Environmental Science and Ecotechnology 16 (2023) 100280

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Perspective

Synergetic roadmap of carbon neutrality and clean air for China☆

Qiang Zhang [a, #, *], Zhicong Yin [b, #], Xi Lu [c, d, #], Jicheng Gong [e, **], Yu Lei [f, g, ***], Bofeng Cai [g], Cilan Cai [a], Qimin Chai [h], Huopo Chen [i], Hancheng Dai [j], Zhanfeng Dong [k], Guannan Geng [c], Dabo Guan [a], Jianlin Hu [l], Cunrui Huang [m], Jianing Kang [n], Tiantian Li [o], Wei Li [a], Yongsheng Lin [p], Jun Liu [q], Xin Liu [r], Zhu Liu [a], Jinghui Ma [s], Guofeng Shen [t], Dan Tong [a], Xuhui Wang [t], Xuying Wang [f], Zhili Wang [u], Yang Xie [v], Honglei Xu [w], Tao Xue [x], Bing Zhang [y], Da Zhang [z], Shaohui Zhang [v], Shaojun Zhang [c], Xian Zhang [aa], Bo Zheng [ab], Yixuan Zheng [f], Tong Zhu [e], Jinnan Wang [f, g, k], Kebin He [c, d]

[a] *Ministry of Education Key Laboratory for Earth System Modelling, Department of Earth System Science, Tsinghua University, Beijing, 100084, China*
[b] *Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/ Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing, 210044, China*
[c] *State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China*
[d] *Institute for Carbon Neutrality, Tsinghua University, Beijing, 100084, China*
[e] *State Key Joint Laboratory for Environment Simulation and Pollution Control, College of Environmental Sciences and Engineering and Center for Environment and Health, Peking University, Beijing, 100871, China*
[f] *Center of Air Quality Simulation and System Analysis, Chinese Academy of Environmental Planning, Beijing, 100012, China*
[g] *Center for Carbon Neutrality, Chinese Academy of Environmental Planning, Beijing, 100012, China*
[h] *National Center for Climate Change, Strategy and International Cooperation, Beijing, 100035, China*
[i] *Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China*
[j] *College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China*
[k] *Institute of Environmental Policy Management, Chinese Academy of Environmental Planning, Beijing, 100012, China*
[l] *Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, School of Environmental Science and Engineering, Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, Nanjing University of Information Science and Technology, Nanjing, 210044, China*
[m] *Vanke School of Public Health, Tsinghua University, Beijing, 100084, China*
[n] *Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing, 100081, China*
[o] *China CDC Key Laboratory of Environment and Population Health, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, 100021, China*
[p] *School of Economics and Resource Management, Beijing Normal University, Beijing, 100875, China*
[q] *Department of Environmental Engineering, School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing, 100083, China*
[r] *Energy Foundation China, Beijing, 100004, China*
[s] *Shanghai Typhoon Institute, Shanghai Meteorological Service, Shanghai, 200030, China*
[t] *College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China*
[u] *State Key Laboratory of Severe Weather and Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing, 100081, China*
[v] *School of Economics and Management, Beihang University, Beijing, 100191, China*
[w] *Laboratory of Transport Pollution Control and Monitoring Technology, Transport Planning and Research Institute, Ministry of Transport of the People's Republic of China, Beijing, 100028, China*
[x] *Institute of Reproductive and Child Health/Ministry of Health Key Laboratory of Reproductive Health and Department of Epidemiology and Biostatistics, School of Public Health, Peking University, Beijing, 100080, China*
[y] *State Key Laboratory of Pollution Control & Resource Reuse School of Environment, Nanjing University, Nanjing, 210008, China*
[z] *Institute of Energy, Environment, and Economy, Tsinghua University, Beijing, 100084, China*
[aa] *The Administrative Centre for China's Agenda 21 (ACCA21), Ministry of Science and Technology (MOST), Beijing, 100038, China*
[ab] *Institute of Environment and Ecology, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, 518055, China*

☆ The original version of this perspective is available as a working report at http://www.ccapp.org.cn/dist/reportInfo/276 in the language of Chinese and it should not be treated as official publication. Publishing of the revised version of this perspective on Environmental Science and Ecotechnology in English is approved by the authors.

* Corresponding author. Department of Earth System Science, Tsinghua University, Beijing, 100084, China.
** Corresponding author. College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China.
*** Corresponding author. Chinese Academy of Environmental Planning, Beijing, 100012, China.
E-mail addresses: qiangzhang@tsinghua.edu.cn (Q. Zhang), jchgong@pku.edu.cn (J. Gong), leiyu@caep.org.cn (Y. Lei).

# These authors contributed equally to this work.

https://doi.org/10.1016/j.ese.2023.100280

ARTICLE INFO

Article history:
Received 11 January 2023
Received in revised form
5 April 2023
Accepted 6 April 2023

Keywords:
Carbon neutrality
Clean air
Synergetic roadmap

ABSTRACT

It is well recognized that carbon dioxide and air pollutants share similar emission sources so that synergetic policies on climate change mitigation and air pollution control can lead to remarkable co-benefits on greenhouse gas reduction, air quality improvement, and improved health. In the context of carbon peak, carbon neutrality, and clean air policies, this perspective tracks and analyzes the process of the synergetic governance of air pollution and climate change in China by developing and monitoring 18 indicators. The 18 indicators cover the following five aspects: air pollution and associated weather-climate conditions, progress in structural transition, sources, inks, and mitigation pathway of atmospheric composition, health impacts and benefits of coordinated control, and synergetic governance system and practices. By tracking the progress in each indicator, this perspective presents the major accomplishment of coordinated control, identifies the emerging challenges toward the synergetic governance, and provides policy recommendations for designing a synergetic roadmap of Carbon Neutrality and Clean Air for China.

1. Introduction

Air pollutants and greenhouse gas (GHG) emissions share the similar sources, in which both were emitted from the combustion and use of fossil fuels [1]. With the successive implementation of the *Action Plan on Prevention and Control of Air Pollution* and the *Three-Year Action Plan for Winning the Blue Sky Defense Battle*, significant declines in China's $PM_{2.5}$ concentrations have occurred since 2013 [2,3]. However, continuous air quality improvement remains challenging as the current level of $PM_{2.5}$ concentrations is still high [4]. Meanwhile, with the implementation of pollution control measures, the future emission reduction potentials of air pollutants from the end-of-pipe controls are gradually narrowed [5]. In September 2020, China's government announced that China would strive to peak its CO_2 emissions by 2030 and achieve carbon neutrality by 2060. This ambitious goal not only provides a future direction for high-level socio-economic development but also sheds new lights on synergizing air pollution control and GHG emission reduction. Given that there are high synergies between tackling climate change and combating air pollution in different aspects such as physical mechanisms, objectives and metrics, control measures, benefits, and the governance system, with continuous low-carbon transition in the next 30 years, the carbon neutrality goal will provide powerful drivers for future air quality improvement.

Climate change and air pollution are intricately linked in physical mechanisms. Climate change induced by GHG emissions could lead to changes in meteorological factors such as temperature, radiation, precipitation, and wind speed (affecting the formation, accumulation, and dispersion of air pollution) [6,7]. Changes in meteorological factors could also impact emissions from natural sources such as vegetation, dust, and wildfires, which have significant contribution to air pollution [8–10]. Aerosols are major air pollutants, and they can also influence the climate system by altering the atmospheric radiation balance and promoting cloud formation [11].

Both climate change and air pollution can greatly affect public health. An increase in the frequency of extreme heat events and compound extremes induced by global climate change would increase the risk of mortality and morbidity [12,13], and the frequency of other extreme weather events (e.g., tropical cyclones and torrential rains) related to climate change would also pose a higher health risk in affected areas [14,15]. Changes in meteorological factors can contribute to the transmission risk of infectious diseases by affecting pathogens and vectors [16–18]. For example, precipitation may wash away pathogens attached to the soil surface, causing surface water pollution and increasing human exposure to diarrheal pathogens [18]. Long-term and short-term exposure to $PM_{2.5}$ or O_3 can increase public health risks [19–21]. $PM_{2.5}$ pollution increases mortality risk by causing cardiovascular, respiratory, and metabolic diseases and poor reproductive outcomes, while O_3 exposure increases mortality risk by causing chronic obstructive pulmonary disease [22,23]. In addition, recent studies have also found that short-term exposure to NO_2 increases the risk of death from cardiovascular and respiratory diseases [24].

In terms of objectives and metrics, China has pledged to peak its CO_2 emissions by 2030 and achieve carbon neutrality by 2060 from climate change mitigation perspective. On the other hand, China proposes to achieve the “Beautiful China” goal and a fundamental improvement of the ecological environment quality by 2035. In the long term, China will fully enhance the ecological civilization, and develop the modernized national governance capacity for ecology and the environment management by the middle of the century. While China's current annual average $PM_{2.5}$ air quality standard ($35\ \mu g\ m^{-3}$) only equals to the Interim target I set by the World Health Organization (WHO) [25], it is expected that future air quality standards in China will be gradually upgraded and eventually meet the WHO guideline.

Given that GHGs and air pollutants share the same sources and processes [1], control measures targeted to reduce fossil fuel consumption and carbon emissions will also mitigate air pollutant emissions, bringing synergetic benefits of air quality improvement [26]. Meanwhile, prompting source-oriented measures (such as fossil energy substitution, industrial process optimization, and upgrading industrial facilities, etc.) in air pollution control policies will in turn bring benefits of carbon reductions. Due to the large diversities in the industrial processes and technologies, emissions of air pollutants can vary by more than one to two orders of magnitude among different industries when same amount of CO_2 were emitted [1]. Prioritizing heavy-polluted industries when selecting GHG emission reduction measures can then achieve higher synergetic benefits in air quality improvement.

Increasing ecosystem carbon sinks is important to achieve carbon neutrality [27]. In the context of carbon neutrality, the remain carbon emissions will increase following the increase of future carbon sink and carbon emission pathways could be consequently changed. In this case, emitting sources that are very difficult to decarbonize (e.g., iron and steel, cement, diesel vehicles, ships) will probably be still existed and damage future air quality [28]. Therefore, the impact of future carbon sink changes on the synergetic reductions of CO_2 and pollutants should be considered when planning carbon reduction pathways.

Synergetic measures to address climate change and air pollution will bring significant health and economic benefits [4,29]. Tackling climate change can reduce the incidence of extreme weather events and thus bring direct health and economic benefits [30]. Furthermore, measures to reduce carbon emissions, such as energy structure optimization, will reduce air pollutant emissions as well as save pollution control costs and bring considerable health benefits [4,29]. Climate change mitigation measures can also improve the structure of the economy and promote new industries, which in turn will lead to job creation [31]. Meanwhile, improvements in air quality will lead to a reduction in the incidence of related diseases and an increase in labor productivity [32].

In terms of the governance system, coordinating climate change mitigation and air pollution control in the areas of strategic planning, laws and regulations, standards, and economic policies will help strengthen the synergetic management of air pollution and GHG emissions. Promoting the synergetic integration of the statistical survey system, evaluation and management system, monitoring and supervision system, inspection and assessment system, and other institutional systems will help promote the capacity of the relevant governance system and lay a sound foundation to support the synergetic management of climate change and air pollution. In this regards, selecting typical cities and regions as pilot demonstrations of air quality compliance and carbon emission peaking, and/or prompting key industries to implement pilot demonstrations on synergetic controls of air pollutants and GHGs will help provide practical experiences for widely performing the synergetic governance in the future.

Given the high synergies between climate change mitigation and air pollution control described above, in this perspective, we designed and analyzed 18 indicators (see Table 1 for details) to track the synergetic progress of carbon neutrality and clean air in China. The indicators cover the following five aspects: air pollution and associated weather-climate conditions; progress in structural transition; sources, sinks, and mitigation pathways of atmospheric composition; health impacts and benefits of the coordinated control; and synergetic governance system and practices. By tracking the progress in each indicator on a regular basis, we aim to establish a theoretical framework for the synergetic governance of carbon neutrality and clean air, identify the challenges in developing a synergetic roadmap for carbon neutrality and clean air for China, and provide corresponding policy recommendations.

This perspective is organized as follows. Sect. 1 focuses on air pollution and associated weather-climate conditions, analyzing the interaction between climate change and air pollution through three indicators: changes in air quality, variations in adverse meteorological conditions, and climate change and its impact on air pollution. Sect. 2 focuses on progress in structural transition by analyzing five indicators: the transition of the energy structure, industrial structure, and transportation structure, the process in air pollution control, and zero-carbon and carbon-negative technologies. Sect. 3 includes four indicators: anthropogenic CO_2 emissions, emissions of air pollutants and progress of coordinated control, land use change and land carbon sinks, and future mitigation potentials and synergetic pathway. Historical changes and drivers of China's emissions of major atmospheric compositions were presented and a synergetic pathway for China's future GHG emission reduction and air pollution control is proposed. Sect. 4 sets out three indicators on the health impacts and benefits of coordinated control: health impacts of air pollution, health impacts of climate change, and health co-benefits of carbon reduction. Sect. 5 focuses on the synergetic governance system and practices, including three indicators, namely construction of a synergetic governance system, economic policies for synergetic governance and local practices, to track the progress of synergetic governance system and summarize the experiences of synergetic governance practices. Summary and policy recommendation are provided at the end of this paper.

2. Air pollution and associated weather-climate conditions

2.1. Changes in air quality

Assessment of the level of national and regional air pollutant concentrations and real-time tracking of the average exposure level to air pollutants are direct and fundamental indicators of air quality improvement in China. Based on the air quality monitoring data published by the China National Environmental Monitoring Center (http://www.cnemc.cn/), this indicator is used to analyze the annual changes in air pollution concentrations in the country and the key regions. Meanwhile, based on a near real-time dataset of surface $PM_{2.5}$ and O_3 concentrations at a spatial resolution of 10 km provided by the Tracking Air Pollution in China (TAP, http://tapdata.org.cn/) [33,34], the long-term and short-term exposure levels to pollutants are also assessed.

In 2020, air pollutant concentrations in 337 cities across China and five key regions, i.e., the Beijing–Tianjin–Hebei and its surrounding regions (BTH), the Fenwei Plain (FWP), the Yangtze River Delta (YRD), Chengdu–Chongqing region (SCB), and the Pearl River Delta (PRD), all decreased compared with those in 2019. Specifically, annual concentrations of SO_2 and NO_2 in all cities reached the national air quality standard. However, $PM_{2.5}$ and O_3 concentrations have failed to meet the standards in many regions.

The average $PM_{2.5}$ concentration in 337 cities was 33 $\mu g\ m^{-3}$ in 2020, lower than the National Ambient Air Quality Standard Grade II (35 $\mu g\ m^{-3}$), which was 28.5% lower than that in 2015 (45 $\mu g\ m^{-3}$; Fig. 1a). In 2020, 202 out of the 337 cities met the ambient air quality standard, accounting for 59.9% of the total 337 cities. Specifically, the annual mean $PM_{2.5}$ concentration met the standard in 212 cities, accounting for 62.9% of the total. The regional average $PM_{2.5}$ concentration in YRD and SCB showed a steady decrease in 2020 and was below the standard for the first time. The $PM_{2.5}$ concentrations in the BTH and FWP were still high and fluctuated in some years. Considering the impact of meteorological conditions and the COVID-19 pandemic in 2020 on the interannual variation of air quality, the change in air quality was also assessed based on the 3-year moving average of pollutant concentrations. From 2015 to 2020, the 3-year moving average of $PM_{2.5}$ concentrations across the country and key regions continued to decrease (Fig. 1b), indicating significant achievements gained through the implementation of air pollution control policies in China (e.g., the *Action Plan on Prevention and Control of Air Pollution* and the *Three-Year Action Plan for Winning the Blue Sky Defense Battle*).

In 2020, the 90% quantiles of the maximum daily 8-h average O_3 concentrations (MDA8 O_3) in 337 cities ranged from 60 $\mu g\ m^{-3}$ to 192 $\mu g\ m^{-3}$, with an average concentration of 136 $\mu g\ m^{-3}$, which was 8.0% lower than that in 2019 and 11.1% higher than that in 2015. Compared with 2015, the O_3 concentrations in the five key regions increased by 11.0–32.1% (Fig. 1c). Based on the three-year moving average, the O_3 concentrations continued to increase from 2015 to 2020, and O_3 pollution gradually aggravated (Fig. 1d).

Changes in air pollution have altered the long-term and short-term exposure levels of Chinese population to air pollutants. The population-weighted mean $PM_{2.5}$ concentration in 2020 was 33.5 $\mu g\ m^{-3}$, which dropped by 36.6% compared to 2015 (Fig. 2a).

Table 1
The description of 18 selected indicators.

Indicators	Description
Air pollution and associated weather-climate conditions	
Changes in air quality	Analyze the annual changes in various air pollution concentrations in the key regions as well as the national scale during 2015–2020.
Variations in adverse meteorological conditions	Quantify the contribution of meteorological factors to the interannual variation in $PM_{2.5}$ concentration; Analyze the impact of interannual variations of total radiation and relative humidity on the O_3 concentration.
Climate change and its impact on air pollution	Explore the trend of climate change in China; Summarize the relevant research on the impact of climate change on air pollution; Analyze the impact of future climate change on the uncertainties of air quality prediction.
Progress in structural transition	
Transition of the energy structure	Present the remarkable achievements in the energy efficiency improvement and low-carbon development.
Transition of the industrial structure	Track the remarkable achievements in the industrial optimization and structural upgrade in China.
Transition of the transportation structure	Summarize the progress in the transformation of transportation structure, including energy efficiency improvement, clean energy substitution, transportation structure optimization, and urban transportation sustainability.
Progress in air pollution control	Summarize the implementation progress of eight key measures in China's air pollution control from 2013 to 2020.
Zero-carbon and carbon-negative technologies	Track the overall progress of zero-carbon and carbon-negative technologies in China; Analyze their future development trends considering technical feasibility and economic affordability.
Sources, sinks, and mitigation pathway of atmospheric composition	
Anthropogenic CO_2 emissions	Track the dynamic changes and driving forces of China's CO_2 emissions.
Emissions of air pollutants and progress of coordinated control	Analyze the trajectories of key air pollutants' emissions (i.e., SO_2, NO_x, primary $PM_{2.5}$, and VOCs) and the progress of synergetic mitigation of CO_2 emissions over the last two decades.
Land use change and land carbon sinks	Summarize contemporary understandings of the magnitude of China's land carbon sinks; Evaluate the factors affecting the land carbon sink quantification and the impacts of land use change on the land carbon balance.
Future mitigation potentials and synergetic pathway	Analyze the synergetic mitigation pathways of China's CO_2 and air pollutants emissions based on a series of established future emission scenarios.
Health impacts and benefits of coordinated control	
Health impacts of air pollution	Analyze the impacts of long-term and short-term $PM_{2.5}$ and O_3 exposures in China on mortality.
Health impacts of climate change	Analyze health impacts of different extreme climate events by summarizing the relevant achievements in the field of climate change and health impact.
Health co-benefits of carbon reduction	Discuss the public health impacts and co-benefits by reviewing the related studies.
Synergetic governance system and practices	
Construction of a synergetic governance system	Review the progress in the construction of the synergetic governance system from strategic planning, laws and regulations, and the management system.
Economic policies for synergetic governance	Review China's economic policies for synergetic controls of environmental pollution and CO_2 emissions in recent years.
Local practices	Summarize the progress of city-level air quality improvement and low-carbon practices; Analyze the city-level synergetic achievements of carbon emission reductions and air quality improvements.

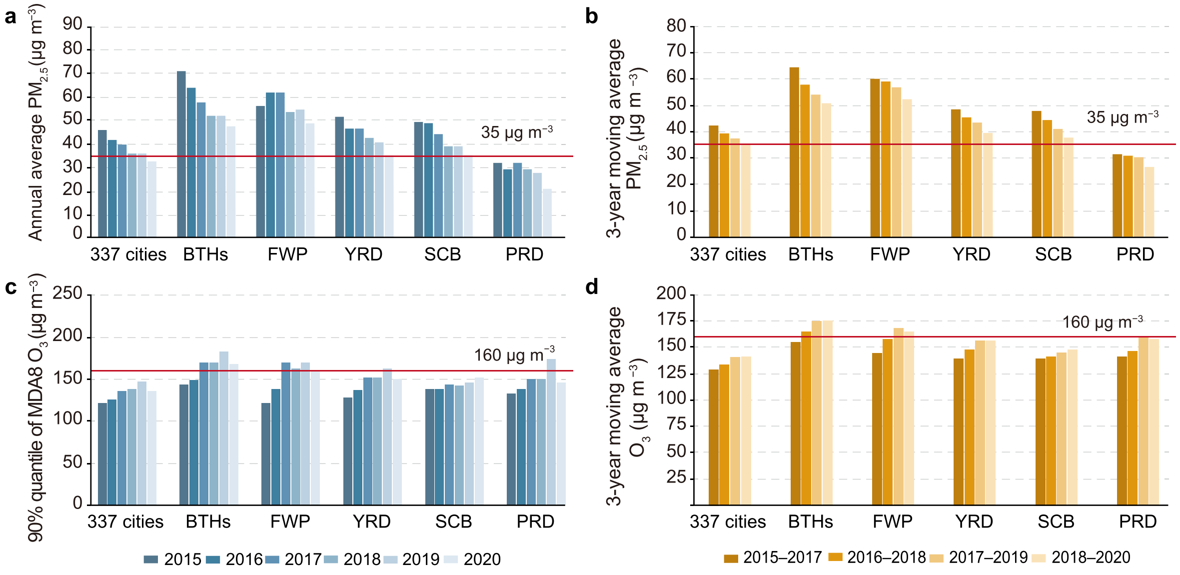


Fig. 1. Annual average and the three-year moving average concentrations of $PM_{2.5}$ (**a**, **b**), and the 90% quantile of the maximum daily 8-h average and the three-year moving average concentrations of O_3 (**c**, **d**) in China and key regions from 2015 to 2020. Data sources: China National Environmental Monitoring Center, http://www.cnemc.cn/.

The annual mean exposure levels of $PM_{2.5}$ in individual key regions varied between 21.5 and 50.7 μg m^{-3}, which was 24.8–42.2% lower than in 2015. Specifically, the improvement was most significant in BTH, followed by YRD. In 2020, approximately 43% of the Chinese population lived in places where the annual mean concentration exceeded the national air quality standard, showing a 43% decrease compared with that in 2015 (76%, Table 2). The chronic exposure level of Chinese residents to $PM_{2.5}$ pollution has significantly decreased. In particular, PRD has met the standards, but 99% of the population in BTH still lived in places where the annual mean $PM_{2.5}$ concentration exceeded the standard, indicating that $PM_{2.5}$ pollution remained severe. The population-weighted average number of

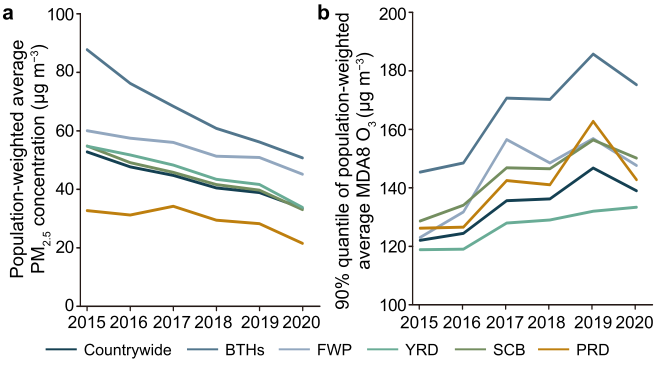


Fig. 2. Annual population-weighted average $PM_{2.5}$ (**a**) and 90% quantile of population-weighted maximum daily 8-h average O_3 (**b**) pollution in China and key regions from 2015 to 2020. Data sources: Tracking Air Pollution in China database, http://tapdata.org.cn/(Geng et al., 2021 [33]; Xiao et al., 2021a [34]).

Table 2
Summary of long-term and short-term exposure levels of $PM_{2.5}$ and O_3 pollution. Data sources: Tracking Air Pollution in China database, http://tapdata.org.cn/, [33,34].

	Population percentage in areas where annual average $PM_{2.5}$ exceeded the standard		Days of population-weighted average $PM_{2.5}$ that exceeded the standard	
Year	2015	2020	2015	2020
Countrywide	76%	43%	75 Days	27 Days
BTH	100%	99%	182 Days	64 Days
FWP	99%	92%	86 Days	58 Days
YRD	92%	37%	79 Days	23 Days
SCB	96%	46%	72 Days	24 Days
PRD	42%	0%	13 Days	1 Day
	Population percentage in areas where annual average MDA8 O_3 exceeded the standard		Days of population-weighted average MDA8 O_3 that exceeded the standard	
Year	2015	2020	2015	2020
Countrywide	3%	22%	7 Days	21 Days
BTH	13%	97%	20 Days	63 Days
FWP	0%	23%	2 Days	23 Days
YRD	3%	23%	11 Days	27 Days
SCB	4%	9%	4 Days	14 Days
PRD	1%	5%	7 Days	20 Days

days exceeding the standard (i.e., daily mean $PM_{2.5}$ concentration >75 μg m^{-3}) was 27 days in 2020, 48 days lower than that in 2015. The acute exposure level of Chinese residents to $PM_{2.5}$ pollution also improved significantly.

However, O_3 pollution shows the opposite trend. The 90% quantile of the population-weighted average MDA8 O_3 was 139.3 μg m^{-3} in 2020, a 13.8% increase compared to 2015 (Fig. 2b). The annual exposure levels to O_3 in individual key regions increased by 12.2–20.5% compared to 2015. The increase was most significant in BTH, followed by FWP. In 2020, approximately 22% of the Chinese population lived in places where the 90% quantile of the annual mean MDA8 O_3 exceeded the air quality standard (i.e., 160 μg m^{-3}, Table 2), which was approximately 6-fold more than that of 2015, and all the key regions experienced increases to different degrees. The population-weighted average number of days that exceeded the standard (MDA8 O_3 > 160 μg m^{-3}) was 21 days in 2020, which was 14 days more than that in 2015, and the number of days in individual key regions varied from 14 to 63 days, indicating an increasingly prominent ozone pollution problem.

2.2. *Variations in adverse meteorological conditions*

The formation, accumulation, and deposition of air pollution, as well as emissions from natural sources, are closely related to many meteorological factors (e.g., wind speed, radiation, humidity, precipitation, etc.) [6,35]. Therefore, analysis of the impact of adverse meteorological conditions on the changes in air quality in China could help design the clean air policies more scientifically. This indicator utilizes Parameter Linking Aerosol-pollution and Meteorology (PLAM index, which is positively and linearly correlated with $PM_{2.5}$ mass concentration) [7,36–38] to comprehensively diagnose and quantify the contribution of meteorological factors to the interannual variation in $PM_{2.5}$ concentration. Furthermore, the interannual variations in total radiation and relative humidity in China and their impacts on the ground-level ozone concentration are analyzed.

Fig. 3 shows the interannual variations of the PLAM index in the key regions from 2015 to 2020. In the Beijing–Tianjin–Hebei region, meteorological conditions continued to improve after 2015. Compared with 2019, meteorological conditions improved by approximately 11% in 2020, indicating that meteorological conditions contributed to approximately 11% of the decrease in $PM_{2.5}$ between the two years in this region. The variation in meteorological conditions in the Fenwei Plain was similar to that in the Beijing–Tianjin–Hebei region. Meteorological conditions in the Yangtze River Delta also improved from 2015 to 2020. Compared with those in 2019, the meteorological conditions in this region improved by approximately 13% in 2020. In the Pearl River Delta, the PLAM index has been decreased after 2017. In the Chengdu–Chongqing region, adverse meteorological conditions showed an improving trend from 2016 to 2020. Compared with

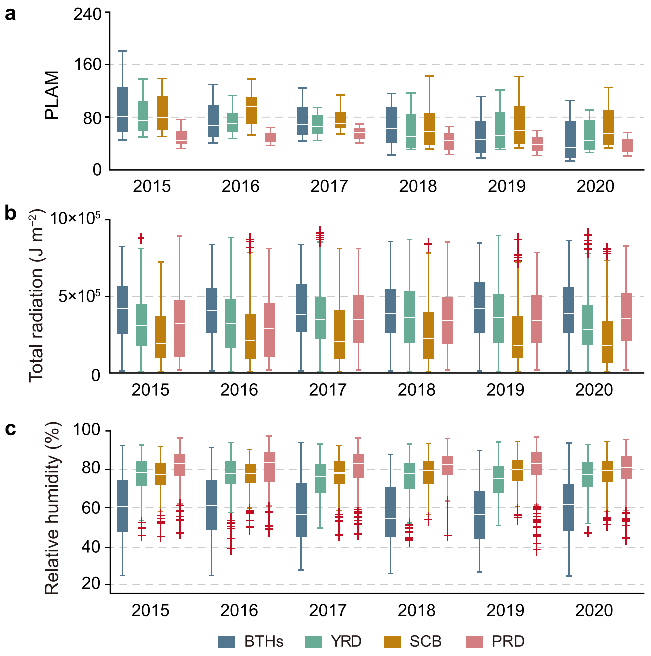


Fig. 3. Variations in annual mean PLAM index (a), total radiation (J m^{-2}) (b) and relative humidity (%) (c) in BTHs, YRD, SCB, and PRD during the 2015–2020 period. PLAM index was estimated by using the methods developed in previous studies (Zhang et al., 2009 and 2019 [7,36]; Wang et al., 2012 and 2013 [37,38]; total radiation and relative humidity data were obtained from China Meteorological Administration [39].

those in 2019, the meteorological conditions in this region improved by approximately 5% in 2020.

Relative humidity and total radiation in the key regions have remarkable impacts on the interannual variation of ground-level ozone pollution. During 2015–2020, the highest annual mean radiation occurred in the Beijing–Tianjin–Hebei region, and the lowest occurred in the Chengdu–Chongqing region. The annual mean radiation in the Beijing–Tianjin–Hebei region decreased by 3.63% in 2020 compared to 2019, which could contribute to the decrease in the ozone concentration. From 2015 to 2020, the annual mean radiation in the Yangtze River Delta showed an increasing trend at first, followed by a decreasing trend later, peaking in 2018 and then decreasing by 8.92% in 2020 compared to 2019. The annual mean radiation in the Pearl River Delta showed an increasing trend from 2015 to 2020 and exhibited a minor increase of 4.03% in 2020 compared to 2019. The interannual variation of the annual mean radiation in the Fenwei Plain was similar to that in the Beijing–Tianjin–Hebei region. In the Chengdu–Chongqing region, the annual mean radiation peaked in 2018 and then slightly decreased by 4.32% in 2020 compared to 2019 [39].

In the Beijing–Tianjin–Hebei region, the annual average relative humidity was approximately 60% during the 2015–2020 period, and the relative humidity was significantly higher in 2020 than in 2019, with an increase rate of 8.42%. In the Yangtze River Delta, the relative humidity in 2020 was 1.91% higher than in 2019. In the Pearl River Delta, the annual average relative humidity was approximately 80% during the 2015–2020 period, and the relative humidity in 2020 slightly decreased by 1.68% compared with that in 2019. The annual mean relative humidity in the Fenwei Plain also shows similar variation features to those in the Beijing–Tianjin–Hebei region. In the Chengdu–Chongqing region, the annual average relative humidity during the 2015–2020 period was approximately 80%, and the relative humidity slightly decreased from 2019 to 2020 by 1.14%.

2.3. Climate change and its impact on air pollution

The warming trend of the surface air temperature (SAT) and the increasing frequency of extreme weather-climate events induced by climate change significantly impact the variation in air pollution [40]. Air pollution is also closely related to variations in local precipitation, SAT, and wind speed at different time scales [41–43]. Abnormal large-scale climate factors (e.g., the East Asian winter monsoon, El Niño, Arctic sea ice, Eurasian snow cover, and the sea surface temperature (SST)) also affect the occurrence of air pollution in China by modulating atmospheric circulations [44–46]. This indicator is used to quantitatively explore the trend of climate change in China, summarize relevant research on the impact of historical climate change on air pollution, and analyze the impact of climate change on future air quality in China.

The global average atmospheric CO_2 concentration in 2020 was 412.5 ppm, which was 2.4 ppm higher than 2019. Comprehensive observations and several key indicators all reveal the significant trend of global warming. The global average of SAT in 2020 increased by approximately 0.98 °C compared with the mean of the 1951–1980 period, and 2020 was the second warmest year on record. China is located in the East Asian monsoon region, where climate variation is extremely complicated. The annual mean SAT in 2020 in China was 0.7 °C higher than that in the 1981–2010 period and slightly lower than 2019, which was the eighth-highest SAT record since 1951. Zhejiang, Jiangxi, Fujian, and Guangdong provinces recorded their highest SATs since 1961. The number of extreme high SAT events in 2020 significantly increased, and the daily maximum SAT at a total of 256 national stations reached the level of extreme events, among which 69 national stations experienced record-breaking extreme high SATs. In contrast, the number of extremely low SAT events in 2020 was less than the climate means but more than those in 2019 [47].

The Northwest Pacific subtropical high was abnormally strong in 2020, leading to more precipitation in most parts of China. The precipitation in winter and summer was 35% and 15% more than the climatological means, respectively, and the annual mean precipitation was 10.3% more than the climatological mean (7.6% more than that in 2019). Meanwhile, the extreme precipitation events occurred more frequently. Daily precipitation reached the level of extreme events at a total of 354 national stations, and historical records were exceeded at 45 national stations. In the winter of 2019/2020, the East Asian winter monsoon was significantly weak, and most parts of the eastern area of China were under the control of abnormal southerly winds, which hindered the dispersion of atmospheric pollutants. At the same time, the weak winter monsoon led to abnormal warm SAT in most regions. The average SAT in China was -2.2 °C in the winter of 2019/2020, which was 1.2 °C higher than the climatological mean.

Variations in meteorological factors (e.g., SAT, precipitation, and wind speed) caused by climate change have significant effects on aerosol pollution. Previous studies have shown that El Niño impacts on winter $PM_{2.5}$ pollution in South China [48]. In 2020, the tropical central-eastern Pacific SST was abnormally low, indicating a La Niña event, which might lead to worse atmospheric dispersion over South China in winter. The autumn external forcing factors (e.g., Arctic sea ice, the SST, and snow cover) can affect the background conditions for haze occurrence in North China by regulating atmospheric circulations [44–46]. In the autumn of 2020, the signals of Arctic sea ice, Pacific SST gradient, Atlantic SST, west Siberian snow depth, and central Siberian soil moisture in the key regions were all weak, and their influences on winter haze pollution in North China were relatively neutral. In the global warming background, the East Asian winter monsoon in the late-21st century will show a weakening trend, which will reduce the atmospheric environment capacity in most parts of China and worsen the ventilation conditions, thus aggravating haze pollution [41–43]. At the same time, the variation in aerosols can also influence the climate system by changing the atmospheric radiation budget, which in turn influences air quality. Previous studies have indicated that China's clean air action plans will significantly reduce pollutant emissions and aerosol concentrations. Aerosol radiative effects will thereby be reduced, and the dispersion conditions will be improved, leading to further air quality improvements and greater health benefits [11].

Regarding to the variations in ground-level ozone pollution in China under the global warming, many studies have indicated that the warming of the SAT and the decrease in cloud cover will likely cause a sharp increase in ozone pollution over the eastern area of China in the mid-21st century due to the co-effects of climate change and anthropogenic emissions [40,49–52]. Recent study also revealed that the indirect effects of changes in atmospheric circulations during the 2060–2100 period under the representative concentration pathway (RCP) 8.5 scenario may be beneficial for mitigating ozone pollution in the Beijing–Tianjin–Hebei region [53]. The results of the aforementioned studies indicate that some uncertainties in predicting future $PM_{2.5}$ and ozone pollution still exist, and further predictions need to be carried out under the carbon peak and carbon neutrality pathway.

3. Progress in structural transition

3.1. Transition of the energy structure

Transition to green and low-carbon energy is an important approach to engage high-quality economic development, to achieve carbon peak and carbon neutrality, and to promote the sustainable development of the economy, society, and the environment. Based on the data on the green energy transition and low-carbon development, this indicator revealed remarkable progress in energy efficiency improvement and green and low-carbon energy development during the 13th Five-Year Plan (FYP) period, and track the consequent social and economic impacts.

As shown in Fig. 4, the capacity of energy supply in China has been continuously increased. Total energy consumption in 2020 in China reached 4.98 billion tons of standard coal equivalent, increased by 2.2% over 2019 [54–56]. The energy intensity continues to decline: energy consumption and CO_2 emissions per unit of GDP in 2020 decreased by 13.2% and 8.8%, respectively, compared with 2015. Energy consumption per unit product also declined. For example, energy consumption per unit of calcium carbide production by key energy-intensive industrial enterprises decreased by 2.1% in 2020 compared to 2019, energy consumption per unit of synthetic ammonia increased by 0.3%, energy consumption per ton of steel decreased by 0.3%, energy consumption per unit of electrolytic aluminum decreased by 1.0%, and the standard coal consumption per kilowatt-hour of thermal power generation decreased by 0.6% [54–56].

The electrification rate continues to accelerate grow. In 2020, the coefficient of elasticity of energy consumption was 0.96, and the coefficient of elasticity of electricity consumption was 1.35, with electricity accounting for 27% of final energy consumption [57]. Clean energy power generation capacity accounted for 43.4% of total power generation capacity, with an increase rate of 2.6% from the previous year [54,55]. Coal consumption in 2020 accounted for 56.8% of total energy consumption, with a decrease rate of 0.9% from the previous year. By 2020, there were 43 pilot cities implemented clean heating actions in winter, covering Beijing–Tianjin–Hebei and its surrounding regions, and the Fenwei Plain. However, the electrification process was affected by the gap between new electricity demand and clean energy, the high economic cost of electrification, and the sustainability of clean energy use.

China continues to make tremendous efforts to develop non-fossil energy sources, promote transition to green and low-carbon energy. With the efforts, energy structure has been optimized and upgraded, contributing to reductions in air pollutants and GHG emissions and to high-quality economic growth. In 2020, non-fossil fuel energy accounted for 15.9% of primary energy consumption, which enabled the country to meet the 13th FYP target a year in advance. With the transition and upgrading of the energy structure, the installed capacity of renewable energy continues to increase. Specifically, the installed thermal power generation capacity, hydropower generation capacity, nuclear power generation capacity, grid-connected wind power generation capacity, and grid-connected solar power generation capacity reached 1.24 billion, 370 million, 49.89 million, 280 million, and 250 million kilowatts in 2020 respectively, increased by 4.7%, 3.4%, 2.4%, 34.6%, and 24.1% compared to the previous year, respectively. In 2020, the installed capacity of latter four non-fossil power sources increased by 1.7, 4.6, 9.5, and 975 times compared to 2010, respectively [58].

In 2020, the development and utilization of renewable energy resources in China reached 680 million tons of standard coal equivalent, which is comparable to replacing around 1 billion tons of raw coal, thus reducing carbon dioxide, sulfur dioxide, and nitrogen oxide emissions by approximately 1.79 billion tons, 0.86 million tons, and 0.80 million tons, respectively [59,60]. During the 14th FYP period, China will aim to develop a modern energy system, accelerate the development of non-fossil energy, increase the generation capacity of wind power and solar photovoltaic power, and accelerate the construction of ultra-high voltage (UHV) power transmission projects. China should slow down the construction of coal-fired power and increase the proportion of non-fossil energy in total energy consumption [61]. A higher electrification rate will help the peak consumption of coal, oil, and natural gas during next decade. In the long-term, the power sector will continuously develop renewable energy and promote carbon capture, usage, and storage (CCUS) to achieve deep decarbonization. A clean power system that can support the enormous energy demand of a highly electrified society must be built to achieve carbon neutrality before 2060.

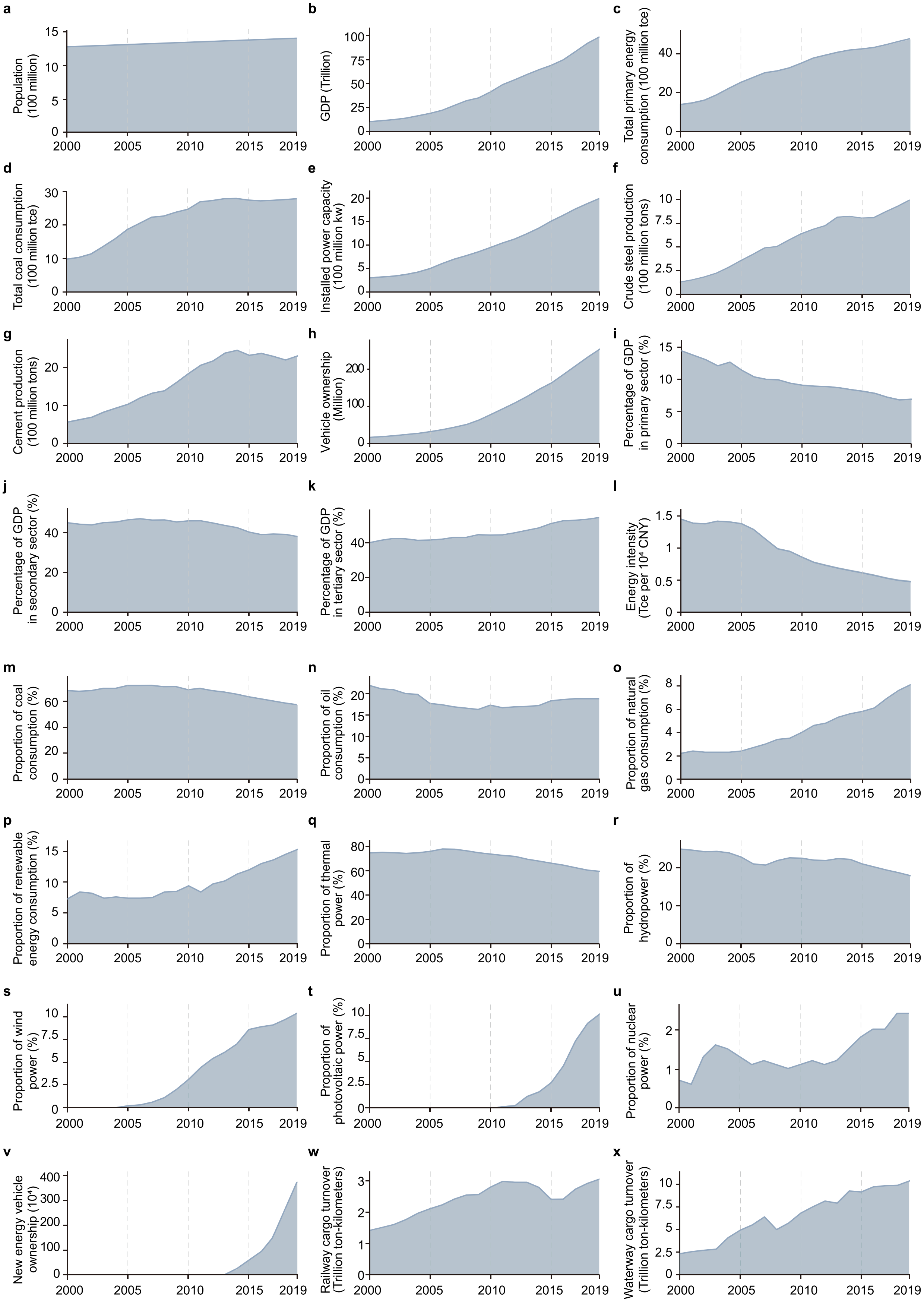
3.2. Transition of the industrial structure

In China, the synergetic action of energy conservation, carbon reduction, and air pollution prevention and control can be augmented by changing and restructuring industries. Resource savings and environmental protection should be incorporated into a modern industrial system that focuses on green and low-carbon circular economic development. Based on recent plans and policies, this indicator is used to track the optimization and structural upgrade in China's industry and review the progress made in transforming the industrial structure. This indicator is also used to track the effectiveness of replacing old growth drivers with new drivers, eliminating the outdated capacity of key industries, and retiring small and polluted enterprises.

From 2015 to 2020, China's GDP increased from 68.9 to 101.6 trillion yuan. Specifically, the added value of the primary and secondary industries decreased from 9.0% and 40.5% to 7.7% and 37.8%, respectively, while that of the tertiary industry increased from 50.5% to 54.5%, making it the country's most prominent driver of economic growth (Fig. 4) [56,62]. Emerging industries grew fast. From 2015 to 2020, among industrial companies with annual revenue of more than 20 million yuan, the added value of the technologically advanced manufacturing industry increased from 11.8% to 13.1%, while that of the equipment manufacturing industry increased from 31.8% to 33.7% [56,62]. These strategic emerging industries have surged as the leading drivers of industrial structure optimization and upgrades in China.

Progress in eliminating outdated capacity and overcapacity in the traditional manufacturing industries has been observed [63,64]. Efforts to reduce the outdated production capacity of the key industries were further enhanced during the 13th FYP. Accordingly, the overcapacity elimination targets for the iron and steel industry, coal industry, and coal-fired power plants were achieved ahead of schedule. From 2013 to 2017, China successfully eliminated 200 million tons of outdated and excess capacity of iron and steel, 250 million tons of cement, 110 million weight boxes of flat glass, and 25 million kilowatts of coal-fired power units [1]. The elimination of outdated production capacity was continued from 2018 to 2020, and excess capacity accounting for 120 million tons of iron and steel, 140 million tons of cement, 50 million weight boxes of flat glass, and 20 million watts of coal-fired power units was further eliminated. Similarly, from 2013 to 2017, approximately 300,000 small and polluted enterprises were identified and retired. From 2017 to 2020, another 360,000 of these enterprises were retired. The upgrading and transition of the industrial structure play a significant role in improving air quality. It is estimated that eliminating outdated production capacities from 2013 to 2017 reduced the national average $PM_{2.5}$ concentration by 2.8 $\mu g\ m^{-3}$ in 2017 [2].

In the future, industrial structure transition in China should focus on developing new and modernized industries that are technologically advanced and environmentally sustainable. Furthermore, promoting the utilization rate of current production capacity is needed. For heavy industries (e.g., iron and steel,


a
Population (100 million)
0
5
10
15
b
GDP (Trillion)
0
25
50
75
100
c
Total primary energy consumption (100 million tce)
0
20
40
d
Total coal consumption (100 million tce)
0
10
20
30
e
Installed power capacity (100 million kw)
0
5
10
15
20
f
Crude steel production (100 million tons)
0
2.5
5
7.5
10
g
Cement production (100 million tons)
0
10
20
h
Vehicle ownership (Million)
0
100
200
i
Percentage of GDP in primary sector (%)
0
5
10
15
j
Percentage of GDP in secondary sector (%)
0
20
40
k
Percentage of GDP in tertiary sector (%)
0
20
40
l
Energy intensity (Tce per 10⁴ CNY)
0
0.5
1
1.5
m
Proportion of coal consumption (%)
0
20
40
60
n
Proportion of oil consumption (%)
0
5
10
15
20
o
Proportion of natural gas consumption (%)
0
2
4
6
8
p
Proportion of renewable energy consumption (%)
0
5
10
15
q
Proportion of thermal power (%)
0
20
40
60
80
r
Proportion of hydropower (%)
0
10
20
s
Proportion of wind power (%)
0
2.5
5
7.5
10
t
Proportion of photovoltaic power (%)
0
2.5
5
7.5
10
u
Proportion of nuclear power (%)
0
1
2
v
New energy vehicle ownership (10⁴)
0
100
200
300
400
w
Railway cargo turnover (Trillion ton-kilometers)
0
1
2
3
x
Waterway cargo turnover (Trillion ton-kilometers)
0
2.5
5
7.5
10
2000
2005
2010
2015
2019

cement, etc.), short-term plans should continue to explore the emission reduction potential through capacity and production reduction, energy efficiency improvement, fuel structure optimization, waste recycling, and the promotion of circular economy. Long-term goals should target to enhanced technology upgrading and process innovation, application of breakthrough low-carbon technology, exploration of hydrogen smelting and innovative cement products, and the development of CCUS technology. Coordination between various emission reduction technologies should be undertaken to strive for deep decarbonization and accelerated carbon neutrality.

As China's economy will continue to maintain a medium-to-high growth rate in the future, and urbanization is still in progress, the key challenges for achieving peak carbon emissions before 2030 include further adjustment and upgrading of the industrial structure, effective reduction for the demand for energy-intensive industrial products, the energy efficiency improvement, and the energy structure optimization. In the context of carbon emission peak and carbon neutrality, it is necessary to consider regional variabilities in natural resources and development stages across China and design feasible transition pathways to promote the synergetic development of the regional economy and industry.

3.3. *Transition of the transportation structure*

China has made substantial progress in developing low-carbon transportation systems in recent years. This indicator is used to summarize the progress in the transition of the transportation structure from the aspects of energy efficiency improvement, the clean energy transition, transportation structure optimization, and urban transportation sustainability.

The energy efficiency of the transportation sector has continued to improve over the past decade. Since 2006, China has gradually implemented fuel consumption standards for light-duty passenger vehicles in five phases [65]. The target for national average fuel consumption in 2020 was set at 5 L per 100 km [66], which was 18% lower than the 2015 level [67]. The energy efficiency of China's civil aviation has also been improved; the estimated fuel consumption per ton-kilometer was 0.285 kg in 2019, 16.2% lower than that in 2005 [68]. Energy consumption per passenger at the airport in 2019 was approximately 15.8% lower than the level at the end of the 12th FYP (2013–2015) [68]. However, the gap between the actual and labeled fuel consumption of passenger cars has been increased in the past decade. For commercial vehicles, actual fuel consumption has rarely been evaluated. Therefore, there is an urgent need to strengthen the evaluation and supervision of real-world energy efficiency.

The transition to clean energy has steadily been promoted, with multiple incentive policies in place, such as the *Ten Cities and Thousand Vehicles* demonstration program for the promotion of new energy vehicles (NEVs) and development plans for NEV industry. As a result, the population of NEVs (mostly electric vehicles, EVs) in China reached four million in 2019 (Fig. 4), accounting for more than 50% of global EV sales [69]. The electrification of railway transportation has gradually been prompted; China's total number of railway locomotives was 21,000 in 2019, 62% of which were electrified locomotives, with less than 8,000 units of internal combustion locomotives [70]. Clean energy has been largely utilized in China's airports and ports. In 2019, 83% of the energy consumption in China's airports was electricity, natural gas, and purchased heat. More than 95% of large-scale airports (i.e., with annual passenger traffic higher than five million people) have completed the installation and utilization of electrified auxiliary power units (APUs). EVs have accounted for approximately 7.5% of the total ground service vehicles in airports, while more than 5,400 sets of port shore power facilities had been built in China by 2020, covering more than 7,000 berths (including water service areas) [71].

The transportation structure has also been gradually improved. In recent years, China has effectively promoted the optimization of freight modes, such as “road to railway” and “road to water”, especially for bulk cargo transportation. Guided by the *Three-Year Action Plan for Promoting Transportation Structure Adjustment*, the freight transportation structure has been significantly optimized, and the volume of bulk cargo transported by railways, and the waterways has increased significantly. In 2020, the total railway freight volume in China was 4.552 billion tons, and waterway freight volume was 7.616 billion tons, increased by 863 million tons and 959 million tons respectively compared to 2017 [72]. During the 13th FYP period, the construction of intercity railways in China's key regions was rapidly implemented. As a result, medium-and long-distance travels were gradually changed from road transportation to high-speed railways. The average annual growth rate of railway passenger traffic in China was 9.6% from 2015 to 2019. By 2020, the operating mileage of China's high-speed railway reached 38,000 km, covering nearly 95% of medium-sized and large cities (i.e., with a population of more than one million) [72].

Urban transportation sustainability has been prompted as well. During the 13th FYP period, NEVs has been developed rapidly in urban public transportation, taxis, and delivery services. The proportion of green travel modes in the urban areas of megacities, such as Beijing and Shanghai, exceeded 70%. By the end of 2020, the operating mileage of urban rail transit systems reached 7,000 km with near 100% 500-m coverage rate for bus stations in the urban areas of medium-sized and large cities [73].

For further improving transportation energy efficiency, energy-saving technologies (such as advanced powertrain technologies), transmission efficiency, better automotive thermal management, and lightweight technologies should all be adopted to conventional energy vehicles [74]. It is estimated that the average fuel consumption of conventional light-duty passenger vehicles will decrease by 30%, and that of heavy-duty commercial vehicles will decrease by 15% from 2020 to 2030 [58]. For clean energy transition, it is important to further promote EVs, particularly with higher penetration in public transport, taxis, and delivery fleets, and to consider formulating a clear schedule for phasing out the sale of conventional fuel vehicles. For heavy-duty vehicles, ships, and aircraft, exploring low-carbon and zero-carbon alternative technologies such as electrification, hydrogen, and renewable fuel technologies are necessary to achieve zero emissions in the transportation sector. For urban transportation sustainability, it is important to accelerate the development of urban public transport and intercity high-speed railway systems, increase the share of other green transportation modes (e.g., bikes), provide rational guidance for the use of passenger cars, and eventually develop an integrated system adapting green travel modes.

Fig. 4. Changes of social economics and progress in structural transition from 2000 to 2019: population (**a**), GDP (**b**), total primary energy consumption (**c**), total coal consumption (**d**), installed power capacity (**e**), crude steel production (**f**), cement production (**g**), vehicle ownership (**h**), percentage of GDP in primary sector (**i**), percentage of GDP in secondary sector (**j**), percentage of GDP in tertiary sector (**k**), energy intensity (**l**), proportion of coal consumption (**m**), proportion of oil consumption (**n**), proportion of natural gas consumption (**o**), proportion of renewable energy consumption (**p**), proportion of thermal power (**q**), proportion of hydropower (**r**), proportion of wind power (**s**), proportion of photovoltaic power (**t**), proportion of nuclear power (**u**), new energy vehicle ownership (**v**), railway cargo turnover (**w**), waterway cargo turnover (**x**). Data sources: National Bureau of Statistics, http://www.stats.gov.cn; Ministry of Public Security, http://www.mps.gov.cn/.

3.4. *Progress in air pollution control*

Since 2013, with the implementation of the *Action Plan on Prevention and Control of Air Pollution* and the *Three-Year Action Plan for Winning the Blue Sky Defense Battle,* China's air pollution prevention and control have accelerated in all respects. Pollution control measures on industry, coal burning, motor vehicles, agriculture, and fugitive dust have comprehensively been implemented and tightened, successfully promoted the “air pollution and carbon emission reduction” synergies. Here we select eight key measures in China's pollution controls, summarize the progress in the implementation of these measures from 2013 to 2020 (Fig. 5), analyze and discuss the future potentials of these eight measures to reduce carbon and pollution in the context of the carbon peak and carbon neutrality targets.

(1) Ultralow emission retrofitting of coal-fired power plants. Since 2015, China has implemented large-scale ultralow emission retrofitting for coal-fired power plants, making the emission levels of coal-fired power plants comparable to those of gas-fired power plants. By the end of 2020, approximately 950 million kW of coal-fired power units in China had achieved ultralow emission standards, forming the world's largest clean coal-fired power generation system [75].

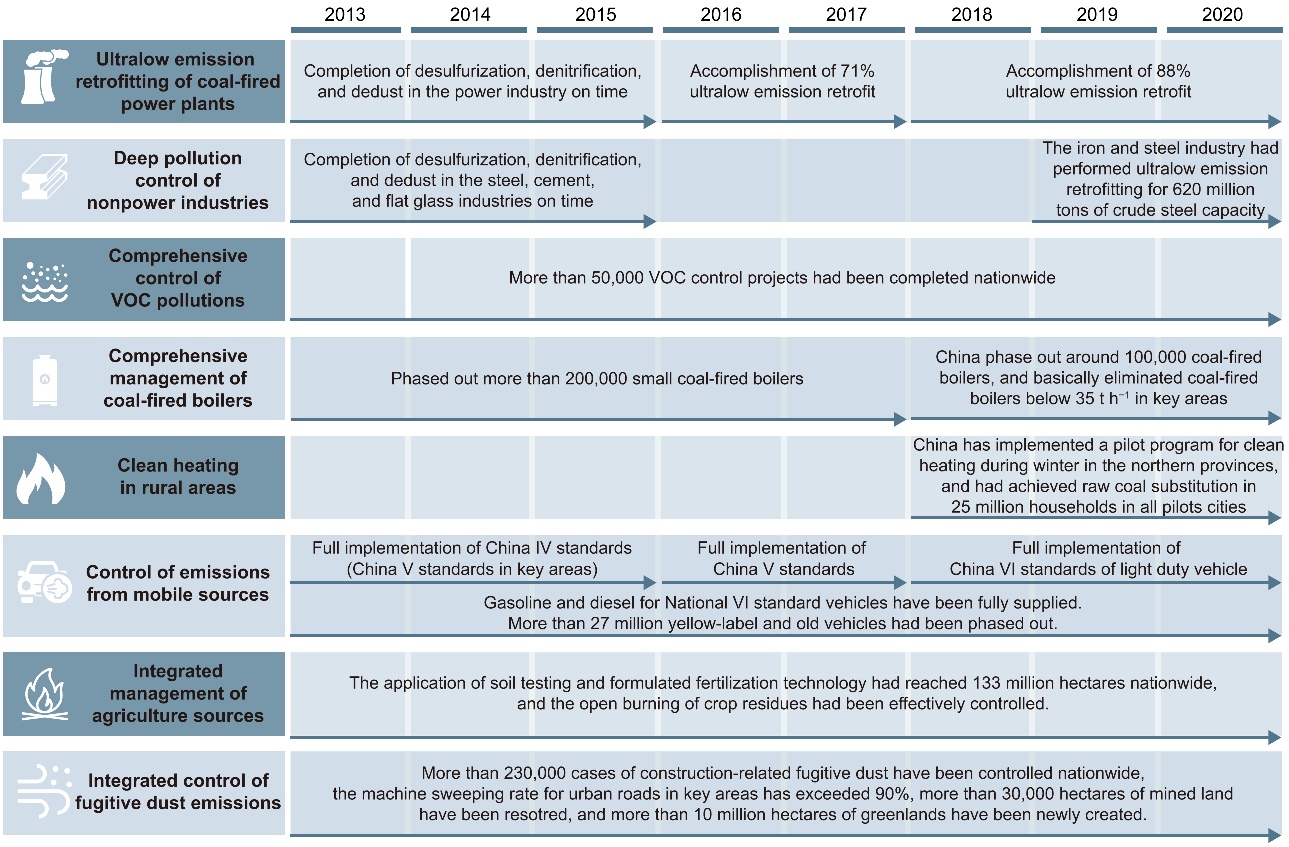
(2) Deep pollution control of industries. Since 2013, China has formulated and revised emission standards for the cement, petrochemical, coatings and inks, pharmaceuticals, and other industries; carried out in-depth emission control of industrial furnaces and kilns; and initiated ultralow emission retrofitting in the iron and steel industries. By the end of 2020, the iron and steel industry had performed ultralow emission retrofitting for 620 million tons of crude steel capacity.

(3) Comprehensive control of VOCs pollution. During the 13th FYP period, China's VOCs pollution prevention and control were rapidly advanced, and a series of industry and product emission standards and related control policy documents was successively released. By the end of 2020, more than 50,000 VOCs control projects had been completed nationwide.

(4) Comprehensive management of coal-fired boilers. During the 2018–2020 period, China phased out around 100,000 coal-fired boilers and basically eliminated coal-fired boilers below 35 t h^{-1} in key areas.

(5) Clean heating in rural areas. Since 2017, China has implemented a pilot program for clean heating during winter in the northern provinces. By the end of 2020, the project had achieved raw coal substitution in 25 million households in all pilot cities in the Beijing–Tianjin–Hebei and its surrounding regions, as well as the Fenwei Plain.

(6) Control of emissions from mobile sources. China has gradually tightened motor vehicle emission standards and phased out high-emission vehicles. Since July 1, 2020, the National VI Standard for light vehicles has been implemented nationwide. Gasoline and diesel for National VI standard vehicles have been fully supplied. For automotive diesel, general diesel, and some marine fuels, “three fuels under one track”



Ultralow emission retrofitting of coal-fired power plants
Completion of desulfurization, denitrification, and dedust in the power industry on time
Accomplishment of 71% ultralow emission retrofit
Accomplishment of 88% ultralow emission retrofit

Deep pollution control of nonpower industries
Completion of desulfurization, denitrification, and dedust in the steel, cement, and flat glass industries on time
The iron and steel industry had performed ultralow emission retrofitting for 620 million tons of crude steel capacity

Comprehensive control of VOC pollutions
More than 50,000 VOC control projects had been completed nationwide

Comprehensive management of coal-fired boilers
Phased out more than 200,000 small coal-fired boilers
China phase out around 100,000 coal-fired boilers, and basically eliminated coal-fired boilers below 35 t h^{-1} in key areas

Clean heating in rural areas
China has implemented a pilot program for clean heating during winter in the northern provinces, and had achieved raw coal substitution in 25 million households in all pilots cities

Control of emissions from mobile sources
Full implementation of China IV standards (China V standards in key areas)
Full implementation of China V standards
Full implementation of China VI standards of light duty vehicle
Gasoline and diesel for National VI standard vehicles have been fully supplied. More than 27 million yellow-label and old vehicles had been phased out.

Integrated management of agriculture sources
The application of soil testing and formulated fertilization technology had reached 133 million hectares nationwide, and the open burning of crop residues had been effectively controlled.

Integrated control of fugitive dust emissions
More than 230,000 cases of construction-related fugitive dust have been controlled nationwide, the machine sweeping rate for urban roads in key areas has exceeded 90%, more than 30,000 hectares of mined land have been resotred, and more than 10 million hectares of greenlands have been newly created.

Fig. 5. Progress in China's air pollution controls from 2013 to 2020. Data sources: Ministry of Ecology and Environment, unpublished data.

has been achieved. By the end of 2020, more than 27 million yellow-label and old vehicles had been phased out.

(7) Integrated management of agriculture sources. By the end of 2020, the application of soil testing and formulated fertilization technology had reached 133 million hectares nationwide, and the open burning of crop residues had been effectively controlled.

(8) Integrated control of fugitive dust emissions. Since 2013, urban and rural environmental management has been gradually strengthened, with fugitive dust pollution being effectively controlled. To date, more than 230,000 cases of construction-related fugitive dust have been controlled nationwide, the machine sweeping rate for urban roads in key areas has exceeded 90%, more than 30,000 ha of mined land have been restored, and more than 10 million hectares of green areas have been newly created.

With the carbon peak and carbon neutrality targets being incorporated into the overall planning for the ecological civilization, China must strengthen the synergetic control of GHG and air pollutant emissions, as well as $PM_{2.5}$ and ozone in the future. With the implementation of clean air actions, the end-of-pipe emission reduction potential has been gradually exhausted, and measures for in-depth pollution control of industries, VOCs control, mobile source emission control, and clean heating in rural areas are expected to play more important roles in the future. For VOCs and NH_3 whose emissions have not yet been reduced effectively, effective emission reduction measures should be promoted and the synergies of pollution and carbon reduction should be considered.

3.5. Zero-carbon and carbon-negative technologies

Scientific and technological innovation are important for achieving the goal of carbon neutrality. The vision of the carbon peak and carbon neutrality proposed by China sets further requirements for research innovation and technological development. Zero-carbon technologies, including wind power, solar power, and biomass power generation, and carbon-negative technologies will provide strong support for the green and low-carbon transition of China's energy system. The indicator proposed in this section is used to summarize the overall progress in zero-carbon and carbon-negative technologies in China and to analyze their future development trends. The indicator is expected to provide a basis for further exploring the technical feasibility and economic affordability of zero-carbon and carbon-negative technologies and seeking the preferential development direction of technological breakthroughs.

Leapfrog development was achieved in the wind power and solar power industries. The installed capacity of wind power and photovoltaic power increased rapidly during the 13th FYP period, reaching 281 GW and 253 GW by the end of 2020, respectively [76]. From 2015 to 2020, the curtailment rates for wind and solar power decreased significantly from 15% and10% to 3% and 2%, respectively. This issue is expected to be fully resolved during the 14th FYP period. In 2019, the average capacity of new wind turbines reached 2,454 kW, with an average wheel diameter of 129 m and an average hub height of 96 m [77]. Compared with the 2015 levels, an increase in these three abovementioned indicators of 33%, 30%, and 22% was gained (Table 3). The average efficiency of the industrial PERC (passivated emitter and rear cell) monocrystalline silicon solar cells reached 22.3% in 2019 and is expected to reach 25.0% in 2025. In the past decade, the average levelized costs of onshore wind and solar power have decreased by 30% and 75%, respectively. The 14th FYP period will become critical for realizing the full grid parity of wind power and solar power without subsidies [78].

Other non-fossil energy technologies have been developed rapidly. By the end of 2020, the cumulative installed capacity of biomass power generation reached 29.52 GW, and the generation efficiency was significantly improved. Domestic waste incineration has become the principal mode of new biomass power generation installations and an industry investment hotspot. In 2020, the new installation capacity of biomass power generation in China reached 5,536 MW, including 3,150 MW of waste incineration, 2,262 MW of agricultural and forestry biomass, and 125 MW of biogas. The installed capacity of hydropower reached 370 GW by the end of 2020, and the hydropower curtailment situation was significantly improved. The overall effective utilization rate of hydropower reached 96% in 2019 [79]. The world's first 1-GW turbines designed and manufactured domestically in China have been successfully installed at the Baihetan Hydropower Station on the Jinsha River. Significant progress in geothermal power generation and concentrating solar power (CSP) generation technologies has been made. The first batch of CSP projects have been completed, and tower CSP equipment has been put into operation. A total of 43 nuclear power generation units are in operation by the end of 2019, with a total installed capacity of 48.75 GW [80]. The independent development of third-generation nuclear power technology, represented by Hualong-1 and Guohe-1, has been completed and implemented.

Research on carbon-negative technology has made significant progress. Carbon-negative technology can directly absorb and convert CO_2, which is necessary for achieving carbon neutrality target. To date, CCUS is the only technology that can be implemented to reduce carbon emissions from fossil fuel on a large scale. In China, the geological carbon storage capacity is estimated to be ~1,500–3,000 Gt [81]. As of 2021, there are about 40 CCUS demonstration projects in operation or under construction in China, with a total capture capacity of ~3 million tons per year and a cumulative injection of ~2 million tons of CO_2 [82]. Bioenergy with carbon capture and storage (BECCS) features large potential for negative emissions. If China fulfills net-zero emission target by 2060, the installed capacity of BECCS technology is expected to reach 250 GW by 2050 [83]. Currently, there are only five BECCS demonstration projects in operation around the world, with a total capture scale of ~1.5 million tons per year. In addition, direct air capture (DAC) technology also has high potential for negative emissions. By Nov. 2021, there are 19 DAC units in operation worldwide, with a total capture scale of more than 0.1 Mt per year [84].

In the future, China intends to accelerate the development of non-fossil energy generation by promoting wind power and solar power, developing offshore wind power, accelerating the construction of hydropower bases in Southwest China, and promoting

Table 3
Development of typical indicators of newly installed wind turbines in China from 2009 to 2019. Data sources: Chinese Wind Energy Association, 2020 [77].

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Average capacity (kW)	1360	1447	1550	1646	1720	1767	1837	1995	2112	2183	2454
Average wheel diameter (m)	72	78	81	85	89	94	99	105	112	120	129
Average hub height (m)	-	-	-	-	-	-	80	82	85	91	96

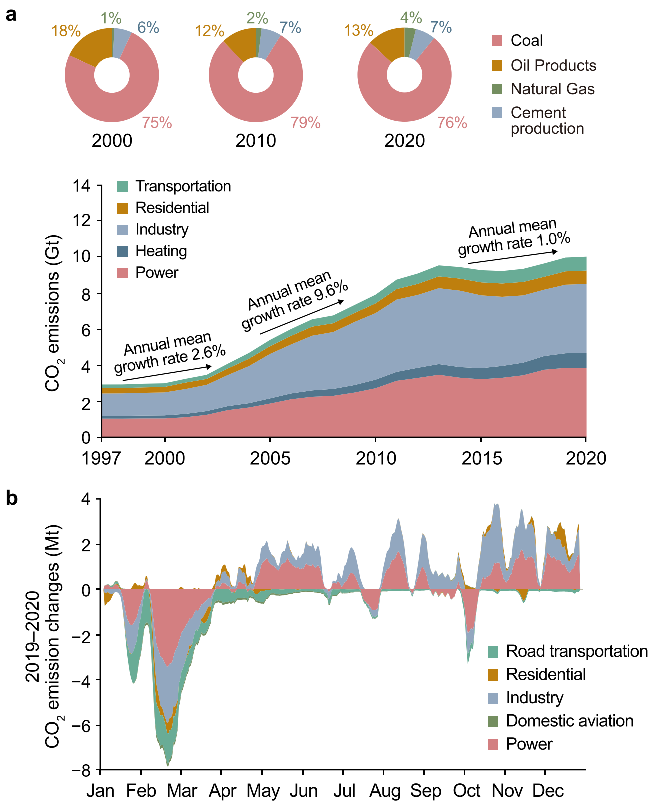


Fig. 6. Trend of China's CO_2 emissions from 1997 to 2020 by sector (i.e., power, heating, industry, residential, and transportation) and fuel type/process (i.e., coal, oil products, natural gas and cement production) (**a**); Monthly variations in China's CO_2 emissions from 2019 to 2020 by sector (i.e., power, industry, residential, road transportation, and domestic aviation) (**b**). Data sources: China Emission Accounts and Datasets, https://ceads.net/; Shan et al., 2018 and 2020 [85,86]; Carbon Monitor, http://carbonmonitor.org; Liu et al., 2020a and 2020b [88,89].

the construction of coastal nuclear power steadily. It is expected that by the end of the 14th FYP period, the installed capacity of renewable energy will exceed 50% of the national total installed capacity. Meanwhile, carbon-negative technology in China has made significant progress on development and demonstration. However, the overall costs of carbon capture and storage are still high. Further technology development and incentive policies (e.g., carbon trading market) will help to prompt the development of a carbon-negative technology industry in the future.

4. Sources, Sinks, and Mitigation Pathway of Atmospheric Composition

4.1. Anthropogenic CO_2 emissions

This indicator aims to track the changes and driving forces of China's CO_2 emissions and investigate the progress and challenges of emission reduction. Annual CO_2 emission data were derived from Carbon Emission Accounts and Datasets (CEADs, https://ceads.net/) [85,86], which is estimated using the data from the China Energy Statistics Yearbook and following the Intergovernmental Panel for Climate Change (IPCC) GHG inventory guidelines [87]. Monthly CO_2 emission data for 2019 and 2020 were taken from Carbon Monitor datasets (http://carbonmonitor.org) [88,89], which is estimated using dynamic proxies such as electricity generation data, industry production data, traffic volume, etc.

Fig. 6a presents China's CO_2 emissions from fossil fuel combustion and industrial processes during 1997–2020. During 1997–2001, CO_2 emissions in China increased slowly with an annual growth rate of 2.6%. In 2001, national total CO_2 emissions were approximately 3.2 Gt. Driven by economic growth and urbanization, CO_2 emissions increased rapidly from 2002 to 2013 with an annual growth rate of 9.6%, making China the world's largest emitter during this period. Emissions were slightly decrease after 2013 but rebounded since 2017. In 2020, national total CO_2 emissions were approximately 10 Gt.

Industry is the largest CO_2 emission sector in China, contributing 41% of total anthropogenic CO_2 emissions in 2000. With the rapid development of heavy industries (e.g., Iron/steel production, cement production, etc.), the contribution from industry sector increased to 46% in 2010. After that, the share of industrial emissions has been decreased gradually, leading to 38% of the national total emissions in 2020. Electricity is the second largest sector of CO_2 emissions, and its contribution to national total emissions was slightly increased from 36% in 2000 to 38% in 2020.

Coal combustion contributed 76% of total CO_2 emissions in China in 2020. During 1997–2020, the contribution from coal emissions initially increased and then slightly decreased. Combustion of oil product is the second largest source of CO_2 emissions, accounted for 12–18% of total emission in different years. Emissions from natural gas increased from 37 Mt in 1997 to 42 Mt in 2020 with an annual growth rate of 11%.

Based on the data from the Carbon Monitor database [88,89], total emissions in China in 2020 slightly increased by 0.5% compared to 2019. Specifically, emissions from industry, power generation, and residential sector increased by 3%, 1%, and 0.5%, respectively, while emissions from the ground transport and aviation sectors decreased by 13% and 18%, respectively.

Specifically, national total CO_2 emissions in the first quarter of 2020 decreased by 11% compared to 2019 due to the impact of COVID-19 pandemic. Emissions from civil aviation, ground transportation, industry, power generation, and residential sector decreased by 10%, 32%, 10%, 8%, and 4%, respectively. Emissions in February 2020 was the lowest due to the combined effects of the Spring Festival vacation and pandemic control measures, with a decreasing rate of 19%. CO_2 emissions from ground transportation and civil aviation in February 2020 decreased by 54% and 71%, respectively, compared to February 2019, due to the strict lockdown measures such as travel restriction and social distancing. CO_2 emissions from power generation and industry sector decreased by 14% and 17%, respectively, in February 2020 compared to 2019. With the rapid control of the COVID-19 pandemic, CO_2 emissions were gradually rebounded. CO_2 emissions in April 2020 have exceeded those in April 2019. Specifically, emissions from power generation, industry and residential sector were 1%, 3%, and 7% higher than emissions in April 2019. After April 2020, monthly emissions all exceeded emissions in the same month in 2019. In 2020, emissions in the second- and third-quarter increased by 3% compared to 2019, and emissions in the fourth-quarter increased by 6% compared to the same period in 2019.

4.2. Emissions of air pollutants and progress of coordinated control

Emissions of CO_2 and air pollutants have not only common sources, but also have large synergetic effects on control measures. Here, Multi-resolution Emission Inventory for China (MEIC, http://meicmodel.org.cn/) [1,90] combined with anthropogenic CO_2 emissions in Sect. 4.1 are used to analyze the trajectories of key air pollutant emissions (i.e., SO_2, NOx, primary $PM_{2.5}$, VOCs) and CO_2 emissions over the last two decades at sectoral level. The synergies between CO_2 and air pollutants are estimated at the same scales.

Driven by various policy packages (Fig. 7a) , primary $PM_{2.5}$, SO_2

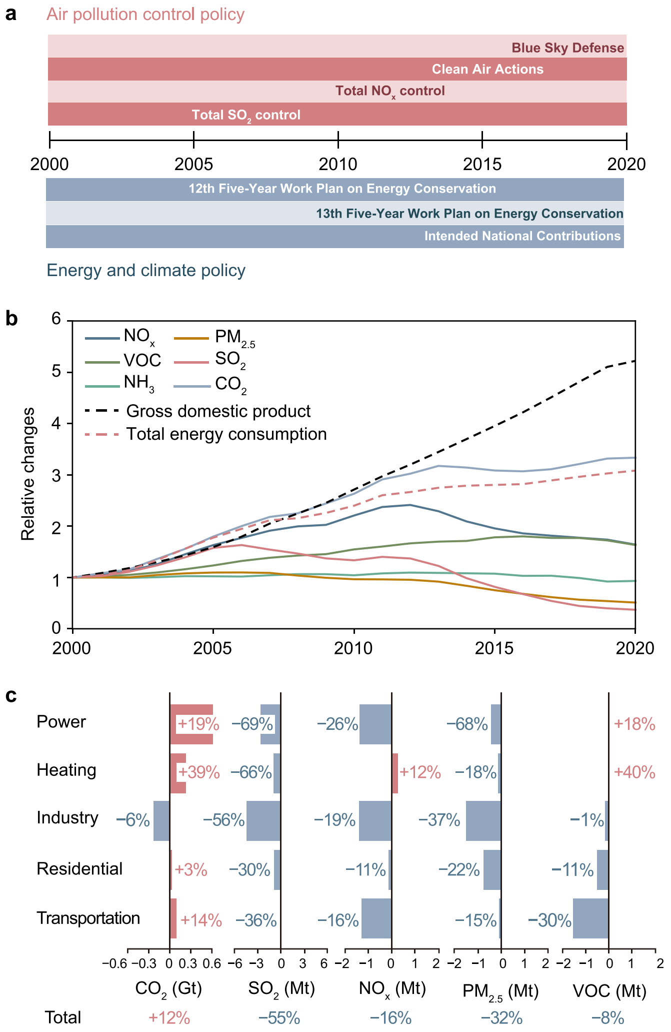


Fig. 7. Relative changes in anthropogenic CO_2 and air pollutant emissions in China from 2000 to 2020 (**a**); Changes of CO_2 and air pollutants emissions from 2015 to 2020 by sector (**b**). Data sources: MEIC, http://meicmodel.org.cn/; Li et al., 2017 [90]; Zheng et al., 2018 [1].

and NOx emission trends have increased first and then decreased significantly during last two decades. However, emissions of VOCs and CO_2 showed a continuous rise during the period (Fig. 7b). Specifically, between 2000 and 2005, emissions of various air pollutants and CO_2 in China continued to increase due to the rapid increase in coal consumption. With the implementation of more stringent emission standards for SO_2 and primary $PM_{2.5}$, the total emissions of these two pollutants have shown a downward trend since 2005, but NOx, VOCs, and CO_2 emissions are still growing fast. Since 2013, with the announcement and implementation of ambitious clean air actions by the Chinese government, many tailored measures (e.g., structural adjustments) have been implemented in various sectors. Compared to 2013, SO_2, NOx, and primary $PM_{2.5}$ emissions in 2020 decreased by 70%, 28%, and 44%, respectively. However, VOCs emissions continued to grow before 2017 due to less stringent emission standards, while there was a downward trend after 2017 due to the promotion of water-based solvents and the treatment and renovation of major industries. CO_2 emissions have continued to grow slowly during 2013-2020 due to the continued increase in fossil energy consumption and the relatively slow progress in the structural adjustment of industrial sectors, the activity of industrial process, and the energy mix, but the rate of emission increase has slowed significantly.

Fig. 7c further analyzes the progress in the synergetic reduction in CO_2 emissions and major air pollutants. During the 2015–2020 period, a synergetic reduction in CO_2 and major pollutant emissions in China's industrial sector was achieved, indicating that a series of measures toward structural adjustment of energy and industrial sectors (e.g., shutting down outdated production facilities, scaling down overcapacity, eliminating small coal-fired boilers, improving enterprise governance for poorly managed and polluting small enterprises, etc.) has shown remarkable progress in recent years. However, CO_2 emissions from the power, heating, residential, and transportation sectors continued to increase while emissions of major air pollutants declined. In particular, the power and heating sectors mainly focused on end-of-pipe control measures, which do not allow for a synergetic reduction in CO_2 emissions. In the residential sector, end-use energy consumption is growing rapidly, but CO_2 emissions have increased by only 3%, indicating that the phasing out of scattered coal is making initial progress in carrying out a synergetic reduction in CO_2 emissions. In the transportation sector, pollutant emission reduction mainly comes from end-of-pipe control measures such as upgrading emission standards. As the total number of motor vehicles in China's cities still increases rapidly, CO_2 emissions from the transportation sector increased by 14% between 2015 and 2020. In summary, the potential for reducing air pollutants from structural adjustments in the energy, industry and transportation sectors in China still needs to be further released. In the next stage, targeted emission reduction measures for realizing the synergy of pollution reduction and CO_2 reduction should be actively promoted.

4.3. Land use change and land carbon sinks

During the past decade, terrestrial ecosystems have removed approximately one-third of the anthropogenic CO_2 emissions [27], meaning that land ecosystems have partially offset CO_2 emissions and slowed down climate change. Maintaining and enhancing land carbon sinks are thus regarded as an important measure for achieving the goal of carbon neutrality. This indicator is used to summarize the contemporary understandings of the magnitude of China's land carbon sinks and analyze the known factors affecting the quantification of land carbon sinks and the impacts of land use change on the land carbon balance.

Based on the sixteen carbon cycle models in the Global Carbon Budget, during the 2009–2018 period, China's land carbon sinks amounted to approximately 224 ± 78 Tg C yr^{-1}, accounting for 3–10% of global land carbon sinks and 3–13% of CO_2 emissions from fossil fuel combustion in China during the same period [27]. Notably, due to limitations of the carbon cycle model [91], the magnitude and spatial pattern of land carbon sinks remain largely uncertain. Over the past ten years, Chinese researchers have applied different methods to assess the carbon sinks of China's land ecosystem (Fig. 8), the approaches of which, in general, can be categorized into two classes. One is the “bottom-up” approach based on the carbon inventory; the other is the “top-down" approach through atmospheric inversion based on atmospheric CO_2 concentration observations. From the inventory perspective, the carbon storage in China's terrestrial ecosystem increases by 177–290 Tg C per year [92–94]. Considering the carbon stock change from the transfer of soil organic carbon from terrestrial ecosystems due to deforestation and soil erosion (48–57 Tg C yr^{-1}) [92,93,95], the range of China's terrestrial ecosystem carbon sink is approximately 225–347 Tg C yr^{-1} based on “bottom-up” approach. Atmospheric inversions based on observations of atmospheric CO_2 concentrations and atmospheric transport models estimate that China's land carbon sinks amount to 180–530 Tg C yr^{-1}

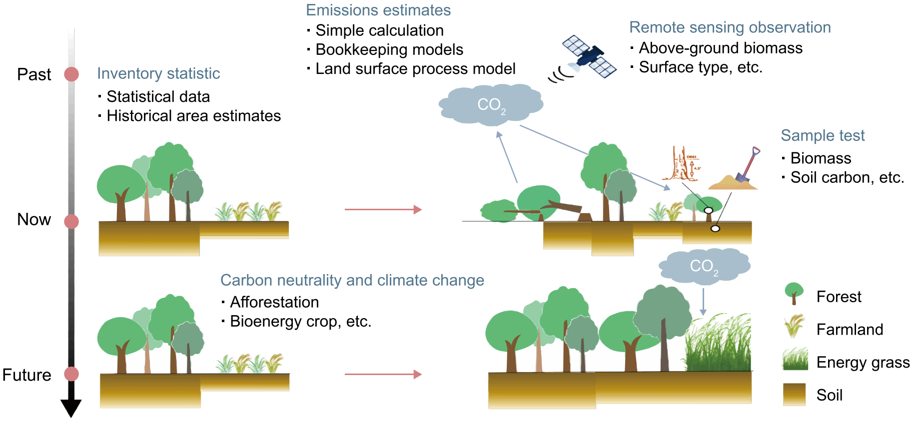


Fig. 8. Illustration of the impacts of land use changes on the carbon balance.

[27,92,93,96]. When taking the CO_2 emissions from imported wood products and food that oxidized within the boundary of China and emissions of CO, CH_4, and VOCs that may not be oxidized inside China (75–84 Tg C yr^{-1}) [92,93], the estimation of China's land carbon sink based on the "top-down" approach is approximately 96–445 Tg C yr^{-1}. This large range implied a large uncertainty, which was found to be closely linked to atmospheric CO_2 observation data and atmospheric transport models. For example, a recent study revealed that applying a site with poor spatial representation in an atmospheric inversion system introduces large systematic bias [96]. In summary, based on the "bottom-up" and "top-down" approaches, China's land carbon sinks offset 4–20% of CO_2 emissions from fossil fuel combustion during the same period.

Land carbon sinks are impacted by climate change, anthropogenic disturbance, and management. Previous studies have shown that atmospheric CO_2 growth, climate change, and land use change (LUC) significantly influence carbon sinks in the terrestrial ecosystems of China [95,97–100]. LUC by urbanization and deforestation induces carbon loss from the ecosystem, while LUC by reforestation absorbs CO_2 from the atmosphere. Therefore, accurately estimating carbon fluxes from LUC and potential land sinks from ecosystem management is crucial for achieving carbon neutrality in China. Although there are many methods of estimating LUC carbon fluxes [101], the long-term global estimates used in the Global Carbon Budget are mainly based on bookkeeping model and dynamic global vegetation models (DGVMs). However, the modeled results from different DGVMs vary largely due to the differences in plant functional type (PFT) maps, processes, and parameterizations [102]. The LUC fluxes estimated among different bookkeeping models are also different. For example, the Bookkeeping of Land Use Emissions (BLUE) model estimated a LUC emission of 159 ± 131 Tg C yr^{-1} in China during the 2009–2018 period [103], while the Houghton and Nassikas (H&N) model estimated a sink of 49 ± 9 Tg C yr^{-1} from LUC [104]. This difference is largely caused by the different LUC area data. The H&N model used forest area changes from Food and Agriculture Organization (FAO) inventory data, which are close to the national forest resource inventory in China [105]. Therefore, the carbon sinks from LUC simulated by the H&N model result mainly from the large area of reforestation in China in recent decades.

Ecosystem management and carbon sink enhancement measures, such as afforestation, bioenergy crop planting, and reduced/no-tillage farming (Fig. 8), can increase the magnitude of land carbon sinks and make an important contribution for mitigating climate change and achieving carbon neutrality. However, the enhancement of China's land carbon sinks also faces many challenges. For example, as the stand age of forest ecosystems in China increases, the intensity of forest ecosystem carbon sinks may decrease. Additionally, as temperature further increases, the negative influence of climate change on land carbon sink may gradually become more obvious. Hence, it is necessary to develop the atmospheric CO_2 concentration observation network, atmospheric inversion models, and process-based carbon cycle models, to improve the precision of land carbon sink estimates and accurately assess the response of land carbon sinks to climate change and various ecosystem management practices.

4.4. Future mitigation potentials and synergetic pathway

China is now facing big challenges in the continuous improvement of air quality, and the achievements of carbon peak by 2030 and carbon neutrality by 2060. This indicator uses a series of China's future emission scenarios developed by the Carbon Neutrality and Clear Air evaluation Platform (CNCAP); and analyzes the synergetic pathways of China's CO_2 emission reduction and air pollution mitigation.

It is estimated that China can reach the CO_2 emissions peak in 2030 with approximately 11 billion tons [4] emissions (Fig. 9) by conducting a series of measures such as increasing the share of renewable power generation, peaking energy-intensive products such as steel and cement, and pushing forward the energy-saving upgrades of power generation and end-use facilities. Other relevant studies have estimated China's peak CO_2 emissions will fall in the range of 9.7 and 13.3 billion tons [106–115]. By further accelerating the low-carbon transformation of the power system, speeding up the phase-out of residential scattered coal use, enhancing the energy-saving transformation and electrification of high-energy-consuming industries, as well as promoting the electrification process of traditional gasoline and diesel vehicles, China can peak its CO_2 emissions around 2025 and reduce the corresponding peak emissions to approximately 10.5 billion tons [4].

After 2030, carbon emissions will rapidly decrease by active implementation of the structural adjustments in energy, industrial, and transportation sector under the ambitious climate target. Aiming to achieve the carbon neutrality target, China could gradually get rid of its reliance on coal use through the low-carbon structural adjustment, energy efficiency improvement, and zero/negative-carbon technology application. The energy mix in China will be dominated by electricity and renewable energy by 2060. The share of coal consumption in primary energy will fall to less than 10% [116], while the proportion of low-carbon energy sources such as renewable energy, biomass, and nuclear will reach more than

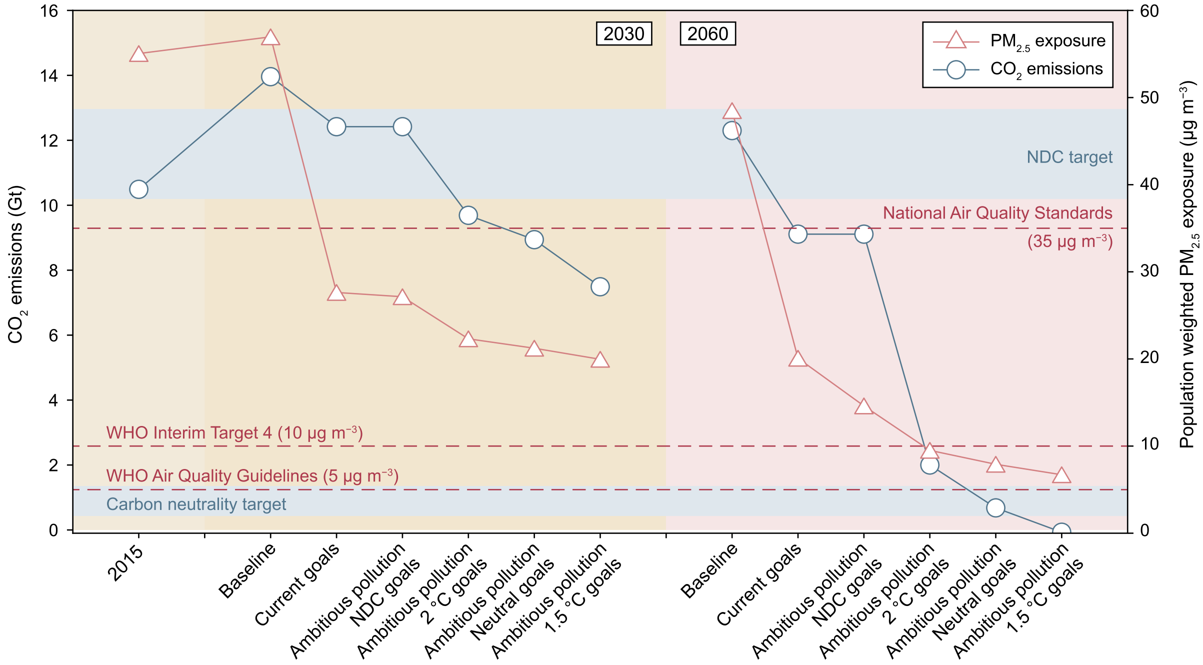


Fig. 9. A synergy pathway for carbon neutrality and clean air in China. The circle and triangle markers represent CO$_2$ emissions and the population-weighted PM$_{2.5}$ concentration, respectively. Figure adopted and revised from Cheng et al., 2021 [4].

70%. As a result, CO$_2$ emissions could be reduced to 680 million tons in 2060, a 93% reduction compared to 2015 [4]. Comparing to the mitigation pathways of current international climate targets of 1.5 °C and 2 °C warming limits, CO$_2$ emissions under the carbon neutrality target pathway are between the 1.5 °C-consistent pathway (~100 million tons negative CO$_2$ emissions of in 2060) and the 2 °C-consistent pathway (~2 billion tons CO$_2$ emissions in 2060) and are closer to the 1.5 °C pathway [4].

In addition to continuous structural adjustments in energy, industrial, and transportation systems, deep reduction of CO$_2$ emissions also relies on the development of emerging low-carbon, zero-carbon, and negative-carbon technologies (e.g., CCUS and BECCS) and their CO$_2$ reduction potentials need to be enhanced especially after the middle of this century. Previous studies have indicated that early implementation of such innovative technologies is critical for carbon mitigation. The deployment of CCUS and BECCS, particularly in the power, cement, and steel industries, could bridge the carbon emission reduction gap of approximately 1.0–2.8 billion tons per year [117–119].

As of the end of 2020, China had launched 35 CCUS demonstration projects that can remove ~3 million tons of CO$_2$ from the atmosphere per year. However, it has yet to begin demonstration projects for negative emission technologies such as BECCS [120–122]. Therefore, it should accelerate the demonstration and deployment of zero/negative-carbon technology such as CCUS and BECCS, which plays an important role in meeting the technological requirements for achieving the carbon neutrality goal.

Achieving ambitious carbon-mitigation-targeted climate goals and synergistically reducing air pollutant emissions have become an inevitable choice for China's long-term climate and environmental governance [116]. Promoting carbon reduction measures will help China meet the NDC climate target in 2030, meanwhile, with the promotion of the in-depth air pollution controls in the highly polluted sources (e.g., heavy industries, diesel-fueled vehicles and engines, and VOC-related industries), 29%–51% of China's pollutant emissions would be reduced by 2030 compared to the 2015 level [116]. The annual average PM$_{2.5}$ concentrations in most regions will reach 35 μg m^{-3}, meeting the current national air quality standard (Fig. 9), and the annual average PM$_{2.5}$ exposure level of the national population will decrease from 55 μg m^{-3} in 2015 to 26–28 μg m^{-3} in 2030 [4].

However, the mitigation potential from end-of-pipe controls will be mostly exhausted by 2030, and achieving the long-term air quality improvement will likely require more ambitious climate mitigation efforts such as China's carbon neutrality goals. Under the carbon neutrality pathway, China will achieve the transformation to low-carbon energy by 2060 by shifting the major energy from coal to the renewables. For example, the renewable energy power generation will account for more than 70%, the share of coal will be less than 15% in the industrial final energy use, electric and hydrogen vehicles will account for more than 60%, and residential fuel will be completely converted to clean and low-carbon energy. Such an in-depth energy transition will reduce China's carbon emissions by 90% under the carbon neutrality pathway and simultaneously reduce major air pollutant emissions by 65–94% [116]. As a result, the average annual exposure level of PM$_{2.5}$ will be approximately 8 μg m^{-3}, ensuring that 78% of the population is exposed to less than 10 μg m^{-3} [4].

5. Health impacts and benefits of coordinated control

5.1. Health impacts of air pollution

Long-term and short-term exposures to PM$_{2.5}$ or O$_3$ are linked to various adverse health outcomes, including total mortality, cardiovascular diseases, respiratory diseases, metabolic diseases, neurological diseases, reproductive diseases, and cancer [22,23]. Based on the review of published research, the Environmental Protection Agency of United States (U.S. EPA) applied a five-scale hierarchy to evaluate potential causality among specific air pollutants and health effects: a causal relationship; likely to be a causal relationship; suggestive of, but not sufficient to infer, a causal relationship; inadequate to infer the presence or absence of a causal relationship; and not likely to be a causal relationship. According to the latest assessments by the U.S. EPA, $PM_{2.5}$ exposure shows a causal relationship with total mortality [22]; the relationship between O_3 exposure and total mortality is suggestive of, but not sufficient to infer, a causal relationship [23].

The Global Burden of Disease (GBD) study suggests that $PM_{2.5}$ increases the risk of death by causing cardiovascular, respiratory, metabolic diseases and/or adverse reproductive outcomes, while O_3 exposure increases death by causing chronic obstructive pulmonary disease [123]. Recent studies have shown that $PM_{2.5}$ exposure is associated with reproductive and neurological diseases [124–127], while O_3 exposure is associated with cardiopulmonary diseases and lung cancer [128]. The physiological mechanisms of various diseases caused by $PM_{2.5}$ and O_3 exposures have not been fully revealed. It is generally believed that air pollution exposure increases the disease burden through molecular mechanisms such as (1) systematic oxidative stress, (2) systemic immune and inflammatory response, (3) central nervous system rhythm disorder, and (4) carcinogenic and teratogenic risk [129].

Over recent decades, environmental health issues have drawn much public attention, especially the health risks of $PM_{2.5}$ pollution [130]. The GBD study estimated that the total number of deaths attributed to long-term outdoor $PM_{2.5}$ exposure in China was approximately 1–2 million [19,20]. Given the high levels of ambient $PM_{2.5}$ pollution and the large population, short-term exposure to $PM_{2.5}$ also poses a great threat of premature death in China. Studies have shown that nationwide premature mortality due to short-term $PM_{2.5}$ exposure was approximately one-seventh of the premature deaths attributable to long-term $PM_{2.5}$ exposure [21]. It is suggested that the health effects from short-term $PM_{2.5}$ exposure should be included in assessing the overall disease burden of ambient $PM_{2.5}$.

Other than using a single exposure metric for $PM_{2.5}$, multiple exposure metrics for O_3 have been used by both academic researchers and policymakers to assess and characterize O_3 pollution. O_3 pollution in China has been worsened in recent years [131]. A study of 272 Chinese cities found that residents' nonaccidental mortality risk increases by 0.24% per 10 $\mu g\ m^{-3}$ increase in the MDA8 O_3 [132]. Supposing ambient O_3 quality meets the national air quality standard, the estimated avoided premature deaths due to short-term O_3 exposure would be approximately 120,000 compared to the current level of ozone pollution [133].

Here, the mortality attributable to long-term and short-term exposures to $PM_{2.5}$ and O_3 in China were evaluated based on the TAP pollution data [33] and the latest exposure-response functions [123]. Since the implementation of Clean Air Actions in 2013, $PM_{2.5}$ pollution in China has considerably improved, thereby resulting in appreciable health benefits. Premature deaths attributable to long-term and short-term exposures to $PM_{2.5}$ in 2020 were 1.39 million

Table 4
Premature deaths attributable to long term (**a**) and short-term (**b**) exposures to $PM_{2.5}$ and O_3 in China from 2013 to 2020. Data sources: Xiao et al., 2022 [3].

a Long-term exposures

Species	Year	Premature deaths to long-term exposure (10^3 person)	95% Confidence Interval	
			Low	Up
$PM_{2.5}$	2013	1,747	1,642	1,852
	2014	1,674	1,566	1,781
	2015	1,650	1,536	1,758
	2016	1,608	1,499	1,715
	2017	1,591	1,478	1,699
	2018	1,524	1,402	1,651
	2019	1,525	1,399	1,651
	2020	1,390	1,265	1,511
O_3	2013	99	41	155
	2014	98	41	155
	2015	99	43	159
	2016	112	48	173
	2017	131	58	203
	2018	137	58	213
	2019	166	73	253
	2020	148	64	224

b Short-term exposures

Species	Year	Premature deaths to short-term exposure (10^3 person)	95% Confidence Interval	
			Low	Up
$PM_{2.5}$	2013	109	80	144
	2014	95	69	127
	2015	93	67	123
	2016	85	60	111
	2017	81	58	107
	2018	74	54	99
	2019	74	53	99
	2020	64	46	85
O_3	2013	51	29	75
	2014	51	29	75
	2015	53	30	78
	2016	58	33	85
	2017	70	40	101
	2018	74	42	108
	2019	86	49	122
	2020	80	44	115

and 64,000, respectively, reducing by 20% and 41%, repsectively, compared to 2013 (Table 4). The short-term $PM_{2.5}$ exposure level and related premature deaths reduced more significantly than the long-term exposure, representing the effectiveness of heavy air pollution control. Meanwhile, O_3 pollution has become increasingly prominent, and the O_3-related mortality burden shows an increasing trend. In 2020, premature deaths attributable to long-term and short-term O_3 exposures were 148,000 and 80,000, increasing by 49% and 51% compared with 2013, respectively.

The disease burden associated with long-term exposure to $PM_{2.5}$ remains the dominant factor among different health impacts of air pollution. However, from the perspective of short-term exposure and health impacts, although the control of $PM_{2.5}$ has brought significant short-term health benefits, the increase in concentrations of O_3 largely offsets the health improvement derived from the decrease in $PM_{2.5}$. In recent years, the disease burden attributable to short-term O_3 exposure has exceeded that of $PM_{2.5}$. At the same time, a recent global study of 398 cities found that a 10 $\mu g\ m^{-3}$ increase in the short-term exposure concentration of nitrogen dioxide (NO_2) was associated with 0.37% and 0.47% increases in cardiovascular and respiratory disease-related mortality, respectively [24]. Thus, in the future, health impacts of NO_2 should be noticed as well.

5.2. Health impacts of climate change

More frequent extreme weather events, rising sea levels, and severe biodiversity reduction caused by climate change threaten human health [12]. These problems have become important unstable factors that impact sustainable development goals and the implementation of the “Healthy China” strategy. Here, associations between climate change and mortality were used as the indicator to summarize the relevant achievements in the field of climate change and health, analyze the health effects of different extreme climate events, and propose suggestions for China to strengthen research on public health to adapt to climate change.

Extreme meteorological conditions can increase the risk of mortality and morbidity, reduce labor efficiency, and result in the spread and pandemics of climate-sensitive infectious diseases. Both extremely high and low temperatures can increase mortality. For example, a systematic review of China showed that for every 1 °C increase or decrease in temperature relative to the optimal temperature, the mortality risk increased by 2% or 4% [12]. A recent multicenter time-series study analyzed the relationship between heat waves and mortality in China, and found that the mortality during a heat wave period was significantly higher than during a non-heat wave period [13]. Compared with non-heat wave periods, the mortality during heat wave periods increased by 15.7% for nonaccidental deaths and 22.0% for cardiovascular disease-related deaths. The study also found that the first heat wave each year had a greater risk of death than subsequent heat waves [13]. The health damage caused by cold spells is also noteworthy. A study based on the health effects of the cold spell in 2008 in 15 provinces in Southern and Central China showed that the mortality risk during the cold spell increased by 43.8% compared to non-cold spell days, and 148,279 excess deaths were attributable to the 2008 cold spell [134].

Global climate change will also result in increases in the frequency and intensity of other extreme weather events, such as tropical cyclones and torrential rains (floods), causing higher health risks to the population in affected areas. Studies for Chinese coastal provinces showed that tropical cyclones not only caused direct casualties but also led to an increase in the all-cause mortality of residents, females, infants, children and elderly individuals, as well as the mortality of malignant tumors [14]. Climate change can increase the risk of respiratory diseases in affected areas [135]. A study on the health impact of the flood in Beijing in July 2012 found that the nonaccidental mortality risk to residents during the torrential rain period was significantly higher than that in unexposed periods, especially the mortality risk from circulatory diseases [15]. A total of 79 excess deaths among Beijing residents were caused by this flood, including 46 excess deaths from circulatory diseases. The estimated numbers caused by this disaster are much higher than those in a study using a traditional surveillance approach in the affected areas [15].

Increasing temperature and extreme weather events in the context of future climate change will harm human health to different extents. A recent study estimated that, under 1.5 °C scenario, the heat-related mortality will increase from 32.1 per million people annually in 1986–2005 to 48.8–67.1 per million people in the future, considering improved adaptation capability [30]. The additional warming from 1.5 °C to 2 °C will lead to 279,000 additional heat-related deaths annually [30]. Under the RCP8.5, heat-related excess mortality is projected to increase from 1.9% in the 2010s to 2.4% in the 2030s and 5.5% in the 2090s. This increasing trend is more pronounced in Southern, Eastern, Central, and Northern China. Population aging further amplifies heat-related excess deaths by 2.3- to 5.8 folds, particularly in the northeast region [136].

The burden of major chronic diseases, such as cardio-cerebrovascular diseases, may increase under the dual influence of climate change and aging in the future. A study predicted cardio-cerebrovascular disease-related deaths due to heat exposure in Beijing, and showed that temperature-related mortality from ischemic stroke would increase significantly due to global warming, while temperature-related mortality from acute ischemic heart disease and hemorrhagic stroke will remain relatively stable [135]. Considering the projected growth in the aging population, the number of heat-related deaths in Beijing will increase rapidly under both the RCP4.5 and RCP8.5 scenarios, and the impacts will be far greater than those under the fixed-population scenario [137].

Meteorological factors can increase the risk of infectious diseases by affecting pathogens and vectors. Precipitation may wash away pathogens attached to the soil surface, causing surface water pollution and increasing human exposure to diarrhea pathogens. Previous studies found a positive relationship between precipitation and the incidence of bacterial dysentery in Northern China [18]. Higher humidity can promote mosquito breeding, increasing the probability of outbreaks of mosquito-borne infectious diseases. A study in Guangzhou revealed that every 1% increase in relative humidity was associated with a 1.95% increase in the risk of dengue fever [16]. Many studies have also reported that meteorological factors are closely related to the outbreak of the COVID-19 pandemic; for example, high temperature and humidity conditions may reduce the confirmed number of cases of COVID-19 [138]. Modest precipitation may accelerate virus infection by decreasing the evaporation of droplets, making them be readily attached to surfaces, while elevated wind speed may facilitate the aerosol dissemination of SARS-CoV-2 [17]. However, the relationship between meteorological factors and COVID-19 is still unclear, and the potential mechanism through which meteorological factors influence SARS-CoV-2 transmission needs to be further explored.

At present, research on climate change and health is still very limited, leading to insufficient decision-making support. Based on current scientific evidences, formulating public health adaptation strategies for climate change should focus on reducing the prevalence of chronic diseases and strengthening public health services, especially for elderly individuals. The global pandemic of COVID-19 has not only revealed the enormous threat of public emergencies to human health but also prompted people to start thinking about the various unsustainable issues under the outbreak of a new epidemic. Due to the complex links between climate change, human activities, the ecological environment, wild animals, and pathogens, China should strengthen multidisciplinary cooperation to cope with the health impacts of climate change, especially the related risk of emerging infectious diseases.

5.3. Health co-benefits of carbon reduction

Climate change mitigation actions could optimize the energy structure, reduce fossil fuel consumption, significantly reduce air pollutant emissions, and bring considerable health co-benefits [4,29,115]. Existing studies on the health co-benefits of carbon reduction can provide valuable scientific recommendations on identifying the key emission sectors and main control policies. Based on the literature review, this indicator presents the health co-benefits of carbon reduction and explore the driving factors from regional and sectoral perspectives.

Previous studies have indicated that without additional climate policies, population-weighted $PM_{2.5}$ concentration in China will reach 69.9–70.1 $\mu g\ m^{-3}$, and O_3 concentration will reach 116.6 $\mu g\ m^{-3}$ by 2030 [139]. By 2050, the average surface ozone concentration will increase by 17.1 $\mu g\ m^{-3}$, leading to 61,884 premature deaths each year [140]. By fulfilling China's NDC goal, population-weighted $PM_{2.5}$ and the MDA8 O_3 will decrease by 8.33 $\mu g\ m^{-3}$ and 3.36 $\mu g\ m^{-3}$ in 2030, respectively, and 54,300 premature deaths caused by ozone exposure and 94,000–95,200 premature deaths caused by $PM_{2.5}$ exposure will be avoided [21]. Strict climate mitigation policies will bring significant of health cobenefits. Achieving 2 °C target will decrease the population-weighted $PM_{2.5}$ concentration by 13.3 $\mu g\ m^{-3}$ in 2030, which will further avoid 160,000–162,000 premature deaths and bring a net benefit of US$534.8 billion [141]. Moreover, if the NDC target is enhanced to be compatible with the "Beautiful China" goal by 2035, another 158,000 premature deaths attributable to $PM_{2.5}$ exposure and 12,000 O_3-related premature deaths could be avoided annually, saving 890 billion yuan of economic losses each year [142].

The health co-benefits derived from the climate mitigation policies exhibit substantial regional disparities. Under the 2 °C climate mitigation scenario, $PM_{2.5}$ concentrations in Central and Southern China will be significantly reduced to below 60 $\mu g\ m^{-3}$ by 2030, whereas the air quality in western China will improve slightly [143]. $PM_{2.5}$ pollution in major coal-consuming provinces, such as Shanxi and Guizhou, will improve significantly. However, decline in $PM_{2.5}$ concentration will be small in coastal provinces due to the relatively high proportion of the light and service industries and higher energy utilization efficiency [143]. The health co-benefits also show large spatial heterogeneity [144]. Under the 2 °C scenario, the avoided premature deaths by 2030 will reach to 86,771 in the eastern region, 49,712 in the central region, and 25,734 in the western region, respectively. Compared to pollution control policies, carbon trading policies can largely improve health benefits and reduce the costs [145]. Specifically, the carbon trading policy will reduce the carbon cost to approximately 63.53 yuan t^{-1} (US$9.47), further avoiding 15,038 acute premature deaths, 87,692 chronic premature deaths, and a loss of statistical life amounting to US$55 billion [146].

GHGs and air pollutants shared the major emitters across different sectors such as coal-fired power generation, industry, transport, and residential [147]. Study found that reducing 195 million tons of CO_2 from power generation in China could avoid 1,120 $PM_{2.5}$-related premature deaths [148]. The large-scale development of solar photovoltaic power generation can then significantly improve air quality and protect human health. For instance, installing 400 GW PV in 2030 could reduce carbon emissions by 4.2% in China in 2030 and avoid 10,000 (95%CI: 5,000–14,000) premature deaths [149]. De-capacity policy in iron and steel industry sectors will also contribute to GHG emission reduction and bring considerable health benefits. When the Beijing–Tianjin–Hebei region reduces its small and inefficient production capacity, $PM_{2.5}$ concentration in 2030 will decrease by as much as 0.7 $\mu g\ m^{-3}$, and the corresponding avoided premature deaths will reach to 51,800, further avoiding economic losses of US$5.6 billion [150]. Another study found that energy efficiency improvement and transportation optimization will substantially reduce primary pollutant emissions, which will avoid 183,000 premature deaths [151]. Furthermore, Tian et al. (2019) [152] found that if the transportation sector achieves 2 °C target, the national average $PM_{2.5}$ concentration will decline by 2.5 $\mu g\ m^{-3}$ with more significant reduction in central and eastern regions (e.g., 4.6 $\mu g\ m^{-3}$ in Henan and 4.4 $\mu g\ m^{-3}$ in Anhui). The avoided premature deaths in China will be 90,000, and the avoided economic loss will be around US$62.5 billion. In the residential sector, if the Beijing–Tianjin–Hebei region promotes the "coal-to-electricity" policy, 37,500 and 43,800 premature deaths can be avoided by 2020 and 2030, respectively [153].

6. Synergetic governance system and practices

6.1. Construction of a synergetic governance system

In 2018, as part of the national institutional reform in China, responsibility for climate change mitigation was transferred from the National Development and Reform Commission (NDRC) to the Ministry of Ecology and Environment (MEE). On January 9, 2021, the MEE promulgated *The Guiding Opinions on Coordinating and Strengthening the Work Related to Climate Change and Ecological Environment Protection* (hereinafter referred to as the "*Guiding Opinions*") as mentioned above. The *Guiding Opinions* clarifies the main pathways of synergetic governance during the 14th FYP period, marking a new stage in constructing the synergetic governance system in China. This indicator aims to review the progress in constructing the synergetic governance system, with aspects including strategic planning, laws and regulations, and the management system.

First, the strategic planning for climate change mitigation and air pollution control have been designed in a synergetic manner by the central government. The *China's* 14th *Five-Year Plan (2021–2025) for National Economic and Social Development and the Outline of 2035 Vision* clearly stated "synergetic control of environmental pollution and carbon emissions". The requirements for environmental pollution control and climate change mitigation have been incorporated and viewed as important component of the governmental duty on "continuously improving environmental quality". When formulating the 14th FYP for the National Ecological Environment Protection, both climate change mitigation and air quality improvement are listed as important targets. These two targets are planned to be addressed in a coordinated manner from their goals, tasks, and measures, with great efforts to promote structure changes in the industrial, energy, and transportation sectors. The synergetic management is expected to positively support China's economic transformation through ecological and environmental protection.

In addition to emphasizing and strengthening the synergetic control in the national plan, the central government has arranged the implementation of relevant tasks at the regional level. The *Guiding Opinions* states, for the first time by the government, that a pilot demonstration of "double reach" synergy at the city level will be implemented, which means attaining both air quality standards and carbon emission peak. Regional governments must clarify the timetable, roadmap, and construction map for environmental quality improvement and carbon peaking according to their socioeconomic development stage, industrial structure, resource endowment, and other important factors. Several industrial sectors, including the petroleum industry, chemical industry, coal industry, iron and steel industry, power sector, automobile manufacturing industry, environmental protection industry, and transportation sector, have proposed their plan for carbon peaking and carbon neutrality. These plans will all play important synergetic roles in reducing air pollutant emissions.

Second, legislation associated with climate change mitigation has been regulated. The *Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution*, which was revised and enacted on August 29, 2015, requires synergetic control of GHGs and air pollutant emissions (i.e., particulate matter, SO_2, NO_x, VOCs, and NH_3). In 2014, the NDRC led the drafting of the Climate Change Act, which ultimately was not enacted. It could be expected that in the near future, China will establish a legislation and regulatory system that supports and promotes the synergetic control of air pollution and climate change mitigation.

Third, the requirements for controlling carbon emissions were integrated into the existing ecological and environmental management system. On the one hand, CO_2 emission statistics were added into the current ecological and environmental statistics when updating the ecological and environmental statistics reporting system, which will ensure the consistency of air pollutants and GHG emissions statistics. On the other hand, CO_2 emissions should be considered in the environmental impact assessment system by setting CO_2 emission control requirements for "Three Lines, One Permit" and environmental impact assessment for planning and projects. This will help to facilitate environmental policies in effectively curbing the growth in both air pollutant and CO_2 emissions.

6.2. Economic policies for synergetic governance

In the 13th FYP period, China adopted various economic policies, such as fiscal policies, subsidies, pricing policies, taxes, fees, pollution permission trading, and finance policies, to support air pollution control and climate change mitigation. Those policies were initially aimed to achieve individual purpose: either air pollution control or CO_2 emission abatements. As air pollutants and GHG emissions share the same sources, most of the policies have resulted in a synergetic emission control of air pollutants and CO_2 by promoting structure changes. This indicator reviews China's economic policies for the synergetic control of air pollutant and CO_2 emissions in recent years and summarizes the investments for the synergetic control.

Regarding financial and subsidy policies, the Air Pollution Control Special Fund have accelerated air pollution control and CO_2 emission abatements in many fields. Since 2013, the Air Pollution Control Special Fund had settled 122.5 billion yuan from the central government by the end of 2020 (Table 5). A total of 25 billion yuan was scheduled in 2020 to support clean air actions such as the clean residential heating in Northern China, and the in-depth pollution control for industrial sectors and mobile sources, which have led to the changes in energy structure. The fund also directly contributed to GHG emission abatements by supporting the destruction and disposal of hydrofluorocarbons. Furthermore, green-oriented financial subsidies for renewable energy, NEVs, green buildings, and ecological protection have effectively promoted simultaneous reductions in both air pollutants and GHG emissions. For example, the renewable power subsidies for 2020 was approximately 92.4 billion yuan, with an increase of 7% from the previous year. These subsidies are used to support wind, PV, and biomass power generation projects.

A green tax system and a differentiated pricing system have been established. The green tax system includes environmental protection tax, resource tax, vehicle and vessel tax, vehicle purchase tax, and consumption tax. Environmental protection tax system implemented in 2018 is applicable to 44 air pollutants. The tax rate ranges from 1.2 yuan to 12 yuan per pollution equivalent. As of 2020, a total of 57.9 billion yuan had been collected for environmental protection tax. At the same time, a differential electricity price policy has been implemented in seven industries, i.e., ferroalloy, calcium carbide, caustic soda, cement, steel, yellow phosphorus, and zinc smelting. Tier-based electricity price policy is adopted for the electrolytic aluminum, cement, and iron and steel industries.

Comprehensive green financial system has been established. By the end of 2020, China's green loan balance had reached 11.95 trillion yuan, ranking first globally. In July 2020, China's National Green Development Fund was formally launched. The capital raised in the first phase reached 88.5 billion yuan, which was invested in green development fields such as environmental protection and pollution control, ecological restoration, territorial space greening, energy conservation and utilization, green transportation, and clean energy. On October 26, 2020, the *Guiding Opinions on Promoting Investment and Financing to Address Climate Change* was published to guide the investment, fund raising and risk control in the field of climate change.

In 2020, the carbon emissions trading volume in the seven pilot carbon markets (Beijing, Tianjin, Shanghai, Hubei, Guangdong, Shenzhen, and Chongqing) reached to 2.15 billion yuan, with an annual average price of 28.6 yuan t^{-1}. As the national carbon emission permit trading scheme has moved from pilot implementation to nationwide launch, the *Interim Rules for Carbon Emissions Trading Management* were issued on December 25, 2020.

6.3. Local practices

Cities are the key units of air pollution control and low-carbon practices. For air pollution control, the *Law of the People's Republic of China on Air Pollution Prevention and Control* requires cities that fail to attain the country's air quality standard to formulate and implement air quality compliance plans. For low-carbon practices, China has also taken a series of actions at the city level. For instance, low-carbon city pilot projects were carried out in 2010, 2012, and 2017, covering 6 provinces and 81 cities. This indicator summarizes the progress in air pollution control and low-carbon practices at the

Table 5
Air pollution control funds from 2013 to 2020 and green tax revenues from 2018 to 2020. Data sources: Ministry of Finance, 2021 [153]; National Bureau of Statistics, 2019 [154] and 2020 [155].

Year		2013	2014	2015	2016	2017	2018	2019	2020
Air pollution control funds (100 Million Yuan)		50	98	106	112	160	200	250	250
Green tax revenues (100 Million Yuan)	Consumption tax	-	-	-	-	-	10632	12562	12028
	Resource tax	-	-	-	-	-	1630	1822	1755
	Environmental protection tax	-	-	-	-	-	151	221	207

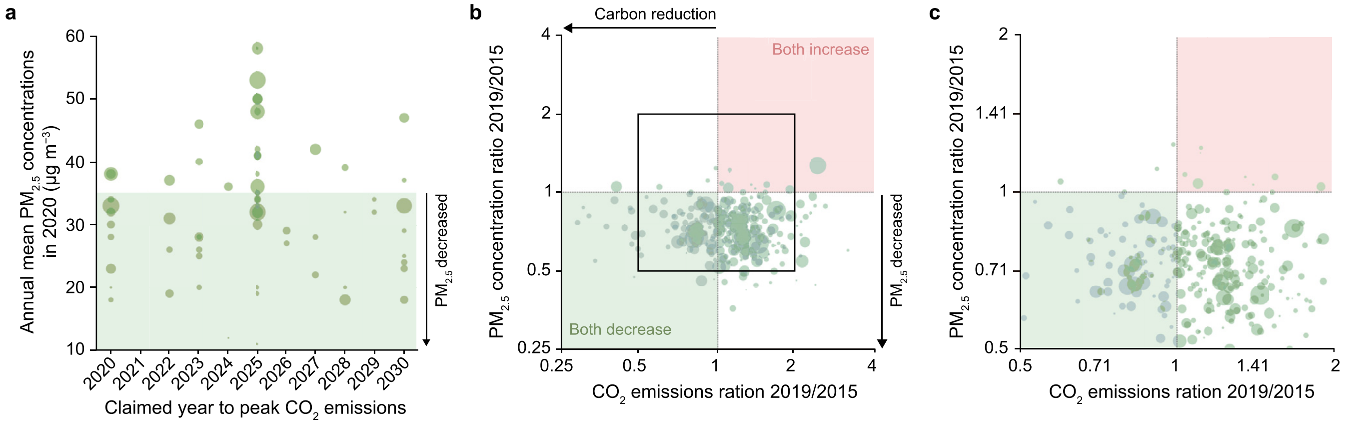


Fig. 10. **a**, Planned target year for carbon dioxide peaking in 70 cities and their PM$_{2.5}$ concentrations in 2020. **b**, The city-level comparison of changes in annual PM$_{2.5}$ concentrations and CO$_2$ emissions from 2015 to 2019. **c**, Details of the area bounded by solid lines in panel **b**. Data sources: China National Environmental Monitoring Center, http://www.cnemc.cn/; Cai et al., 2018, 2019a, and 2019b [150–152]; China City Greenhouse Gas Working Group, 2020 [153].

city level in China, with a focus on the cities that have set a target for their carbon peaking year.

Since 2013, local governments have been continuously taking actions to control air pollution, which have led to considerable improvements in air quality in most Chinese cities [2,156,157]. 70 prefecture-level (or above) cities have set their target for the year of CO$_2$ emission peaking (Fig. 10a). The direct CO$_2$ emissions of these 70 cities are accounted for 30.1% of the national total CO$_2$ emissions in 2019, according to the *China City Greenhouse Gases and Air Pollutant Emissions Dataset (2020)* [158–161]. Among them, 51 cities have planned to peak their CO$_2$ emissions in or before 2025, and other 19 cities have planned to peak their CO$_2$ emissions between 2026 and 2030. In 2020, the annual mean PM$_{2.5}$ concentration in the 70 cities ranged from 11 μg m^{-3} to 58 μg m^{-3}, with an average value of 32 μg m^{-3}. Among them, 47 cities have attained the national ambient air quality standard for PM$_{2.5}$ (35 μg m^{-3} for the annual average concentration).

As shown in Fig. 10b, the changes in PM$_{2.5}$ concentration and CO$_2$ emission from 2015 to 2019 in 335 prefecture-level (or above) cities were analyzed based on city-level PM$_{2.5}$ concentrations obtained from the China National Environmental Monitoring Center and city-level CO$_2$ emissions from the *China City Greenhouse Gases and Air Pollutant Emissions Dataset (2020)* [162]. The results show that from 2015 to 2019, the annual mean PM$_{2.5}$ concentrations decreased in 318 cities, accounting for 94.9% of the total number of cities analyzed in this indicator [162]. Among them, 98 cities achieved a simultaneous decline in PM$_{2.5}$ concentrations and CO$_2$ emissions, accounting for 29.3% of the total cities. In contrast, the PM$_{2.5}$ concentrations and CO$_2$ emissions in 11 cities increased simultaneously, accounting for 3.3% of the total number of cities.

It can be expected that during the 14th FYP period, more cities will carry out and explore the synergetic governance of air pollution control and low-carbon practices in line with cities' development planning. These efforts will eventually lead to effective progress in advancing air quality compliance and carbon dioxide peak, and will help cities to pursue high-quality development in the new development stage.

7. Discussion and concluding remarks

Achieving ambitious climate targets to synergistically reduce CO$_2$ and air pollutant emissions have become an inevitable choice for China's long-term climate and environmental governance. In the design of future carbon emission reduction pathways, various approaches should be included, including improvement of efficiency, adjustment in energy structure, decarbonization of industrial processes, promotion of CCUS technology, enhancement of ecosystem carbon sink, and development of carbon market mechanism. Meanwhile, to maximize the synergetic effects of air pollution and carbon reduction, the effects on air pollution emission reduction should be taken into consideration as an important constraint when selecting the carbon emission reduction measures.

Improvement of efficiency. Efficient use of resources and energy is a fundamental way to reduce emissions of GHGs and air pollutants. Recycling of resources should be reinforced, including the recycling of products from energy-intensive industries (e.g., iron and steel, aluminum, and plastics) and the energy-efficient use of waste (e.g., straw and household waste). Energy intensity should be further reduced and energy management systems should be established. Energy conservation in key areas (e.g., industry, construction, and transport) should be further promoted and the energy efficiency of new infrastructure should be improved.

Adjustment in energy structure. Adjusting the fossil-fuel dominant energy mix is the core way to achieve carbon neutrality. A new power system with wind power and PV power generation as the mainstay should be developed, and the flexibility of the power grid system should be simultaneously improved to enhance its ability to consume renewable energy. Furthermore, the electrification of end-use energy should be accelerated. To achieve synergies in emission reductions, priority should be given to the implementation of electrification in industries with high pollutant emissions, e.g., measures to accelerate the replacement of residential coal use with clean fuels and promote vehicle electrification should be taken.

Decarbonization of industrial process. Air pollutant emissions from industrial processes such as iron and steel, cement, and petrochemicals are key for air pollution control, and carbon emissions from those sectors are also difficult to reduce. Therefore, decarbonization technologies in those industries should be developed, e.g., hydrogen energy steelmaking, oxygen blast furnaces, and non-blast furnace smelting in iron and steel industry, non-calcium carbonate clinker substitution and plasma electric furnaces in cement industry, and the replacement of traditional petrochemical-based materials with biobased materials. The demonstration and application of these technologies should be accelerated.

Promotion of CCUS technology. CCUS and BECCS are key technologies for achieving large-scale emission reduction in power plants and industrial sectors. CCUS and BECCS technologies are still in the experimental demonstration period and demonstrations at large and integrated scale should be prompted. Costs of CCUS technologies could be further reduced through the large-scale demonstration, and experience could be gained for medium- and long-term commercial application.

Enhancement of ecosystem carbon sink. Maintaining and enhancing land carbon sinks is regarded as an important measure for achieving the goal of carbon neutrality. In the future, the cultivation of forest resources should be strengthened, the area and accumulation of forests should be continuously increased, ecological protection and restoration should be enhanced, and the carbon sequestration capacity of natural ecosystems such as grasslands, green lands, lakes, and wetlands should be strengthened. At the same time, the impact of increasing carbon sinks in ecosystems on carbon emission pathways and coordinated emission reduction pathways should be investigated and used to optimize the design of synergies in emission reduction pathways in the future.

Development of carbon market mechanism. The market mechanism for carbon emissions trading should be steadily promoted. Risk control mechanism for the carbon emissions trading market should be established, and national regulations on carbon emissions trading should be introduced as soon as possible to provide legislative support for the development of the carbon market system. The coordinated management of carbon emission trading and pollutant emission trading should be promoted to achieve synergies effects. Financial products and services related to carbon emission permits should be developed, and policy synergies, standard system, and comprehensive demonstrations should be strengthened.

Coordinating carbon peak policies and end-of-pipe control measures will ensure China meeting its NDC climate target in 2030 and the annual average $PM_{2.5}$ exposure level of the national population will reduce from 55 $\mu g\ m^{-3}$ in 2015 to 28 $\mu g\ m^{-3}$ in 2030 [4]. However, the benefits from end-of-pipe controls will mostly be exhausted by 2030, and achieving long-term air quality improvement will likely require more ambitious climate mitigation efforts, such as China's carbon neutrality goal. Under the carbon neutrality pathway, China's carbon emissions will decrease to 0.68 Gt CO_2 in 2060 and the average annual exposure level of $PM_{2.5}$ will be approximately 8 $\mu g\ m^{-3}$, ensuring that 78% of the population is exposed to less than 10 $\mu g\ m^{-3}$ in 2060 [4].

In summary, accelerating energy and economic structural adjustment to meet China's carbon neutrality goal can not only make a significant contribution to fulfilling the terms of the Paris Agreement [163], but also reduce the $PM_{2.5}$ exposure of the majority of the Chinese population to below the 2005-version WHO air quality guideline (i.e., 10 $\mu g\ m^{-3}$), achieving substantial long-term air quality improvement. For the next stage of China's development, the government should pay more attention to the synergy and efficiency of the reductions in air pollutants and carbon emissions. The governance of air pollution issues (i.e., $PM_{2.5}$ and O_3 pollution) should be jointly connected with China's carbon peak and carbon neutrality goals. First, the government should further engage the energy and economic structural adjustment, accelerate the transition to clean and low-carbon energy systems, and gradually build up a zero-carbon energy system. Second, the scientific and technologically innovative mechanisms should be prompted, and a new generation of synergetic air pollution-carbon prevention and control technology systems should be developed. Finally, the protection of public health should be taken as the key point for the synergetic management of climate change and air pollution, and current air quality standard should be further tightened after 2030 and gradually conform to WHO air quality guideline, leading to fundamental improvements in air quality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (41921005, 42130708, and 72140003) and the Energy Foundation.

References

[1] B. Zheng, D. Tong, M. Li, F. Liu, C. Hong, G. Geng, H. Li, X. Li, L. Peng, J. Qi, L. Yan, Y. Zhang, H. Zhao, Y. Zheng, K. He, Q. Zhang, Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions, Atmos. Chem. Phys. 18 (19) (2018) 14095–14111, https://doi.org/10.5194/acp-18-14095-2018.

[2] Q. Zhang, Y. Zheng, D. Tong, M. Shao, S. Wang, Y. Zhang, X. Xu, J. Wang, H. He, W.Q. Liu, Y. Ding, Y. Lei, J. Li, Z. Wang, X. Zhang, Y. Wang, J. Cheng, Y. Liu, Q. Shi, L. Yan, G. Geng, C. Hong, M. Li, F. Liu, B. Zheng, J. Cao, A. Ding, J. Gao, Q. Fu, J. Hao, B. Liu, Z. Liu, F. Yang, K. He, J. Hao, Drivers of improved PM2.5 air quality in China from 2013 to 2017, Proc. Natl. Acad. Sci. U.S.A. 116 (49) (2019) 24463–24469, https://doi.org/10.1073/pnas.1907956116.

[3] Q. Xiao, G. Geng, T. Xue, S. Liu, C. Cai, K. He, Q. Zhang, Tracking $PM_{2.5}$ and O_3 pollution and the related health burden in China 2013-2020, Environ. Sci. Technol. (2021b), https://doi.org/10.1021/acs.est.1c04548.

[4] J. Cheng, D. Tong, Q. Zhang, Y. Liu, Y. Lei, G. Yan, L. Yan, S. Yu, R.Y. Cui, L. Clarke, G. Geng, B. Zheng, X. Zhang, S.J. Davis, K. He, Pathways of China's $PM_{2.5}$ air quality 2015-2060 in the context of carbon neutrality, Natl. Sci. Rev. 8 (12) (2021) nwab078, https://doi.org/10.1093/nsr/nwab078.

[5] Y. Liu, D. Tong, J. Cheng, Q. Zhang, S.J. Davis, S.C. Yu, Q. Zhang, Y. Liu, D. Tong, J. Cheng, S.J. Davis, S. Yu, B. Yarlagadda, L.E. Clarke, M. Brauer, A.J. Cohen, H. Kan, T. Xue, Role of climate goals and clean-air policies on reducing future air pollution deaths in China: a modelling study, Lancet Planet. Health 6 (2) (2022) e92–e99, https://doi.org/10.1016/S2542-5196(21)00326-0.

[6] J. He, S. Gong, Y. Yu, L. Yu, L. Wu, H. Mao, C. Song, S. Zhao, H. Liu, X. Li, R. Li, Air pollution characteristics and their relation to meteorological conditions during 2014–2015 in major Chinese cities, Environ. Pollut. 223 (2017) 484–496, https://doi.org/10.1016/j.envpol.2017.01.050.

[7] X. Zhang, X. Xu, Y. Ding, Y. Liu, H. Zhang, Y. Wang, J. Zhong, The impact of meteorological changes from 2013 to 2017 on $PM_{2.5}$ mass reduction in key regions in China, Sci. China Earth Sci. 62 (12) (2019) 1885–1902, https://doi.org/10.1007/s11430-019-9343-3.

[8] D.J. Jacob, D.A. Winner, Effect of climate change on air quality, Atmos. Environ. 43 (1) (2009) 51–63, https://doi.org/10.1016/j.atmosenv.2008.09.051.

[9] J. Liu, L.J. Mickley, M.P. Sulprizio, F. Dominici, X. Yue, K. Ebisu, G.B. Anderson, R.F.A. Khan, M.A. Bravo, M.L. Bell, Particulate air pollution from wildfires in the Western US under climate change, Clim. Change 138 (2016) 655–666, https://doi.org/10.1007/s10584-016-1762-6.

[10] R.A. Silva, J.J. West, J.F. Lamarque, D.T. Shindell, W.J. Collins, G. Faluvegi, G.A. Folberth, L.W. Horowitz, T. Nagashima, V. Naik, S.T. Rumbold, K. Sudo, T. Takemura, D. Bergmann, P. Cameron-Smith, R.M. Doherty, B. Josse, I.A. MacKenzie, D.S. Stevenson, G. Zeng, Future global mortality from changes in air pollution attributable to climate change, Nat. Clim. Change 7 (9) (2017) 647–651, https://doi.org/10.1038/nclimate3354.

[11] C. Hong, Q. Zhang, Y. Zhang, S.J. Davis, X. Zhang, D. Tong, D. Guan, Z. Liu, K. He, Weakening aerosol direct radiative effects mitigate climate penalty on Chinese air quality, Nat. Clim. Change 10 (9) (2020) 845–850, https://doi.org/10.1038/s41558-020-0840-y.

[12] Q. Luo, S. Li, Y. Guo, X. Han, J.J.K. Jaakkola, A systematic review and meta-analysis of the association between daily mean temperature and mortality in China, Environ. Res. 173 (2019) 281–299, https://doi.org/10.1016/j.envres.2019.03.044.

[13] Z. Sun, C. Chen, M. Yan, W. Shi, J. Wang, J. Ban, Q. Sun, M.Z. He, T. Li, Heat wave characteristics, mortality and effect modification by temperature zones: a time-series study in 130 counties of China, Int. J. Epidemiol. 49 (6) (2020) 1813–1822, https://doi.org/10.1093/ije/dyaa104.

[14] X. Wang, H. Xun, R. Kang, W. Wang, W. Ma, Effects of typhoon on mortality and burden of disease of residents in Yuexiu district of Guangzhou from 2008 to 2011, J. Environ. Health 2 (4) (2015) 315–318, https://doi.org/10.16241/j.cnki.1001-5914.2015.04.010. In Chinese.

[15] M. Yan, A. Wilson, J.L. Peel, S. Magzamen, Q. Sun, T. Li, G.B. Anderson, community-wide mortality rates in Beijing, China, during the July 2012 flood compared with unexposed periods, Epidemiology 31 (3) (2020) 319–326, https://doi.org/10.1097/EDE.0000000000001182.

[16] X. Wu, L. Lang, W. Ma, T. Song, M. Kang, J. He, W. Zhang, L. Lu, H. Lin, L. Ling, Non-linear effects of mean temperature and relative humidity on dengue incidence in Guangzhou, China, Sci. Total Environ. 628–629 (2018) 766–771,

https://doi.org/10.1016/j.scitotenv.2018.02.136.

[17] J. Wei, Y. Liu, Y. Zhu, J. Qian, R. Ye, C. Li, X. Ji, H.-K. Li, C. Qi, Y. Wang, F. Yang, Y. Zhou, R. Yan, X. Cui, Y. Liu, N. Jia, S. Li, X. Li, F. Xue, L. Zhao, W. Cao, Impacts of transportation and meteorological factors on the transmission of COVID-19, Int. J. Hyg Environ. Health 230 (2020), 113610, https://doi.org/10.1016/j.ijheh.2020.113610.

[18] X. Zhang, X. Gu, L. Wang, Y. Zhou, Z. Huang, C. Xu, C. Cheng, Spatiotemporal variations in the incidence of bacillary dysentery and long-term effects associated with meteorological and socioeconomic factors in China from 2013 to 2017, Sci. Total Environ. 755 (2021), 142626, https://doi.org/10.1016/j.scitotenv.2020.142626.

[19] M.H. Forouzanfar, A. Afshin, L.T. Alexander, H. Ross Anderson, Z. Bhutta, S. Biryukov, M. Brauer, R. Burnett, K. Cercy, F.J. Charlson, J. Geleijnse, Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2015: a systematic analysis for the Global Burden of Disease Study 2015, Lancet 388 (10053) (2016) 1659−1724, https://doi.org/10.1016/S0140-6736(16)31679-8.

[20] R. Burnett, H. Chen, M. Szyszkowicz, N. Fann, B. Hubbell, C.A. Pope, J.S. Apte, M. Brauer, A. Cohen, S. Weichenthal, J. Coggins, Q. Di, B. Brunekreef, J. Frostad, S.S. Lim, H. Kan, K.D. Walker, G.D. Thurston, R.B. Hayes, D. Krewski, Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, Proc. Natl. Acad. Sci. U.S.A. 115 (38) (2018) 9592−9597, https://doi.org/10.1073/pnas.1803222115.

[21] T. Li, Y. Guo, Y. Liu, J. Wang, Q. Wang, Z. Sun, M.Z. He, X. Shi, Estimating mortality burden attributable to short-term $PM_{2.5}$ exposure: a national observational study in China, Environ. Int. 125 (2) (2019) 245−251, https://doi.org/10.1016/j.envint.2019.01.073.

[22] U.S. EPA, Integrated Science Assessment (ISA) for Particulate Matter (Final Report, 2019), U.S. Environmental Protection Agency, Washington, DC, 2019. EPA/600/R-19/188, https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534.

[23] U.S. EPA, Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants, U.S. Environmental Protection Agency, Washington, DC, 2020. EPA/600/R-20/012, https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NCEA&dirEntryId=247492.

[24] X. Meng, C. Liu, R. Chen, F. Sera, A.M. Vicedo-Cabrera, A. Milojevic, Y. Guo, S. Tong, M. Coelho, Z.S. de S, P.H.N. Saldiva, E. Lavigne, P.M. Correa, N.V. Ortega, S. Osorio, J. Garcia, Kyselý, A. Urban, H. Orru, M. Maasikmets, H. Kan, Short term associations of ambient nitrogen dioxide with daily total, cardiovascular, and respiratory mortality: multilocation analysis in 398 cities, 2021, BMJ (2021) 372. n534, https://www.bmj.com/content/372/bmj.n534.

[25] World Health Organization, WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide, World Health Organization, 2021. https://apps.who.int/iris/handle/10665/345329.

[26] D. Shindell, C.J. Smith, Climate and air-quality benefits of a realistic phase-out of fossil fuels, Nature 573 (7774) (2019) 408−411, https://doi.org/10.1038/s41586-019-1554-z.

[27] C. Li, X. Bai, Q. Tan, G. Luo, L. Wu, F. Chen, H. Xi, X. Luo, C. Ran, H. Chen, S. Zhang, M. Liu, S. Gong, L. Xiong, F. Song, B. Xiao, C. Du, High-resolution mapping of the global silicate weathering carbon sink and its long-term changes, Global Change Biol. 28 (2022) 4377−4394, https://doi.org/10.1111/gcb.16186.

[28] S.J. Davis, N.S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I.L. Azevedo, S.M. Benson, T. Bradley, J. Brouwer, Y.M. Chiang, C.T.M. Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C.B. Field, B. Hannegan, B.M. Hodge, M.I. Hoffert, K. Caldeira, Net-zero emissions energy systems, Science 360 (2018), eaas9793, https://doi.org/10.1126/science.aas9793.

[29] S. Zhang, K. An, J. Li, Y. Weng, S. Zhang, S. Wang, W. Cai, C. Wang, P. Gong, Incorporating health co-benefits into technology pathways to achieve China's 2060 carbon neutrality goal: a modelling study, Lancet Planet. Health 5 (11) (2021) e808−e817, https://doi.org/10.1016/S2542-5196(21)00252-7.

[30] Y. Wang, A. Wang, J. Zhai, H. Tao, T. Jiang, B. Su, T. Fischer, Tens of thousands additional deaths annually in cities of China between 1.5 °C and 2.0 °C warming, Nat. Commun. 10 (1) (2019) 1−7, https://doi.org/10.1038/s41467-019-11283-w.

[31] B.V. Mathiesen, H. Lund, K. Karlsson, 100% Renewable energy systems, climate mitigation and economic growth, Appl. Energy 88 (2) (2011) 488−501, https://doi.org/10.1016/j.apenergy.2010.03.001.

[32] S. Chen, D. Zhang, Impact of air pollution on labor productivity: evidence from prison factory data, China Econ. Quart. Int. 1 (2) (2021) 148−159, https://doi.org/10.1016/j.ceqi.2021.04.004.

[33] G. Geng, Q. Xiao, S. Liu, X. Liu, J. Cheng, Y. Zheng, T. Xue, D. Tong, B. Zheng, Y. Peng, X. Huang, K. He, Q. Zhang, Tracking air pollution in China: near real-time $PM_{2.5}$ retrievals from multiple data sources, Environ. Sci. Technol. 55 (2021) 12106−12115, https://doi.org/10.1021/acs.est.1c01863.

[34] Q. Xiao, G. Geng, J. Cheng, F. Liang, R. Li, X. Meng, T. Xue, X. Huang, H. Kan, Q. Zhang, K. He, Evaluation of gap-filling approaches in satellite-based daily $PM_{2.5}$ prediction models, Atmos. Environ. 244 (2021a), 117921, https://doi.org/10.1016/j.atmosenv.2020.117921.

[35] Y. Zhang, H. Mao, A. Ding, D. Zhou, C. Fu, Impact of synoptic weather patterns on spatio-temporal variation in surface O3 levels in Hong Kong during 1999-2011, Atmos. Environ. 73 (2013) 41−50, https://doi.org/10.1016/j.atmosenv.2013.02.047.

[36] X. Zhang, Y. Wang, W. Lin, Y. Zhang, X. Zhang, S. Gong, P. Zhao, Y. Yang, J. Wang, Q. Hou, X. Zhang, H. Che, G. Guo, Y. Li, Changes of atmospheric composition and optical properties over beijing 2008 olympic monitoring campaign, Bull. Am. Meteorol. Soc. 90 (11) (2009) 1633−1651, https://doi.org/10.1175/2009BAMS2804.1.

[37] J. Wang, S. Gong, X. Zhang, Y. Yang, Q. Hou, C. Zhou, Y. Wang, A parameterized method for air-quality diagnosis and its applications, Adv. Meteorol. (2) (2012), https://doi.org/10.1155/2012/238589, 2012.

[38] J. Wang, Y. Wang, H. Liu, Y. Yang, X. Zhang, Y. Li, Y. Zhang, G. Deng, Diagnostic identification of the impact of meteorological conditions on $PM_{2.5}$ concentrations in Beijing, Atmos. Environ. 81 (2013) 158−165, https://doi.org/10.1016/j.atmosenv.2013.08.033.

[39] China Meteorological Administration, Bulletin of atmospheric. Environ. Meteorology. http://www.cma.gov.cn/zfxxgk/gknr/qxbg/202104/t20210406_3052405.html, 2020. (Accessed 18 November 2021). In Chinese.

[40] P. Wang, Y. Chen, J. Hu, H. Zhang, Q. Ying, Source apportionment of summertime ozone in China using a source-oriented chemical transport model, Atmos. Environ. 211 (2019) 79−90, https://doi.org/10.1016/j.atmosenv.2019.05.006.

[41] W. Cai, K. Li, H. Liao, H. Wang, L. Wu, Weather conditions conducive to Beijing severe haze more frequent under climate change, Nat. Clim. Change 7 (4) (2017) 257−262, https://doi.org/10.1038/nclimate3249.

[42] Z. Han, B. Zhou, Y. Xu, J. Wu, Y. Shi, Projected changes in haze pollution potential in China: an ensemble of regional climate model simulations, Atmos. Chem. Phys. 17 (16) (2017) 10109−10123, https://doi.org/10.5194/acp-17-10109-2017.

[43] H. Chen, H. Wang, J. Sun, Y. Xu, Z. Yin, Anthropogenic fine particulate matter pollution will be exacerbated in eastern China due to 21st century GHG warming, Atmos. Chem. Phys. 19 (1) (2019) 233−243, https://doi.org/10.5194/acp-19-233-2019.

[44] H. Wang, H. Chen, J. Liu, Arctic sea ice decline intensified haze pollution in Eastern China, Atmospheric. Ocean. Sci. Lett. 8 (1) (2015) 1−9, https://doi.org/10.3878/AOSL20140081.

[45] Z. Yin, H. Wang, The relationship between the subtropical western pacific SST and haze over north-central North China plain, Int. J. Climatol. 36 (10) (2016) 3479−3491, https://doi.org/10.1002/joc.4570.

[46] Y. Zou, Y. Wang, Y. Zhang, J.H. Koo, Arctic sea ice, Eurasia snow, and extreme winter haze in China, Sci. Adv. 3 (3) (2017) 1−9, https://doi.org/10.1126/sciadv.1602751.

[47] National Climate Center, China climate bulletin. http://zwgk.cma.gov.cn/zfxxgk/gknr/qxbg/202104/t20210406_3051288.htmln, 2020. (Accessed 4 November 2021). In Chinese.

[48] C. He, R. Liu, X. Wang, S.C. Liu, T. Zhou, W. Liao, How does El Niño-Southern Oscillation modulate the interannual variability of winter haze days over eastern China? Sci. Total Environ. 651 (2019) 1892−1902, https://doi.org/10.1016/j.scitotenv.2018.10.100.

[49] Y. Wang, L. Shen, S. Wu, L. Mickley, J. He, J. Hao, Sensitivity of surface ozone over China to 2000-2050 global changes of climate and emissions, Atmos. Environ. 75 (x) (2013) 374−382, https://doi.org/10.1016/j.atmosenv.2013.04.045.

[50] J. Lee, J. Cha, S. Hong, J. Choi, J. Myoung, R.J. Park, J. Woo, C. Ho, J. Han, C. Song, Projections of summertime ozone concentration over East Asia under multiple IPCC SRES emission scenarios, Atmos. Environ. 106 (2015) 335−346, https://doi.org/10.1016/j.atmosenv.2015.02.019.

[51] M.J. Kim, R.J. Park, C.H. Ho, J.H. Woo, K.C. Choi, C.K. Song, J.B. Lee, Future ozone and oxidants change under the RCP scenarios, Atmos. Environ. 101 (2015) 103−115, https://doi.org/10.1016/j.atmosenv.2014.11.016.

[52] C. Hong, Q. Zhang, Y. Zhang, S.J. Davis, D. Tong, Y. Zheng, Z. Liu, D. Guan, K. He, H.J. Schellnhuber, Impacts of climate change on future air quality and human health in China, Proc. Natl. Acad. Sci. U.S.A. 116 (35) (2019) 17193−17200, https://doi.org/10.1073/pnas.1812881116.

[53] B. Cao, Z. Yin, Future atmospheric circulations benefit ozone pollution control in Beijing-Tianjin-Hebei with global warming, Sci. Total Environ. 743 (219) (2020), 140645, https://doi.org/10.1016/j.scitotenv.2020.140645.

[54] National Bureau of Statistics, China Statistical Yearbook 2020, China statistics press, Beijing, 2020a. In Chinese, http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm. (Accessed 4 November 2021).

[55] National Bureau of Statistics, Statistical communiqué of the people's Republic of China on national economic and social development in 2020. http://www.stats.gov.cn/xxgk/sjfb/tjgb2020/202006/t20200617_1768655.html, 2020b. (Accessed 4 November 2021). In Chinese.

[56] National Bureau of Statistics, Statistical Communiqué of the People's Republic of China on national economic and social development in 2019. http://www.stats.gov.cn/tjsj/zxfb/202102/t20210227_1814154.html, 2021. (Accessed 10 November 2021). In Chinese.

[57] National Energy Conservation center, New highlights of energy economy. http://www.chinanecc.cn/website/News!view.shtml?id=245621, 2021. (Accessed 10 November 2021). In Chinese.

[58] National Bureau of Statistics Division of the energy, China Energy Statistical Yearbook, China statistics press, Beijing, 2021. In Chinese, https://www.yearbookchina.com/navibooklist-n3022013309-1.html. (Accessed 4 November 2021).

[59] National Energy Administration, The State Council information office. P.R.C held a press conference on the development of renewable energy in China.

http://www.nea.gov.cn/2021-03/30/c_139846095.htm, 2021a. (Accessed 4 November 2021). In Chinese.

[60] National Energy Administration, Transcript of the national energy administration's online press conference for the first quarter of 2021. http://www.nea.gov.cn/2021-01/30/c_139708580.htm, 2021b. (Accessed 12 November 2021). In Chinese.

[61] National Development and Reform Commission, Outline of the 14th five-year plan for national economic and social development of the people's Republic of China and the vision for 2035. https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202103/t20210323_1270124_ext.html, 2021. (Accessed 24 October 2021). In Chinese.

[62] National Bureau of Statistics, Statistical Communiqué of the People's Republic of China on national economic and social development in 2015. http://www.stats.gov.cn/tjsj/zxfb/201602/t20160229_1323991.html, 2016. (Accessed 10 November 2021). In Chinese.

[63] Ministry of Industry and Information Technology of the People's Republic of China, Circular on printing and distributing the 12th five-year development plan for the iron and steel industry. http://www.gov.cn/zwgk/2011-11/07/content_1987459.htm, 2011a. (Accessed 20 October 2021). In Chinese.

[64] Ministry of Industry and Information Technology of the People's Republic of China, The 12th Five-Year Plan for cement industry development. http://www.ccement.com/news/Content/48009.html, 2011b. (Accessed 12 November 2021). In Chinese.

[65] Standardization Administration, Fuel consumption limits for passenger cars (GB19578-2004. https://www.antpedia.com/standard/602624-1.html, 2004. (Accessed 12 November 2021). In Chinese.

[66] Standardization Administration, Fuel consumption limits for passenger cars (GB19578-2021. http://c.gb688.cn/bzgk/gb/showGb?type=online&hcno=57DA347FDF48E4743786873E5B2D670A, 2021. (Accessed 17 October 2021). In Chinese.

[67] Standardization Administration, Fuel consumption limits for passenger cars (GB19578-2014. https://www.miit.gov.cn/cms_files/filemanager/oldfile/miit/n1146295/n7281315/c7282880/part/7282887.pdf, 2014. (Accessed 12 November 2021). In Chinese.

[68] China Aviation Administration of China, Civil aviation industry development Statistics Bulletin. http://www.caac.gov.cn/XXGK/XXGK/TJSJ/202006/t20200605_202977.html, 2019. (Accessed 5 June 2020). In Chinese.

[69] IEA, Global EV outlook 2020. https://www.iea.org/reports/global-ev-outlook-2020, 2020. June 2020).

[70] National Railway Administration of the People's Republic of China, Railway statistics bulletin. http://www.nra.gov.cn/xwzx/zlzx/hytj/202204/t20220405_338085.shtml, 2019. (Accessed 30 April 2020). In Chinese.

[71] The State Council Information Office of the People's Republic of China, White paper on sustainable development of transport in China, in: Chinese, 2020. http://www.gov.cn/zhengce/2020-12/22/content_5572212.htm. (Accessed 22 December 2020).

[72] Ministry of Transport of the People's Republic of China, Statistical bulletin on development of transport industry. https://xxgk.mot.gov.cn/2020/jigou/zhghs/202105/t20210517_3593412.html, 2020. (Accessed 19 May 2021). In Chinese.

[73] The State Council Information Office of the People's Republic of China, Press conference on the achievements of the 13th five-year plan of transport development. http://www.scio.gov.cn/xwfbh/xwbfbh/wqfbh/42311/44029/index.htm, 2020. (Accessed 22 October 2020). In Chinese.

[74] C. Liu, X. Jiang, Domestic and International Oil and Gas Industry Development Report 2020, Petroleum industry press, Beijing, 2019 (In Chinese).

[75] IEA, Energy Technology Perspectives 2020 - Special Report on Clean Energy Innovation, OECD Publishing, Paris, 2020, https://doi.org/10.1787/ab43a9a5-en. (Accessed 12 November 2021).

[76] Z. Zhuo, E. Du, N. Zhang, C. Nielsen, X. Lu, J. Xiao, J. Wu, C. Kang, Cost increase in the electricity supply to achieve carbon neutrality in China, Nat. Commun. 13 (2022) 3172, https://doi.org/10.1038/s41467-022-30747-0.

[77] Chinese Wind Energy Association, China Wind Power Industry Mapping 2019, China Renewable Energy Society, Beijing, 2020 (In Chinese).

[78] Global Energy Interconnection Development and Cooperation Organization, Research of the 14th five-year plan of electric power development. https://www.cec.org.cn/upload/1/pdf/1609833054935.pdf, 2020. (Accessed 14 November 2021). In Chinese.

[79] China Renewable Energy Engineering Institute, China renewable energy development report 2019. http://www.creei.cn/portal/article/index/id/25365.html, 2020. (Accessed 14 November 2021). In Chinese.

[80] China Nuclear Energy Association, The report on the development of China's nuclear energy. http://china-nea.cn/upload/ebook/lps/lps2020-v1/mobile/index.html, 2020. (Accessed 17 November 2021), 2020). In Chinese.

[81] X. Li, N. Wei, Z. Jiao, S. Liu, R. Dahowski, Cost curve of large-scale deployment of CO_2-enhanced water recovery technology in modern coal chemical industries in China, Int. J. Greenh. Gas Control 81 (2019) 66–82, https://doi.org/10.1016/j.ijggc.2018.12.012.

[82] The Administrative Center for China's Agenda 21 Ministry of Science and Technology, Roadmap for Carbon Capture, Utilization and Storage Technology in China, Science press, Beijing, 2019. In Chinese. (Accessed 18 November 2021).

[83] Kejun Jiang, Chenmin He, Hancheng Dai, Liu Jia, Xiangyang Xu, Emission scenario analysis for China under the global 1.5 °C target, Carbon Manag. 9 (5) (2018) 481–491, https://doi.org/10.1080/17583004.2018.1477835.

[84] IEA, Direct Air Capture, IEA, Paris, 2021. November 2021, https://www.iea.org/reports/direct-air-capture.

[85] Y. Shan, D. Guan, H. Zheng, J. Ou, Y. Li, J. Meng, Z. Mi, Z. Liu, Q. Zhang, China CO_2 emission accounts 1997–2015, Sci. Data 5 (2018), 170201, https://doi.org/10.1038/sdata.2017.201.

[86] Y. Shan, Q. Huang, D. Guan, K. Hubacek, China CO_2 emission accounts 2016–2017, Sci. Data 7 (1) (2020) 54, https://doi.org/10.1038/s41597-020-0393-y.

[87] IPCC, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2006. https://www.ipcc-nggip.iges.or.jp/public/2006gl/. (Accessed 15 November 2021).

[88] Z. Liu, P. Ciais, Z. Deng, S.J. Davis, B. Zheng, Y.L. Wang, F. Chevallier, Carbon Monitor, a near-real-time daily dataset of global CO_2 emission from fossil fuel and cement production, Sci. Data 7 (1) (2020a) 1–12, https://doi.org/10.6084/m9.figshare.12994058.

[89] Z. Liu, P. Ciais, Z. Deng, R. Lei, S.J. Davis, S. Feng, B. Zheng, D. Cui, X. Dou, B. Zhu, R. Guo, P. Ke, T. Sun, C. Lu, P. He, Y. Wang, X. Yue, Y. Wang, Y. Lei, H.J. Schellnhuber, Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic, Nat. Commun. 11 (1) (2020b) 1–12, https://doi.org/10.1038/s41467-020-18922-7.

[90] M. Li, H. Liu, G. Geng, C. Hong, F. Liu, Y. Song, D. Tong, B. Zheng, H. Cui, H. Man, Q. Zhang, K. He, Anthropogenic emission inventories in China: a review, Natl. Sci. Rev. 4 (2017) 834–866, https://doi.org/10.1093/nsr/nwx150.

[91] T.F. Keenan, C.A. Williams, The terrestrial carbon sink, Annu. Rev. Environ. Resour. 43 (2018) 219–243, https://doi.org/10.1146/annurev-environ-102017-030204.

[92] S. Piao, J. Fang, P. Ciais, P. Peylin, Y. Huang, S. Sitch, T. Wang, The carbon balance of terrestrial ecosystems in China, Nature 458 (7241) (2009) 1009–1013, https://doi.org/10.1038/nature07944.

[93] F. Jiang, J.M. Chen, L. Zhou, W. Ju, H. Zhang, T. Machida, P. Ciais, W. Peters, H. Wang, B. Chen, L. Liu, C. Zhang, H. Matsueda, Y. Sawa, A comprehensive estimate of recent carbon sinks in China using both top-down and bottom-up approaches, Sci. Rep. 6 (2016) 1–9, https://doi.org/10.1038/srep22130. August 2015.

[94] J. Fang, G. Yu, L. Liu, S. Hu, F. Stuart Chapin, Climate change, human impacts, and carbon sequestration in China, Proc. Natl. Acad. Sci. U.S.A. 115 (16) (2018) 4015–4020, https://doi.org/10.1073/pnas.1700304115.

[95] S. Piao, P. Ciais, M. Lomas, C. Beer, H. Liu, J. Fang, P. Friedlingstein, Y. Huang, H. Muraoka, Y. Son, I. Woodward, Contribution of climate change and rising CO_2 to terrestrial carbon balance in East Asia: a multi-model analysis, Global Planet. Change 75 (3–4) (2011) 133–142, https://doi.org/10.1016/j.gloplacha.2010.10.014.

[96] Y. Wang, X. Wang, K. Wang, F. Chevallier, D. Zhu, J. Lian, J.G. Canadell, The size of the land carbon sink in China, Nature 603 (2022) E7–E9, https://doi.org/10.1038/s41586-021-04255-y.

[97] H. Tian, J. Melillo, C. Lu, D. Kicklighter, M. Liu, W. Ren, X. Xu, G. Chen, C. Zhang, S. Pan, J. Liu, S. Running, China's terrestrial carbon balance: contributions from multiple global change factors, Global Biogeochem. Cycles 25 (1) (2011) 1–16, https://doi.org/10.1029/2010GB003838.

[98] G. Yu, Z. Chen, S. Piao, C. Peng, P. Ciais, Q. Wang, X. Zhu, High carbon dioxide uptake by subtropical forest ecosystems in the East Asian monsoon region, Proc. Natl. Acad. Sci. U.S.A. 111 (13) (2014) 4910–4915, https://doi.org/10.1073/pnas.1317065111.

[99] L. Lai, X. Huang, H. Yang, X. Chuai, M. Zhang, T. Zhong, Z. Chen, Y. Chen, X. Wang, J.R. Thompson, Carbon emissions from land-use change and management in China between 1990 and 2010, Sci. Adv. 2 (11) (2016), https://doi.org/10.1126/sciadv.1601063.

[100] H. He, S. Wang, L. Zhang, J. Wang, X. Ren, L. Zhou, S. Piao, H. Yan, W. Ju, F. Gu, S. Yu, Y. Yang, M. Wang, Z. Niu, R. Ge, H. Yan, M. Huang, G. Zhou, Y. Bai, G. Yu, Altered trends in carbon uptake in China's terrestrial ecosystems under the enhanced summer monsoon and warming hiatus, Natl. Sci. Rev. 6 (3) (2019) 505–514, https://doi.org/10.1093/nsr/nwz021.

[101] J. Pongratz, C.H. Reick, R.A. Houghton, J.I. House, Terminology as a key uncertainty in net land use and land cover change carbon flux estimates, Earth Syst. Dyn. 5 (1) (2014) 177–195, https://doi.org/10.5194/esd-5-177-2014.

[102] W. Li, P. Ciais, S. Peng, C. Yue, Y. Wang, M. Thurner, S.S. Saatchi, A. Arneth, V. Avitabile, N. Carvalhais, A.B. Harper, E. Kato, C. Koven, Y.Y. Liu, J.E.M.S. Nabel, Y. Pan, J. Pongratz, B. Poulter, T.A.M. Pugh, S. Zaehle, Land-use and land-cover change carbon emissions between 1901 and 2012 constrained by biomass observations, Biogeosciences 14 (22) (2017) 5053–5067, https://doi.org/10.5194/bg-14-5053-2017.

[103] E. Hansis, S.J. Davis, J. Pongratz, Relevance of methodological choices for accounting of land use change carbon fluxes, Global Biogeochem. Cycles 29 (8) (2015) 1230–1246, https://doi.org/10.1002/2014GB004997.

[104] R.A. Houghton, A.A. Nassikas, Global and regional fluxes of carbon from land use and land cover change 1850–2015, Global Biogeochem. Cycles 31 (3) (2017) 456–472, https://doi.org/10.1002/2016GB005546.

[105] National Forestry and Grassland Administration, China Forest Resources Report, China Forestry Publishing House, Beijing, 2019 (In Chinese).

[106] N. Zhou, D. Fridley, N.Z. Khanna, J. Ke, M. McNeil, M. Levine, China's energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model, Energy Pol. 53 (2013) 51–62, https://doi.org/10.1016/j.enpol.2012.09.065, 2013.

[107] Q. Chai, H. Xu, Modeling an emissions peak in China around 2030: synergies

or trade-offs between economy, energy and climate security, Adv. Clim. Change Res. 5 (4) (2014) 169–180, https://doi.org/10.1016/j.accre.2015.06.001.

[108] J. He, Analysis of CO_2 emissions peak: China's objective and strategy, Chinese J. Popul. Resour. Environ. 12 (3) (2014) 189–198, https://doi.org/10.1080/10042857.2014.932266.

[109] M. Grubb, F. Sha, T. Spencer, N. Hughes, Z. Zhang, P. Agnolucci, A review of Chinese CO_2 emission projections to 2030: the role of economic structure and policy, Clim. Pol. 15 (sup1) (2015) S7–S39, https://doi.org/10.1080/14693062.2015.1101307.

[110] M. Meinshausen, L. Jeffery, J. Guetschow, Y. Robiou Du Pont, J. Rogelj, M. Schaeffer, N. Meinshausen, National post-2020 greenhouse gas targets and diversity-aware leadership, Nat. Clim. Change 5 (12) (2015) 1098–1106, https://doi.org/10.1038/nclimate2826.

[111] M. den Elzen, H. Fekete, N. Höhne, A. Admiraal, N. Forsell, A.F. Hof, J.G.J. Olivier, M. Roelfsema, H. van Soest, Greenhouse gas emissions from current and enhanced policies of China until 2030: can emissions peak before 2030? Energy Pol. 89 (2016) 224–236, https://doi.org/10.1016/j.enpol.2015.11.030. June 2015.

[112] X. Zhang, V.J. Karplus, T. Qi, D. Zhang, J. He, Carbon emissions in China: how far can new efforts bend the curve? Energy Econ. 54 (2016) 388–395, https://doi.org/10.1016/j.eneco.2015.12.002, 2016.

[113] X. Pan, M. den Elzen, N. Höhne, F. Teng, L. Wang, Exploring fair and ambitious mitigation contributions under the Paris Agreement goals, Environ. Sci. Pol. 74 (May) (2017) 49–56, https://doi.org/10.1016/j.envsci.2017.04.020.

[114] K.S. Gallagher, F. Zhang, R. Orvis, J. Rissman, Q. Liu, Assessing the Policy gaps for achieving China's climate targets in the Paris Agreement, Nat. Commun. 10 (1) (2019) 1256, https://doi.org/10.1038/s41467-019-09159-0.

[115] N. Li, W. Chen, P. Rafaj, G. Kiesewetter, W. Schöpp, H. Wang, H. Zhang, V. Krey, K. Riahi, Air quality improvement co-benefits of low-carbon pathways toward well below the 2 °C climate target in China, Environ. Sci. Technol. 53 (10) (2019) 5576–5584, https://doi.org/10.1021/acs.est.8b06948.

[116] D. Tong, J. Cheng, Y. Liu, S. Yu, L. Yan, C. Hong, Y. Qin, H. Zhao, Y. Zheng, G. Geng, M. Li, F. Liu, Y. Zhang, B. Zheng, L. Clarke, Q. Zhang, Dynamic projection of anthropogenic emissions in China: methodology and 2015–2050 emission pathways under a range of socioeconomic, climate policy, and pollution control scenarios, Atmos. Chem. Phys. (2020) 1–49, https://doi.org/10.5194/acp-2019-1125.

[117] J. Huang, China's goal of carbon neutrality by 2060 needs to be reinforced by science and technology, China. Sustain. Trib. 10 (2020) 15–16. In Chinese, http://sdg-china.net/portal/article/index/id/546/cid/15.html.

[118] Y.-M. Wei, J.-N. Kang, L.-C. Liu, Q. Li, P.-T. Wang, J.-J. Hou, B. Yu, A proposed global layout of carbon capture and storage in line with a 2 °C climate target, Nat. Clim. Change 11 (2) (2021) 112–118, https://doi.org/10.1038/s41558-020-00960-0.

[119] B. Yu, G. Zhao, R. An, J. Chen, J. Tan, X. Li, Research on China's CO_2 emission pathway under carbon neutral target, J. Beijing Inst. Technol. (Soc. Sci. Ed.) 23 (2) (2021) 18–24, https://doi.org/10.15918/j.jbitss1009-3370.2021.7380.

[120] J. Zhang, L. Zhang, Preliminary discussion on development of carbon capture, utilization and storage for carbon neutralization, Therm. Power Gener. 50 (1) (2021) 1–6, https://doi.org/10.19666/j.rlfd.202011253. In Chinese.

[121] X. Zhang, The Application Prospects of CCUS in China under the target of carbon neutrality, China. Sustain. Trib. 12 (22–24) (2020). In Chinese, http://sdg-china.net/portal/article/index/id/599.html.

[122] M. Liu, X. Liang, Q. Lin, Economic analysis and risk assessment for carbon capture, utilization and storage project under the background of carbon neutrality in China, Therm. Power Gener. 50 (9) (2021) 18–26, https://doi.org/10.19666/j.rlfd.202101009. In Chinese.

[123] C.J.L. Murray, A.Y. Aravkin, P. Zheng, C. Abbafati, K.M. Abbas, M. Abbasi-Kangevari, F. Abd-Allah, A. Abdelalim, M. Abdollahi, I. Abdollahpour, K.H. Abegaz, H. Abolhassani, V. Aboyans, L.G. Abreu, M.R.M. Abrigo, A. Abualhasan, L.J. Abu-Raddad, A.I. Abushouk, M. Adabi, V. Adekanmbi, S.S. Lim, Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019, Lancet 396 (10258) (2020) 1223–1249, https://doi.org/10.1016/S0140-6736(20)30752-2, 2020.

[124] T. Xue, T. Guan, G. Geng, Q. Zhang, Y. Zhao, T. Zhu, Estimation of pregnancy losses attributable to exposure to ambient fine particles in south Asia: an epidemiological case-control study, Lancet Planet. Health 5 (1) (2021a) e15–e24, https://doi.org/10.1016/S2542-5196(20)30268-0.

[125] T. Xue, T. Zhu, Y. Zheng, Q. Zhang, Declines in mental health associated with air pollution and temperature variability in China, Nat. Commun. 10 (1) (2019) 1–8, https://doi.org/10.1038/s41467-019-10196-y.

[126] T. Xue, T. Guan, Y. Zheng, G. Geng, Q. Zhang, Y. Yao, T. Zhu, Long-term $PM_{2.5}$ exposure and depressive symptoms in China: a quasi-experimental study, The Lancet Reg. Health - West. Pacif. 6 (2021b), 100079, https://doi.org/10.1016/j.lanwpc.2020.10.

[127] Y. Yao, Y. Zeng, X. Lv, H. Wang, B. Dementia Key Lab, H.J. Li MS, T. Xue, K. Liu, E. Salah Eshak, Y. Yao, X. Lv, C. Qiu, J. Li, X. Wu, H. Zhang, D. Yue, K. Liu, E. Salah Eshak, T. Lorenz, Y. Zeng, The effect of China's Clean Air Act on cognitive function in older adults: a population-based, quasi-experimental study, The Lancet Healthy Longevity 3 (2) (2022) e98–e108, https://doi.org/10.1016/S2666-7568(22)00004-6, 2022.

[128] F. Kazemiparkouhi, K.-D. Eum, B. Wang, J. Manjourides, H.H. Suh, Long-term ozone exposures and cause-specific mortality in a US Medicare cohort, J. Expo. Sci. Environ. Epidemiol. 30 (4) (2020) 650–658, https://doi.org/10.1038/s41370-019-0135-4.

[129] R.D. Brook, S. Rajagopalan, C.A. Pope, J.R. Brook, A. Bhatnagar, A.v. Diez-Roux, F. Holguin, Y. Hong, R.v. Luepker, M.A. Mittleman, A. Peters, D. Siscovick, S.C. Smith, L. Whitsel, J.D. Kaufman, Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American heart association, Circulation 121 (21) (2010) 2331–2378, https://doi.org/10.1161/CIR.0b013e3181dbece1.

[130] R. Chen, P. Yin, X. Meng, C. Liu, L. Wang, X. Xu, J.A. Ross, L.A. Tse, Z. Zhao, H. Kan, M. Zhou, Fine particulate air pollution and daily mortality: a nationwide analysis in 272 Chinese cities, Am. J. Respir. Crit. Care Med. 196 (1) (2017) 73–81, https://doi.org/10.1164/rccm.201609-1862OC.

[131] X. Lu, L. Zhang, X. Wang, M. Gao, K. Li, Y. Zhang, X. Yue, Y. Zhang, Rapid increases in warm-season surface ozone and resulting health impact in China since 2013, Environ. Sci. Technol. Lett. 7 (4) (2020) 240–247, https://doi.org/10.1021/acs.estlett.0c00171.

[132] P. Yin, R. Chen, L. Wang, X. Meng, C. Liu, Y. Niu, H. Kan, Ambient ozone pollution and daily mortality: a nationwide study in 272 Chinese cities, Environ. Health Prospect. 125 (11) (2017), 117006, https://doi.org/10.1289/EHP1849.

[133] S. Liang, X. Li, Y. Teng, H. Fu, L. Chen, J. Mao, H. Zhang, S. Gao, Y. Sun, Z. Ma, M. Azzi, Estimation of health and economic benefits based on ozone exposure level with high spatial-temporal resolution by fusing satellite and station observations, Environ. Pollut. 255 (2019), 113267, https://doi.org/10.1016/j.envpol.2019.113267.

[134] M. Zhou, L. Wang, T. Liu, Y. Zhang, H. Lin, Y. Luo, J. Xiao, W. Zeng, Y. Zhang, X. Wang, X. Gu, S. Rutherford, C. Chu, W. Ma, Health impact of the 2008 cold spell on mortality in subtropical China: the climate and health impact national assessment study (CHINAs), Environ. Health 13 (1) (2014) 1–13, https://doi.org/10.1186/1476-069X-13-60.

[135] J. Li, R. Wei, A. Zhang, W. Hu, J. Lin, W. Ma, A case-crossover study on the tropical cyclones and daily outpatient numbers of respiratory diseases, J. Shandong Univ. (Nat. Sci.) 56 (8) (2018) 43–49. http://yxbwk.njournal.sdu.edu.cn/EN/10.6040/j.issn.1671-7554.0.2018.055.

[136] J. Yang, M. Zhou, Z. Ren, M. Li, B. Wang, D.L. Liu, Q. Liu, Projecting heat-related excess mortality under climate change scenarios in China, Nat. Commun. 12 (1) (2021) 1–11, https://doi.org/10.1038/s41467-021-21305-1.

[137] T. Li, R.M. Horton, D.A. Bader, M. Zhou, X. Liang, J. Ban, Q. Sun, P.L. Kinney, Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China, Sci. Rep. 6 (May) (2016) 1–9, https://doi.org/10.1038/srep28161.

[138] J. Liu, J. Zhou, J. Yao, X. Zhang, L. Li, X. Xu, X. He, B. Wang, S. Fu, T. Niu, J. Yan, Y. Shi, X. Ren, J. Niu, W. Zhu, S. Li, B. Luo, K. Zhang, Impact of meteorological factors on the COVID-19 transmission: a multi-city study in China, Sci. Total Environ. 726 (2020), 138513, https://doi.org/10.1016/j.scitotenv.2020.138513.

[139] M. Li, D. Zhang, C.T. Li, N.E. Selin, V.J. Karplus, Co-benefits of China's climate policy for air quality and human health in China and transboundary regions in 2030, Environ. Res. Lett. 14 (8) (2019), https://doi.org/10.1088/1748-9326/ab26ca.

[140] D.M. Westervelt, C.T. Ma, M.Z. He, A.M. Fiore, P.L. Kinney, M.-A. Kioumourtzoglou, S. Wang, J. Xing, D. Ding, G. Correa, Mid-21st century ozone air quality and health burden in China under emissions scenarios and climate change, Environ. Res. Lett. 14 (7) (2019), https://doi.org/10.1088/1748-9326/ab260b.

[141] Y. Xie, Y. Wu, M. Xie, B. Li, H. Zhang, T. Ma, Y. Zhang, Health and economic benefit of China's greenhouse gas mitigation by 2050, Environ. Res. Lett. 15 (10) (2020), https://doi.org/10.1088/1748-9326/aba97b.

[142] J. Xing, X. Lu, S. Wang, T. Wang, D. Ding, S. Yu, J. Hao, The quest for improved air quality may push China to continue its CO_2 reduction beyond the Paris Commitment, Proc. Natl. Acad. Sci. U.S.A. 117 (47) (2020) 29535–29542, https://doi.org/10.1073/pnas.2013297117.

[143] C. Qu, X. Yang, D. Zhang, X. Zhang, Estimating health co-benefits of climate polices in China: an application of the Regional Emissions-Air Quality-Climate-Health (REACH) framework, Clim. Chang. Econ. 11 (2020), 2041004, https://doi.org/10.1142/S2010007820410043, 03.

[144] X. Cui, W. Cai, X. Shi, T. Li, Q. Wang, P. Gong, The nature and scale of the response to climate change will determine the human health for centuries to come in China, Chin. Sci. Bull. 65 (1) (2020) 12–17, https://doi.org/10.1360/N972019-00185.

[145] L. Cao, Y. Tang, B. Cai, P. Wu, Y. Zhang, F. Zhang, B. Xin, C. Lv, K. Chen, K. Fang, Was it better or worse? Simulating the environmental and health impacts of emissions trading scheme in Hubei province, China, Inside Energy 217 (2021), 119427, https://doi.org/10.1016/j.energy.2020.119427.

[146] S. Chang, X. Yang, H. Zheng, S. Wang, X. Zhang, Air quality and health co-benefits of China's national emission trading system, Appl. Energy 261 (2020), 114226, https://doi.org/10.1016/j.apenergy.2019.114226. February 2019.

[147] M. Zhang, S.M. Jordaan, W. Peng, Q. Zhang, S.M. Miller, Potential uses of coal methane in China and associated benefits for air quality, health, and climate, Environ. Sci. Technol. 54 (19) (2020) 12447−12455, https://doi.org/10.1021/acs.est.0c01207.

[148] C. Cao, X. Cui, W. Cai, C. Wang, L. Xing, N. Zhang, S. Shen, Y. Bai, Z. Deng, Incorporating health co-benefits into regional carbon emission reduction policy making: a case study of China's power sector, Appl. Energy 253 (June) (2019), 113498, https://doi.org/10.1016/j.apenergy.2019.113498.

[149] J. Yang, X. Li, W. Peng, F. Wagner, D.L. Mauzerall, Climate, air quality and human health benefits of various solar photovoltaic deployment scenarios in China in 2030, Environ. Res. Lett. 13 (6) (2018), https://doi.org/10.1088/1748-9326/aabe99.

[150] B.S. Li, Y. Chen, S. Zhang, Z. Wu, J. Cofala, H. Dai, Climate and health benefits of phasing out iron & steel production capacity in China: findings from the IMED model, Clim. Chang. Econ. 11 (2020), 2041008, https://doi.org/10.1142/S2010007820410080, 03.

[151] L. Liu, K. Wang, S. Wang, R. Zhang, X. Tang, Assessing energy consumption, CO2 and pollutant emissions and health benefits from China's transport sector through 2050, Energy Pol. 116 (100) (2018) 382−396, https://doi.org/10.1016/j.enpol.2018.02.019.

[152] X. Tian, H. Dai, Y. Geng, S. Zhang, Y. Xie, X. Liu, P. Lu, R. Bleischwitz, Toward the 2-degree target: evaluating co-benefits of road transportation in China, J. Transport Health 15 (2019), 100674, https://doi.org/10.1016/j.jth.2019.100674. October.

[153] X. Zhang, Y. Jin, H. Dai, Y. Xie, S. Zhang, Health and economic benefits of cleaner residential heating in the Beijing−Tianjin−Hebei region in China, Energy Pol. 127 (2019) 165−178, https://doi.org/10.1016/j.enpol.2018.12.008. October 2018.

[154] National Bureau of Statistics, China Statistical Yearbook 2019, China statistics press, Beijing, 2019. In Chinese, http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm. (Accessed 4 November 2021).

[155] Ministry of Finance of the People's Republic of China, Budgetary revenue and expenditure in 2020, in: Chinese, 2020. http://gks.mof.gov.cn/tongjishuju/202101/t20210128_3650522.htm. (Accessed 20 October 2021).

[156] J. Huang, X. Pan, X. Guo, G. Li, Health impact of China's Air Pollution Prevention and Control Action Plan: an analysis of national air quality monitoring and mortality data, Lancet Planet. Health 2 (7) (2018) e313−e323, https://doi.org/10.1016/S2542-5196(18)30141-4.

[157] D. Ding, J. Xing, S. Wang, K. Liu, J. Hao, Estimated contributions of emissions controls, meteorological factors, population growth, and changes in baseline mortality to reductions in ambient $PM_{2.5}$ and $PM_{2.5}$-related mortality in China, 2013-2017, Environ. Health Perspect. 127 (6) (2019), 67009, https://doi.org/10.1289/EHP4157.

[158] B. Cai, S. Liang, J. Zhou, J. Wang, L. Cao, S. Qu, M. Xu, Z. Yang, China high resolution emission database (CHRED) with point emission sources, gridded emission data, and supplementary socioeconomic data, Resour. Conserv. Recycl. 129 (2018) 232−239, https://doi.org/10.1016/j.resconrec.2017.10.036. October 2017.

[159] B. Cai, C. Cui, D. Zhang, L. Cao, P. Wu, L. Pang, J. Zhang, C. Dai, China city-level greenhouse gas emissions inventory in 2015 and uncertainty analysis, Appl. Energy 253 (June) (2019a), 113579, https://doi.org/10.1016/j.apenergy.2019.113579.

[160] B. Cai, H. Guo, Z. Ma, Z. Wang, S. Dhakal, L. Cao, Benchmarking carbon emissions efficiency in Chinese cities: a comparative study based on high-resolution gridded data, Appl. Energy 242 (February) (2019b) 994−1009, https://doi.org/10.1016/j.apenergy.2019.03.146.

[161] China City Greenhouse Gas Working Group, Urban Carbon Dioxide Emissions and Air Pollutants in China 2020, Institute of Environmental Planning, Ministry of Ecology and Environment, Beijing, 2020. In Chinese.(13 November 2021.

[162] Chinese Academy of Environmental Planning, Assessment report on collaborative management of Carbon dioxide and Air Pollution in Chinese cities. http://www.cityghg.com/uploads/soft/201103/1-2011031I117.pdf, 2020. (Accessed 16 November 2021). Chinese.

[163] D. Tong, Q. Zhang, Y. Zheng, K. Caldeira, C. Shearer, C. Hong, Y. Qin, S.J. Davis, Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target, Nature 572 (7769) (2019) 373−377, https://doi.org/10.1038/s41586-019-1364-3.