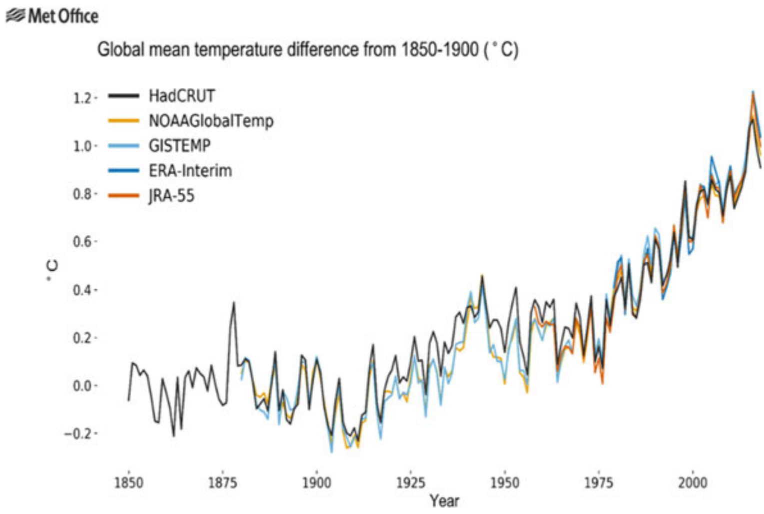

Fig. 1.1 Global mean surface temperature changes since 1850 (*Source* World Meteorological Organization (WMO), 2019. WMO statement on the state of global climate in 2018) (*Note* HadCRUT—UK Met Office Hadley Centre for Climate Science and Services and the Climatic Research Unit of the University of East Anglia; NOAAGlobalTemp—US National Oceanic and Atmospheric Administration Global Surface Temperature Dataset; GISTEMP—NASA Goddard Institute for Space Studies (GISS) surface temperature analysis for the globe; ERA-Interim-European Centre for Medium-Range Weather Forecasts; JRA-55—Japan Meteorological Agency's the Japanese 55-year Reanalysis)

In the meantime, the impact of climate change is increasingly visible. Natural disasters, mostly linked with extreme weather and climate events, hit 62 million people in 2018. Floods affected the largest number of people—over 35 million. It was estimated that the number of undernourished population increased to 821 million in 2017, partly because of severe droughts linked to El Niño between 2015 and 2016. Climate change has also triggered population displacement. As of September 2018, out of the 17.7 million Internally Displaced Persons (IDPs) tracked by the International Organization for Migration, over two million were displaced due to disasters linked to weather and climate events. Climate and air quality have many interactions, which are exacerbated by climate change. According to the World Health Organization, between 2000 and 2016, the number of people exposed to heat waves grew by around 125 million, while the duration of the average heatwave is 0.37 days longer compared to the period 1986–2008. Other impacts include the loss of "blue carbon" ecosystems found along the world's coasts and ocean in habitats such as mangrove forests, seagrass meadows, and salt marshes [2].

The *IPCC Special Report on Global Warming of 1.5°C (SR15)* released in 2018 pointed out that climate change is no longer a future challenge, but an immediate threat. The report emphasized the need for urgent climate actions. Global warming has already reached 1°C above pre-industrial levels and might reach 1.5°C as soon as 2030. At this rate, the warming might reach or even surpass 2°C around 2065, which would mean that the global temperature increase target set by the Paris Agreement for the end of the century would be exceeded four decades in advance. The report also indicated that there is a big difference in climate impacts between 1.5 and 2°C. If global warming rises from 1.5 to 2°C, more devastating consequences, such as loss of habitats, melting of ice sheets, sea level rise, will occur. This would further threaten the survival and development of human beings, and inflict more damage on the global economy. IPCC points out that in order to hold global warming within 1.5°C, rapid and far-reaching transformation is required in land, energy, industry, buildings, transport, cities, and other relevant areas. By 2030, global net human-caused CO_2 emissions would need to reduce by around 45% from 2010 levels, reaching net zero around 2050. Meanwhile, a significant reduction in non-CO_2 GHG emissions is also required [3].

In 2019, the IPCC issued the *Special Report on Climate Change and Land*, which underscored the threat climate change posed to food security, how it could be a driver of desertification and land degradation, and called on countries to use land in a sustainable manner. Land is of vital importance in the climate systems across the world. Agriculture, forestry and other types of land use account for 23% of human greenhouse gas emissions. In the meantime, the terrestrial biosphere absorbs one-third of carbon emissions from fossil fuel and industry. The land has long been overtaxed by human activities, while climate change exacerbated the situation. At 2°C of global warming, the risks from permafrost degradation and food supply instabilities are projected to be very high. At 1.5°C, the risks from dryland water scarcity, wildfire damage, permafrost degradation and food supply instabilities are all on the rise. Land must remain productive to maintain food security as the population grows and the negative impacts of climate change on vegetation is expected to increase. This has posed limits to the role that land can play in addressing climate change. In addition, it also takes time for trees and soil to effectively store carbon efficiently [4].

In the subsequent *Special Report on the Ocean and Cryosphere in a Changing Climate*, IPCC highlighted the urgency of timely, resolute and determined and coordinated actions to address unprecedented and enduring changes in the ocean and cryosphere. The ocean and cryosphere (the frozen parts of the planet) have served as a crucial buffer for life on earth against global warming, with the ocean absorbing more than 90% of the excess heat trapped on earth by greenhouse gases, and soaking up a quarter of human CO_2 emissions. The report assessed and encapsulated a series of scientific discoveries related to climate change. For instance, the sea level rose globally by 15 cm during the whole of the twentieth Century, and it is currently rising at double that speed; if greenhouse gas emissions are not curtailed, by 2100, the rate of sea level rise will be over 10 times that in the twentieth century; high greenhouse gas emissions will lead to the loss of over one-third of glacier ice on average by 2100, threatening people who rely on glaciers as a water resource, etc. With the increase in ocean surface temperature and acidification, marine life and marine ecosystems are facing tremendous challenges. Even if the global warming is held at 1.5°C, it is estimated that as much as 90% of warm water coral reefs that exist today will disappear [5].

1.1.2 The Impact of Climate Change on China

China is one of the regions in the world that are vulnerable to climate change. The country has experienced a faster rate of warming than the global average, which has produced a significant impact on its water resources, agriculture and ecosystems, etc. In 2018, warming persisted in the climate system ofChina. The mean surface temperature showed a clear upward trend; extreme weather and climate events increased with greater intensity; the cryosphere melted faster; and climate risk was on the rise. The climate change in China in the past 50 years has been sparked by a combination of rising temperatures due to human activity and natural climatic fluctuations. Meanwhile, China saw higher rates of warming between the 1970s and the turn of the century, and rapid urbanization may also have had varying degrees of impact on local temperature rises [6].

Atmosphere: In line with global surface temperature warming trends, not only has China witnessed rising surface temperatures, temperatures recorded across the country have been rising faster than the global average. The past two decades have been the warmest since the turn of the century, and 2018 was an exceptionally warm year. From 1951 to 2018, China's annual average temperature increased by 0.24°C every decade, and the rate of increase was remarkably higher than the global average. Consistent with the global and China's surface temperature warming trends, the temperature in the upper-troposphere has also shown a notable increase since 1961. In the meantime, annual precipitation averaged across the country has increased slightly, with apparent regional and seasonal differences, and extreme precipitation events has also increased. From a long-term perspective, manual observations and satellite imagery have shown a decreasing trend of total cloud cover over the country since 1961. During the same period, consistent with global changes in solar radiation, the average amount of sunlight reaching the Earth's surface in China has gone down steadily. A significant reduction in sunshine duration of 1.4% every decade on average was also reported. The average terrestrial wind speed has also decreased. Extreme heat events have seen a sharp uptick since the mid-1990s [6].

Ocean: Climate along the coast is dominated by monsoon winds. Changes in the East Asian monsoon, subtropical highs and Arctic Oscillation (atmospheric circulation pattern over the mid-to-high latitudes) have generated profound impact on the variability of parameters such as offshore surface temperature and sea level. China's coastal sea surface temperatures have shown significant increase since 1980, rising by 0.23°C on average every decade between 1980 and 2018, and remained at a historically high level for four consecutive years between 2015 and 2018. During the same period, the sea levels along the coast saw fluctuations in an upward trend at an average rate of 3.3 mm/year from 1980 to 2017, higher than the global average. China's coastal areas, featured by developed local economies, dense populations and fragile ecosystems, are especially vulnerable to the impacts of climate change. In the context of global warming, warmer seas, higher sea levels and increasing intensity of extreme weather and climate events (such as typhoons, tidal waves, and storm surges) have all had a sizable impact on China's marine environment and the socioeconomic conditions of the coastal communities [7]. Due to various challenges such as data collection through ocean observations, climate model uncertainties and water pollution, current research on the impact of climate change on China's offshore waters is still lacking severely.

Cryosphere: China is the largest country at mid- and low- latitudes cryosphere region. A great deal of research has found that the cryosphere in China has been shrinking in the past few decades, and this trend has markedly accelerated in the past ten years and more. The second Glacier Inventory of China confirmed that there were 48,571 glaciers with an area of 51,800 km^2 in the country, where glaciers have exhibited a general trend of retreat. The total area has reduced by 18% and lost some 243.7 km^2 in mass on average each year. Over the past few decades, permafrost temperatures, principally on the Qinghai-Tibetan Plateau, have risen on the whole. The specific symptoms include: decrease in size and thickness of frozen ground; rise in the lower altitudinal limit of permafrost; shortening of period in which the ground is frozen; increase in maximum thaw depths while larger areas of permafrost are experiencing melt, and the disappearance of discontinuous permafrost zones. China has a snow cover totalling to 9×10^6 km^2, of which 5×10^4 km^2 is stable. They are scattered in the accumulation zones of alpine glaciers in western China. In the five decades between 1958/1959 and 2007/2008, the number of snow-covered days and the maximum snow depth in spring and autumn slowly dropped, while such days and depth rose in winter [8].

Extreme weather and climate events: From 1961 to 2018, the interdecadal changes in the frequency of extreme heat events in China are apparent. The frequency of extreme daily precipitation events has increased. Since the late 1990s, the average intensity of typhoons landing in China has risen dramatically. A litany of extreme weather and climate events such as heat waves, cold waves, drought, heavy precipitation, floods, typhoons, sandstorms have become commonplace and resulted in extensive impacts. Between 1961 and 2018, China's climate risk index was generally on the rise, with major changes in stages and upward fluctuations since the late 1970s. Climate change is and will continue to affect natural ecosystems and socioeconomic development, with a rise in the frequency and intensity of extreme climate events such as heat waves and heavy precipitation and growing instability in the cryosphere. As of today, climate change now constitutes a grave challenge to a wide spectrum of fields including food security, water resources, ecological environment, energy, development of major projects, human health, and socioeconomic development. With the ongoing pace of socioeconomic development and growing urbanization, the risks of high temperature, floods, and droughts facing China is expected to be aggravated. It is imperative that serious attention be paid to climate security [6].

1.2 Theoretical Framework

The key to tackling climate change lies in the reduction of greenhouse gas emissions from human activities. CO_2 emissions from the burning of fossil energy accounts for two-thirds of the global greenhouse gas emissions. The fact that fossil fuel use is concentrated makes the implementation of emission reduction measures easier. The ever-increasing demand for energy to support economic development and the need to cut CO_2 emissions are in fundamental conflict. Low-carbon development has become the only viable path in dealing with climate change under the framework of sustainable development. It refers to a model of economic growth where relatively high carbon productivity, high level of economic and social development and quality of life are achieved with less consumption of natural resources, emissions, and pollution. At its core lies the development of low-carbon technologies, the improvement of energy efficiency and energy structure, the establishment of a low-carbon economic development and social consumption model, the complete decoupling of long-term economic and social development from GHGs.

The Paris Agreement sets out the goal of holding global warming to well below 2°C and pursuing efforts to limit it within 1.5°C. In order to meet this target, global emissions of greenhouse gases must reduced sharply, and net-zero emissions should be achieved by the second half or even the middle of this century. The world must continue to ramp up emission reduction efforts. All countries, especially the developing nations, are also faced with pressing challenges in sustainable development such as economic growth, improvement of people's livelihood, promotion of social progress, and the protection of regional ecological environment. The response to climate change must be aligned with domestic sustainable development priorities. Meanwhile, cooperation among countries and joint actions must be strengthened to create win–win for all parties.

1.2.1 Climate Change and Sustainable Development

Climate change and sustainable development have always been intertwined in global diplomacy and governance. The United Nations 2030 Agenda for Sustainable Development (hereafter the Agenda) adopted in 2015 emphasized that the economic, social and environmental damages are interrelated and inseparable. The 2030 Agenda called attention to the fact that climate change has put at risk the well-being of humanity and the planet's life support system. Therefore, the Agenda calls for urgent actions to combat climate change and its impacts (SDG13), and ensure climate actions and climate restoration is at the core of the sustainable development transition. Eleven targets in the agenda explicitly related to addressing climate mitigation, adaptation, and resilience efforts, while a total of 28 secondary targets are specific climate actions related. In recent developments, the two agenda of sustainable developmetn adn mitigating climate change are inclined to merge into one discourse. From the perspective of the goals set out in the Agenda, sustainable development is presented as a solution to the humanity's development problem, and climate change response is the pathway to solving the global ecological crisis. The ultimate goal of these two agendas is to achieve global sustainable development [9]. Globally speaking, since Paris Agreement took effect, the actions taken by countries in response to climate change have also became the key driver for achieving other Sustainable Development Goals [9].

There is a complex relationship between climate change and sustainable development. From a systematic point of view, it is a relationship that consists of both trade-offs and synergies. Within this context, there are also differences in the impacts of climate adaptation and mitigation efforts on sustainable development. In general, limiting warming to 1.5 and 2°C makes it easier to achieve a number of the Sustainable Development Goals, such as those related to poverty, hunger, health, water, sanitation, cities and ecosystems (SDGs 1, 2, 3, 6, 11, 14, 15) has been made easier. The avoided climate change impacts on poverty reduction and inequality eradication would be greater if global warming were Limiting to 1.5°C warming shows greater potential, such as in poverty alleviation and inequality eradication. By targeting 1.5°C, we could reduce the number of people under poverty line due to climate change by 62 million more than the 2°C target. Under the 1.5°C scenario, there are multiple synergies and trade-offs between mitigation measures and Sustainable Development Goals, but there are more synergies than trade-offs. Further breaking matters down, strong synergistic effects of mitigation and sustainable development can be found in the areas of health, energy, responsible consumption and production and ocean sustainability (SDGs 3, 7, 12, 14); and trade-offs or negative effects rest between strict mitigation measures and SDGs in the areas of poverty and hunger reduction, water, sanitation and energy (SDGs 1, 2, 6, 7). In contrast, the impact of adaptation measures on poverty alleviation, reduction of general inequalities, agriculture, health, and SDGs is projected to be mostly positive [3].

1.2.2 Promote the Coordinated Governance of Climate, Energy and Environment

Climate change is a critical environmental challenge facing humanity. In the meantime, other environmental problems are also threatening human health and the Earth's ecosystems on which humanity depends. In almost all countries, the most important driver of climate policy is not only to avoid the long-term effects of climate change, but also to achieve the SDGs in the short term. The most pressing of which is combating domestic air pollution [1]. The very sources and impacts of air pollution and climate change are closely linked (Fig. 1.2). Therefore, seeking policies or action plans that synergize mitigating climate change and reducing air pollution enable countries to better integrate short-term Sustainable Development Goals with the long-term global climate change mitigation strategy, encouraging them to take more ambitious emission reduction actions. In practice, the close interrelationship

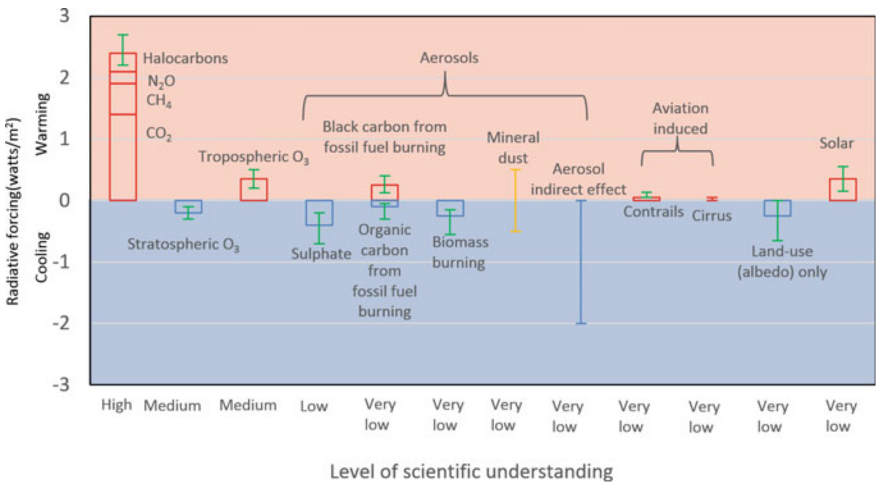

Fig. 1.2 The global mean radiative forcing of the climate system for the year 2000, relative to 1750 (*Source* IPCC. 1990. First Assessment Report. Intergovernmental Panel on Climate Change)

between environment and climate issues, effective policy measures for one cause may benefit the other. Coordinated policies and actions, i.e. coordinated governance, proves to be an effective win–win approach [3].

Many recent studies have suggested that actions to mitigate the impacts of climate forcing agents can have an immediate positive effect on economic and social welfare by improving public health and ecosystem sustainability. For instance, a model-based analysis found that, compared with the 2°C scenario, stricter short-term emission reduction measures under the 1.5°C scenario can reduce the number of premature deaths due to air pollution by 110 to 190 million [10]. Similarly, a comprehensive assessment of air pollution and climate change mitigation in the Asia–Pacific region concluded that by implementing 25 measures to improve air quality, CO_2 emissions can be cut by nearly 20% by 2050 [11]. According to a study by the United Nations Economic Commission for Europe, the average economic value of the health benefits arising from reduced air pollution ranges from \$58 to \$380 per ton of CO_2 world-wide, and the health benefits are even more significant in developing countries. In East Asia, the benefits are expected to be 10–70 times the marginal abatement cost by 2030 [12]. In 2011, the United Nations Environment Program and the World Meteorological Organization conducted a comprehensive assessment of control measures for short-lived climate pollutants, and discovered that these measures can slow the rate of global warming by half while avoiding 4 to 32 billion U.S. dollars annually of crop yield losses (estimated using global market prices) as well as 2 to 10 trillion U.S. dollars each year spent on health damages [13]. The mitigation of climate change has also created synergies in improving energy efficiency and the development of renewable energy. The synergies in these areas are equivalent to 50% to 350% of project investment. Research shows that in certain forestation projects aimed at mitigating climate change, the co-benefits can make up between 53 to 92% of total benefits [14].

1.2.3 Pathways and Technology Options to Mitigating Climate Change

Under the pathways for keeping global temperature rise to within 2°C and/or 1.5°C, the reduction of greenhouse gas emissions across all sectors, including industry, building, transport, energy, agriculture, forestry and other land use, is essential, where technology will play a key role. Across all industries, it is imperative to establish a non-fossil based energy supply system. Energy consumption by the end-use sectors needs to be revolutionized; industrial production needs to shift toward low-carbon technology, eco-design, flexible manufacturing systems and circular economy; carbon capture, storage and removal technologies should be applied on a large scale; innovations in energy saving and carbon emission reduction should be coordinated including materials, intelligent manufacturing, and information technology. In addition, revolutionary technological breakthroughs are essential.

1. **Conserving energy and improving energy efficiency:** China has made improvements in energy efficiency mainly through technological advancement. Energy conservation and energy efficiency improvement should be the long-term priorities for low-carbon development. China is one of the countries with the fastest improvement in energy efficiency aroundthe world. From 2005 to 2018, energy consumption per unit of GDP dropped by 41.5%, the cumulative energy savings reached 2.12 billion tonnes of coal equivalent (tce). Presently, China has put in place an energy-saving policy system with Chinese characteristics, which has evolved from restricting energy intensity alone to coordinated control of both energy intensity and total consumption. However, daunting challenges remain in further improving energy conservation and energy efficiency. In the next stage, efforts need to shift from single pieces of technology and equipment to system optimization, from structural adjustments to quality enhancement and content upgrade, and from curbing the growth in energy consumption to transforming consumption and reducing demand.
2. **Low-carbon transition of the energy mix:** Limiting global temperature rise within and/or 1.5°C requires a non-fossil fuel -based energy system. Coal is rapidly exiting the energy system, and oil consumption is expected to peak before 2035. In the past decade, the cost of renewable energy technology has been effectively reduced, wind and solar power are set to reach grid parity between 2020 and 2030. The biggest challenge appears on the grid side. When renewables, which are associated with such issues as supply volitility and uncertainty, become the dominating source of energy, the mechanisms for balance

management and overall planning in the power system will have to undergo qualitative changes. Therefore, it is crucial to address the issues of power system stability and optimized grid operations across time series under the paradigm of high penetration of power electronics throughout all sections of the power system, i.e. source, grid and load.

3. **Revolutionizing energy consumption in end-use sectors:** Electrification is the most important hallmark of the transformation of energy consumption in the end-use sectors. Both pathways of 2°C and 1.5°C targets call for deeper electrification of the end-use sectors. The rate of electrification society-wide should be more than doubled by 2050. Besides, on average two-thirds of the energy efficiency potential for end use remains untapped globally. The combination of energy efficiency technologies with digitalization, intelligent solutions and additive manufacturing will usher in new potential.
4. **Revolutionary advanced technological breakthroughs:** By 2050, under a deep decarbonization scenario that is compatible with the target of holding temperature rise within 2°C, the marginal abatement cost is expected to show a rapid, nonlinear upward trend. Technological breakthroughs are essential for such break through. It is vital to intensify the R&D and proliferation of technologies that drive deeper reductions in CO_2 emissions, such as large-scale energy storage and smart grid technologies with high levels of renewables connected to the grid, negative emissions technologies such as Biomass Energy Carbon Capture and Storage systems (BECCS), technologies for the production, storage and utilization of hydrogen energy—a clean zero-carbon secondary source of energy and an important industrial raw material, and zero carbon manufacturing technologies for raw materials such as chemicals, steel, cement, etc.; in the meantime, the R&D and pilotingof deep emissions reduction technologies for non-CO_2 greenhouse gases such as methane are required to achieve deep emissions reduction of all GHGs [15].

1.2.4 Nature-Based Solutions

The role of natural ecosystems in mitigating and adapting to climate change is getting increasing attention, nature-based solutions (NbS) have been put forward in this context (see Fig. 1.3). It refers to the conservation, restoration and sustainable management of ecosystem for mitigating climate change, and the use of ecosystem and its services to help humans and wildlife adapt to the impacts and challenges brought by climate change [16]. Research on the global carbon cycle shows that terrestrial ecosystems have absorbed roughly one-third of anthropogenic CO_2 emissions since the industrial revolution [4]. NbS can also provide a buffer against the impacts and long-term risks of climate change.[17], [18]. Therefore, efforts to halt the loss or degradation of ecosystems, other misuses of land and ocean, and the protection, restoration, and sustainable management of global ecosystems can ensure that nature continues to provide these essential services to humanity [19].

Fig. 1.3 NbS as an umbrella term for ecosystem-related approaches (*Source* Cohen-Shacham E, Walters G, Janzen C, Maginnis S (eds) 2016 Nature-based solutions to address global societal challenges. IUCN, Gland, Switzerland, 11 pp)

The Paris Agreement recognizes the importance of natural ecosystems in mitigating and adapting to climate change, as well as their broader social values. Throughout the agreement, in the Preamble and Articles 4, 5, 6, and 7, concepts associated with "Nature-based Solutions" are referred to either directly or indirectly. In the Nationally Determined Contributions provided by the nations signed on the Paris Agreement, at least 66% of the NDCs contain some form of NbS to help achieve climate mitigation and/or adaptation goals. At present, NbS mostly aim to achieve climate change mitigation goals through the management, conservation, and restoration of terrestrial forest ecosystems, while the role of grasslands, drylands, wetlands, coastal and marine ecosystems in climate change mitigation has yet to garner sufficient attention. In this sense, enormous potential remains for the application of NbS in future climate change mitigation and adaptation programs [20]. According to an analysis of 16 dynamic global vegetation models provided by the Global Carbon Project, the increase in atmospheric CO_2 concentrations and climate change resulted in an annual mean net carbon storage of ecosystems in China of 85~310 TgC yr^{-1} [21] from 2000 to 2017. In spite of large uncertainties, the methods based on field surveys and atmospheric retrieval all point to China's terrestrial ecosystems being a major carbon sink (96~435 TgC yr^{-1}) than had, offsetted 6~29% of CO_2 emissions from fossil fuels between 2000 and 2009 in the country [21].

1.3 China's Policies on Low-Carbon Transition

1.3.1 Green Development and the Construction of Ecological Civilization

As a developing country, China faces daunting challenges on the triple fronts of climate change, environment and development. As of the end of 2018, China's per capita GDP is approximately US$ 9,780, while its per capita disposable income was only US$ 4,266 [22]. In the past few decades, China has relied on a path adopted by western countries in their early stages of development, extensive growth based on resources input, thus formed an industrial structure dominated by heavy industries. After the reform and opening-up in 1978, China followed the example of Japan and other East Asian countries and pursued an export-led growth strategy, which sought to create a net export surplus to make up for insufficient domestic demand. This "extensive growth" and "export-oriented strategy" have directly led to vast fossil fuel consumption and severe environmental pollution [23]. Meanwhile, the soaring energy consumption makes China the world's largest energy consumer and carbon emitter. China's primary energy consumption in 2018 amounted to 3.27 billion tons of oil equivalent (4.68 billion tce), which is 23.6% of the world total. CO_2 emissions in China reached 9.43 billion tonnes in the same year, or 27.8% of the world's total [24].

The Chinese government has always had grand ambitions for green development. As early as the 1990s, sustainable development became part of the top agendas officially in government documents. In 1992, shortly after the United Nations Conference on Environment and Development, the Chinese government released the *Ten Major Measures to Enhance the Environment and Development*, which, for the first time, proposed the implementation of sustainable development strategy in China, and formulated China's Agenda for 21st Century, the world's first national-level strategy for sustainable development. At the 17th National Congress of the CPC in 2007, the philosophy of "ecological civilization" was brought forward. The 18th CPC National Congress in 2012 elevated the building of ecological civilization into China's guiding principle and governance philosophy. Ecological civilization is also a key building block of the 13th Five-Year Plan adopted in 2016.

In 2015,the Chinese government issued the *Opinions of the Central Committee of the Communist Party of China and the State Council on Accelerating the Construction of Ecological Civilization*. The document evolved the notion of ecological civilization from a governance philosophy into a concrete strategy for action. The main goals for the development of ecological civilization were established, and the philosophy of ecological civilization was integrated into all spheres of China's economic, political, cultural, and social development, including the blueprints for the country's new model of urbanization, industrialization and agricultural modernization. More importantly, the document proposed the "formation of a full-fledged system of ecological civilization", which entailed the improvement of legislation, standards, the system of property rights of natural resource assets and usage regulation, the monitoring and supervision of the ecological environment, the strict observance of the red lines of resources, environment and ecology, the betterment of economic policies, the roll-out of market-based mechanisms, the enhancement of mechanism of compensation for ecological protection, government performance assessment as well as the accountability system. In September 2015, the Chinese government introduced the Integrated Reform Plan for Promoting Ecological Progress, setting clear target and timeframe for the reform. By then, ecological civilization had become the overarching policy to guild China's economic transformation.

The Chinese government has embraced ecological civilization as a central policy objective, and elevated it into one of the strategic pillars of the country's long-term development. China pursues a coordinated relationship among economic development, social progress and environmental protection under the steering of ecological civilization in a bid to strive for the coordinated and sustainable development. The country's efforts in promoting green development have also been recognized internationally. The UNEP's 27th council meeting in 2013 adopted a decision promoting the philosophy of ecological civilization, and in 2015, UNEP published a report entitled *Green is Gold: The Strategy and Actions of China's Ecological Civilization.* The country's remarkable achievements and successful practices in building an ecological civilization and protecting the environment will contribute China's experience and wisdom to a global community faced with the common threat of an environmental crisis.

Resource conservation, environmental protection, and CO_2 emission reduction are the key pillars of China's efforts in building ecological civilization. In the 11th Five-Year Plan (FYP), the country has set binding targets for reducing energy intensity and for the share of new and renewable energy in total energy consumption. The targets were further tailored to the provinces and municipalities and became an important metric for evaluating government performance at all levels. The 12th FYP added the target of CO_2 intensity reduction per capita of GDP, and share of non-fossil fuels in primary energy consumption mix. The 13th FYP put a ceiling for total energy consumption, strengthened policies on energy conservation and carbon reduction, and introduced a range of fiscal, tax and financial incentives. China's 2030 NDC commitments under the Paris Agreement will also be incorporated and implemented in the 14th and 15th FYPs. The NDC targets are an integral part of building ecological civilization during the 14th and 15th FYP periods.

1.3.2 Xi Jinping's Thought on Ecological Civilization and New Development Philosophies for the New Era

The report of the 19th National Congress of the CPC laid out the goals, basic strategies and blueprint of socialist modernization with Chinese characteristics in the new era. It listed climate change as a major non-conventional security threat, and stated that China has been actively fostering international cooperation in response to climate change, and has become an important participant, contributor, and torchbearer in the global endeavor for ecological civilization. It was highlighted in the report that China would pursue environmentally friendly growth and international cooperation on climate change, protect the planet that humanity depends on, and contribute to global ecological safety. In regard to the construction of ecological civilization, China aims to facilitate green, circular and low-carbon development, foster a new model of modernization with harmonious development between human and nature, while meeting the growing needs for a better life and a beautiful environment. This echoes the advocacy of Paris Agreement for a climate-friendly low-carbon economy. The tremendous progress China has made in energy conservation and economic transformation resulted in part from integrating the management of climate change with China's sustainable development. The ultimate goal is a win–win scenario for the economy, people's livelihood, energy, environment, and CO_2 emission reduction. Xi Jinping's Thought on Ecological Civilization has become a key guiding ideology and a powerful driver for China's low-carbon transition.

The report of the 19th National Congress of the CPC called for intensified efforts to develop a system for building an ecological civilization, facilitate green development, establish a green, low-carbon, and circular economy. The policy measures for the string of targets and tasks set out in the report, "controlling environment pollution" and "building a beautiful China" are consistent with the goals of addressing climate change and mitigating carbon emissions, resulting in win-win solution. An energy revolution on both the production and consumption sides and the transition to a green and low-carbon economy are not only crucial measures for protecting the environment, improving the ecology and building a "beautiful China", but also key strategies for CO_2 emissions reduction and global climate change response. To realize the objectives which "the ecology and environment fundamentally improved, and the goal of a beautiful China basically achieved by 2035", having pollution prevention and control measures that solely rely on improving energy efficiency and "end-of-pipe" techniques are far from sufficient. The total consumption of fossil fuels such as coal and oil must be reduced so that pollution can be curbed at the source. This will also effectively cut CO_2 emissions. Capping and reducing the consumption of coal and oil has been an important step for the eastern coastal areas in the "blue skies" campaigns, and will aid in the reduction of CO_2 emissions. Addressing climate change and implementating emission reduction commitments are also powerful drivers and synergies for domestic environmental improvement. China is currently translating its new development philosophies into concrete actions by transforming the drivers of economic development through innovation, and reshaping the model of development through green initiatives. The key to steering the Chinese economy onto a track of high-quality development instead of merely focusing on high-speed growth is to transform the development model, to improve economic structure, unlock new drivers of growth, deepen supply-side structural reform, and to increase total factor productivity. These initiatives will help shift the model of development from extensive growth driven by additional inputs of labor and capital at the expense of resources and the environment toward an innovation-driven, green and low-carbon endogenous development path. They will also boost energy conservation, improve the energy utilization and output efficiency. They reflect a paradigm shift that fosters an enabling institutional environment for promoting low-carbon transition and reforms, setting the stage for accelerated low-carbon transition of the economic and energy systems.

China's accelerating low-carbon transitions in its economic and energy sectors not only aligns with the global agenda on low-carbon development, but also presents a great opportunity to enhance its global competitiveness and influence. The urgent call for global response to climate change will reshape the world's landscape in economic, trade, and technological competition. Advanced low-carbon and decarbonization technologies will become the frontiers of global technological innovation and competition. As the world undergoes profound changes, the body that masters advanced technology in the above-mentioned areas will gain initiative and enhanced competitive advantage. China's active pursuit of an energy revolution and low-carbon transition of the economy are integrated with the strategic blueprint for developing its own technological capabilities and low-carbon development drivers.China also seeks the opportunity to share its findings and experience in low-carbon transition in a world-wide context, enhancing global competitiveness and influence.

1.4 Research Objectives and Overall Structure

1.4.1 Context and Objectives

The report from the 19th National Congress of the Communist Party (CPC) of China put forward the goals, fundamental 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. The Paris Agreement set out the goal of holding the increase in global average temperature to well -below 2°C and pursuing efforts towards limiting it to 1.5°C. To achieve this target, all countries must increase their efforts to curb and reduce greenhouse gas emissions. The world should cut CO_2 emissions to near-zero by 2050, and strive to achieve carbon neutrality. Addressing the challenges of climate change is a common cause for all humankind, and China will play an important role in this process as a 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 fitted to the 2°C global target. 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 and renewable energy as pillars. 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 19th Party Congress presented the two-stage arrangement of socialist modernization. China's long-term low-carbon development strategy should be formulated and deployed in accordance with the two-stage arrangement. The period 2020–2035 marks the first stage of China's socialist modernization fulfilling 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. As a result, 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 stage of socialist modernization, from 2035 to 2050, after having basically realized modernization and entered a post-industrial society, China's economic and social development will be featured by quality, intensive endogenous growth, and China will have already peaked and lowered CO_2 emissions, which is more conducive to a low-carbon transition. During this stage, the need for global CO_2 emission reduction is more urgent, which should reach 6~7% on an annual basis. With substantive improvements in the environment and attenuated environmental stress, the goal and strategy of deep decarbonization will take precedence over the endogenous requirements of resource conservation, environmental protection and sustainable development in China, and more consideration should be given to assuming international responsibilities consistent with its ever-increasing national strength and international influence. China must take the goal of deep decarbonization through keeping global temperature rise to well -below 2°C and striving for 1.5°C as a key component of the overall strategy of building a modern socialist country, and assume its responsibilities and leadership in safeguarding the ecological safety of the Earth and the common interests of humankind, and contribute to the development of humanity. China should examine its due and potential responsibilities and obligations as determined by the goals and requirements of the Paris Agreement, gradually expand the scope of GHG reduction efforts from mainly CO_2 emissions from energy consumption to all six GHGs, and develop absolute reduction targets and measures aimed at 2050 that cover all GHGs across the entire economy. The Paris Agreement requests all parties to submit their 2050 low GHGs development strategies prior to 2020. This project will also provide support for the Chinese government in formulating and submitting the country's long-term low-emission development strategy.

1.4.2 Research Framework and Scenarios

Focusing on China's long-term low-carbon development strategy and pathways, this study encompassed a total of 18 topics (see Fig. 1.4), and pulled together the collective effort of domestic top research institutions in China. From a macroscopic point of view, areas under study include the medium- to -long- term socioeconomic goals and strategies, the coordinated development of the eastern, central and western regions and their respectivelow-carbon strategies and pathways in the process of urbanization, the impacts of international trade and industrial relocation, etc. From a sectoral perspective, the research covered low-carbon development strategies and pathways for the energy and power supply sector and the major end-use sectors such as industry, building, and transport. In addition, strategies, measures and pathways for non-energy related CO_2 and other GHG emission reductions are also presented under the section. Policy-related topics under study include energy-saving potential and pathways, the evaluation of advanced decarbonization technologies, infrastructure investment and financing, transformation of consumption patterns, and research on coordinated measures and effect analysis for the climate and environment. Furthermore, the project explores five comprehensive and integrated topics, including the formulation of vision statement for medium and long-term low-carbon emissions, policy and institutional support systems, and global climate governance and international cooperation, etc.

This project consists of both bottom–up and top–down approaches. Bottom–up approaches include scenario analysis and technical evaluation of energy consumption and CO_2 technologies of all sectors. Top–down approaches include a macro-model calculation and policy simulation. The study is oriented toward problem-solving and

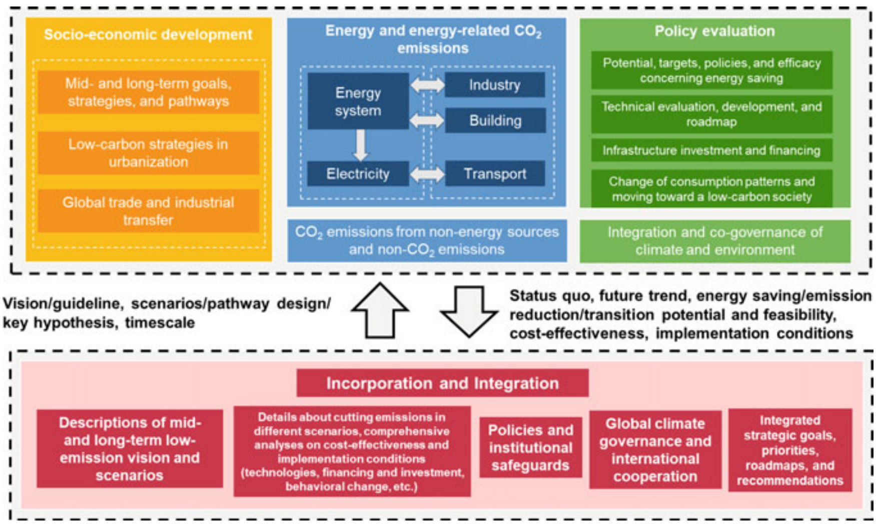

Fig. 1.4 Project framework of China's low-carbon transition pathways

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. The 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. Four scenarios have been designed and all topics studied and analyzed based on these four scenarios.

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 remains.
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, exploring 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. 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, analyzing the emission reduction measures and roadmaps driven by the deep decarbonization goals to be achieved by the middle of the century, and demonstrate and evaluate the associated technology and capital needs, costs and prices, and policy support.
4. 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 evaluating 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 and 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 feasibility for realizing net-zero CO_2 emissions and deep emission reduction of other GHGs by 2050 to attain the 1.5°C goal. It is worth noting that the connections between the scenarios and the NDCs before 2035 are taken into consideration, as well as the coordination of low-emission goals and strategies in these two stages.

1.4.3 Overall Structure

This comprehensive report on the research on China's Long-term Low-carbon Development Strategies and Pathways, is based on the consolidation of the first 17 topics of the entire research project (the 18th topic is the comprehensive report), and focuses on the strategic objectives, key conclusions, roadmaps and policy recommendations. The report is divided into twelve chapters. The first chapter, the introduction, deals primarily with the context, theoretical framework, guidelines and overall design. The second chapter offers an overall analysis of long-term low-carbon emission development, and delves into the state and trends of low-carbon development both in China and internationally under the Paris Agreement.

Chapters 3–6 attempt to outline the scenarios of future emissions of GHGs, key emission reduction technologies and policy requirements across all sectors. Chapter 3 dedicated to end-use energy consumption and CO_2 emissions, is primarily concerned with the current state of development of the industry, building and transport sectors, decarbonization pathways, overall energy consumption and carbon emissions, and activity levels, as well as analysis of the potential costs, and crucial supporting policies. Chapters 4 and 5 focus on the power and energy system, and assess the future development and policy support needed for the power and energy system based on power demand from the end-use sectors. Chapter 6 mainly explores the current state of emissions of non-CO_2 GHGs, future emission scenarios and outcomes, and key emission reduction technologies and policy requirements. Chapters 7–9 consolidate and evaluate the three aspects of low-carbon technology, transition costs, and long-term low-carbon development pathways. Chapters 7 and 8 sort through critical zero-carbon and carbon negative technologies (including hydrogen energy technologies, energy storage technologies, CCS & BECCS, and zero-emission technologies in the production of steel, cement and chemical, etc.), and examine their current stages of development and future investment needs, etc. Chapter 9, devoted to an overall analysis and evaluation of pathways, integrates in a systematic manner the low-carbon strategies mentioned in Chapters 3–6, proposes an enhanced NDC pathway, 2°C pathway and 1.5°C pathway.

Chapter 10, titled strategic linchpins and policy safeguards, examines the existing low-carbon development policies and measures in China, and proposes key strategies to support the country's low-emission development in the future while taking into full account China's goals and strategies for building itself into a great modern socialist country by mid-twenty-first century. Chapter 11, dedicated to the topic of global climate governance and international cooperation, delves into the development, principles and new realities of the global climate governance system. Chapter 12 offers policy recommendations for China's mid—and long-term low-carbon development goals, strategies and implementation measures.

References

1. Intergovernmental Panel on Climate Change (IPCC) (2013) Climate change 2013: the physical science basis. Cambridge University Press, Cambridge
2. World Meteorological Organization (WMO) (2019) WMO statement on the state of global climate in 2018. WMO, Geneva
3. Intergovernmental Panel on Climate Change (IPCC) (2018) Special report on global warming of 1.5°C. an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC, Geneva
4. Intergovernmental Panel on Climate Change (IPCC) (2019) Climate and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva
5. Intergovernmental Panel on Climate Change (IPCC) (2019) Special report on the ocean and cryosphere in a changing climate. IPCC, Geneva
6. Climate Change Center, China Meteorological Administration (2019) Blue paper on climate change in China. China Meteorological Administration, Beijing
7. National Marine Information Center (2019) Ocean blue book of China's climate change in 2019. National Marine Information Center, Tianjin
8. Shijin W, Yongjian D, Cunde X (2018) Comprehensive influence of cryosphere change on economic and social systems and its adaptive management strategy. Journal of Glacial Permafrost 40(05):7–18
9. United Nations Climate Change (UNCC) (2017) Climate action plays central role in achieving the sustainable development goals (2017–07–18) [2020–04–30]. https://unfccc.int/news/climate-action-plays-central-role-in-achieving-the-sustainable-development-goals
10. Shindell DT, Faluvegi G, Seltzer K et al (2018) Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. Nat Clim Chang 8:291–295
11. United Nations Environment Programme (UNEP) and Climate & Clean Air Coalition (CCAC) Air pollution in Asia and the Pacific: Science-based Solutions. UNEP and CCAC, Nairobi and Paris
12. United Nations Economic Commission for Europe (UNECE) Programmes (2016) The co-benefits of climate change mitigation (2016–01–22) [2019–08–28] http://www.unece.org/fileadmin/DAM/Sustainable_Development_No._2__Final__Draft_OK_2.pdf
13. United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) (2011) Integrated assessment of black carbon and tropospheric ozone. UNEP and WMO, Nairobi and Geneva
14. Urge-Vorsatz D, Herrero S T, Dubash N K and Lecocq F (2014) Measuring the co-benefits of climate change mitigation. Annual Review of Environ Resour 39: 549–582
15. Jiankun He (2019) New situation of global climate governance and China's countermeasures. Environmental Economics Research 3:1–9
16. Zhang X, Xie Q, Zeng N. Nature-based climate change solutions. Progress in climate change research (2020–02–17) http://kns.cnki.net/kcms/detail/11.5368.p.20200215.2003.002.html
17. Hochard JP, Hamilton S, Barbier EB (2019) Mangroves shelter coastal activity from cyclones. Proc Natl Acad Sci USA 116:12232–12237
18. Beck MW, Losada IJ, Menéndez P et al (2018) The global flood protection savings provided by coral reefs. Nat Commun 9:2186
19. Seddon N, Sengupta S, García M et al (2019) Nature-based solutions in nationally determined contributions: Synthesis and recommendations for enhancing climate ambition and action by 2020. IUCN and University of Oxford, Gland and Oxford
20. Le Quéré C, Andrew RM, Friedlingstein P, et al (2018) Global carbon budget 2018. Earth Syst. Sci. Data 1(4)
21. Lu F, Hu HF, Sun WJ et al (2018) Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. Proc Natl Acad Sci 115(16):4039–4044

22. National Bureau of Statistics (2019) 2018 residents income and consumption expenditure (2019–01–21) [2019–11–16] http://www.stats.gov.cn/tjsj/zxfb/201901/t20190121_1645791.html
23. Wu J (2014) Preface 1. // Ma Jun, Li Zhiguo et al. Economic policy for $PM_{2.5}$ emission reduction, 1–3. China Economic Press, Beijing
24. British Petroleum (BP) BP statistical review of world energy (2020–06–17) [2020–06–22] http://www.bp.com/statisticalreview