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Synergetic Roadmap

The 2024 report of the synergetic roadmap on carbon neutrality and clean air for China: Pollution and carbon reduction promote green economic development

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A B S T R A C T

Addressing climate change and air pollution exhibits strong synergy, and the Chinese government is actively promoting the integrated management of these two issues. Since 2019, the China Clean Air Policy Partnership has released annual reports on China's progress in climate and air pollution governance. These reports track and analyze the challenges and propose solutions for China's pursuit of carbon neutrality and clean air by developing and monitoring key indicators across five areas. This report is the fourth annual report. Building on previous research, it further refines the collaborative governance monitoring indicator system, including the addition of climate change and extreme weather, atmospheric greenhouse gases, and enhanced efficiency of pollution removal technologies. The report includes the following components: (1) an analysis of the interactions between air pollution and climate change; (2) a discussion of governance systems and practices, with an emphasis on policy implementation and local experiences; (3) coverage of structural changes and emission reduction technologies, including energy and industrial transitions, transportation, low-carbon buildings, carbon capture and storage, and power systems; (4) an overview of atmospheric dynamics and emission pathways, examining emission drivers and offering insights for future coordinated governance; and (5) an evaluation of the health impacts and benefits of joint actions. These efforts underscore China's commitment to integrated control, resulting in slowed carbon emission growth, improved air quality, and enhanced health benefits.

1. Introduction

Under the new circumstances of ecological civilization development, China faces two major strategic tasks simultaneously: achieving carbon peaking and carbon neutrality ("dual carbon goals") and constructing a Beautiful China. Coordinating the advancement of carbon reduction and pollution control has become an inevitable trend for China's socio-economic development, enabling it to achieve a comprehensive green transformation. In recent years, a series of air pollution prevention and control policies and measures implemented in China have led to a significant improvement in air quality [1,2]. However, these improvements are not yet stable, and severe pollution weather still occurs frequently, especially during the autumn and winter seasons [3–5]. A key focus of attention and exploration across various sectors of society is how to optimize technological pathways and design policy combinations to promote the synergistic efforts of clean air initiatives and measures for carbon peaking and carbon neutrality [6,7].

To comprehensively and objectively track and review China's progress in co-governance of climate change and air pollution, a collaborative effort was launched in 2021. Supported by the Energy Foundation and the China Clean Air Policy Partnership, Tsinghua University, the Chinese Academy of Environmental Planning, Peking University, and Nanjing University of Information Science and Technology jointly initiated the compilation of the “Annual Report on China's Carbon Neutrality and Clean Air Co-Beneficial Pathways." This initiative brings together experts from diverse fields like atmospheric science, environmental engineering, energy, public health, and management. The goal is to track, review, summarize, and analyze China's progress in the coordinated governance of air pollution and climate change, identify challenges, and propose solutions to support the formation of a closed loop for policy development, evaluation, and optimization, promoting the effective implementation of synergistic governance policies.

This report is the fourth in the annual series [8,9]. Building upon previous research, this study further refines the monitoring indicator system, establishing twenty indicators across five areas: air pollution and climate change; a synergetic governance system and practices; structural transformation and control technologies; the source, sinks, and mitigation pathways of atmospheric composition; and health impacts and co-benefits. The description of each indicator is documented in Supplementary Table S1. Compared to the previous report [9], the 2024 report includes several updates. To better understand the characteristics of extreme climate events and changes in atmospheric greenhouse gases (GHGs) in the context of accelerating global warming, and to highlight the importance of collaborative governance of climate

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change and air pollution, indicators 1.2 (climate change and extreme weather) and 1.3 (atmospheric GHGs) have been added. To summarize the implementation progress of eight key measures in China's air pollution control from 2013 to 2023, indicator 3.7, "enhanced efficiency of pollution removal technologies," has been added. Regular tracking of these twenty indicators gradually establishes a theoretical framework for the synergistic governance of carbon neutrality and clean air, identifies key challenges in China's synergistic pathway, and proposes the design of corresponding solutions.

2. Air pollution and climate change

Air pollution and climate change serve as monitoring indicators for assessing the effectiveness of "pollution reduction and carbon mitigation" efforts at national and urban levels, with remarkable interactions between the two [10–12]. Real-time monitoring of atmospheric pollution and climate change at national and regional scales can facilitate more scientific and precise development of synergistic pathways for achieving "carbon neutrality" and "clean air" [13,14]. Thus, this section reviews the air quantity and climate changes in 2023, with a particular focus on the interaction between these two factors.

2.1. Changes in air quantity

In 2023, the average $PM_{2.5}$ concentration across 339 cities at or above the prefecture level was 30 μg m^{-3} (Fig. 1a), 33.3% lower than the 2015 level (45 μg m^{-3}). Spatially, the high-value pollution zones shifted from Hebei and Shandong in 2015 to Shanxi and Henan in 2023, with the value decreasing from approximately 100 to around 50 μg m^{-3}. The number of cities with annual average $PM_{2.5}$ concentrations below the national secondary standard (35 μg m^{-3}) in 2023 increased by 83% compared to 2015. This indicates notable progress in air pollution control during the "National 14th Five-Year Plan (FYP)" period. Notably, $PM_{2.5}$ concentrations in the Beijing–Tianjin–Hebei and its surrounding regions (BTHs), the Yangtze River Delta (YRD), Sichuan Basin (SCB), and Pearl River Delta (PRD) regions in 2023 experienced a slight increase compared to 2022.

In 2023, the 90th percentile of the maximum 8-h average (MDA8) O_3 concentrations across 339 Chinese cities ranged from 89 to 198 μg m^{-3}, with an average of 144 μg m^{-3} (Fig. 1b). 73% cities had an MDA8 O_3 concentration below the national secondary standard (160 μg m^{-3}). Compared to 2022, the O_3 concentrations in the SCB, BTHs, and Fen–Wei Plain (FWP) increased by 1.0%, 1.4%, and 1.5%, respectively, while the YRD and PRD saw decreases of 2.3% and 7.4%, respectively. Analysis of three-year averages indicates that O_3 concentrations in China and key regions increased continuously from 2015 to 2019 but stabilized or slightly declined from 2020 to 2023. In 2015, the most severe O_3 pollution was concentrated in the BTHs, SCB, and YRD. By 2023, national O_3 concentrations increased overall, with persistent severe O3 concentrations in the BTHs, whereas the SCB and YRD regions experienced notable reductions.

The proportion of days with severe $PM_{2.5}$ pollution across 339 Chinese cities was 1.1% in 2023, which was 0.7% higher than in 2022 but 60.7% lower than in 2015, indicating effective control of $PM_{2.5}$ pollution. Among the key regions, the proportion in BTHs and FPW was 2.2% and 3.2% in 2023, representing a decrease of 78.2% and 36.0% compared to 2015. The YRD and SCB exhibited the lowest proportion, at 0.6% and 0.7%, respectively. The PRD has

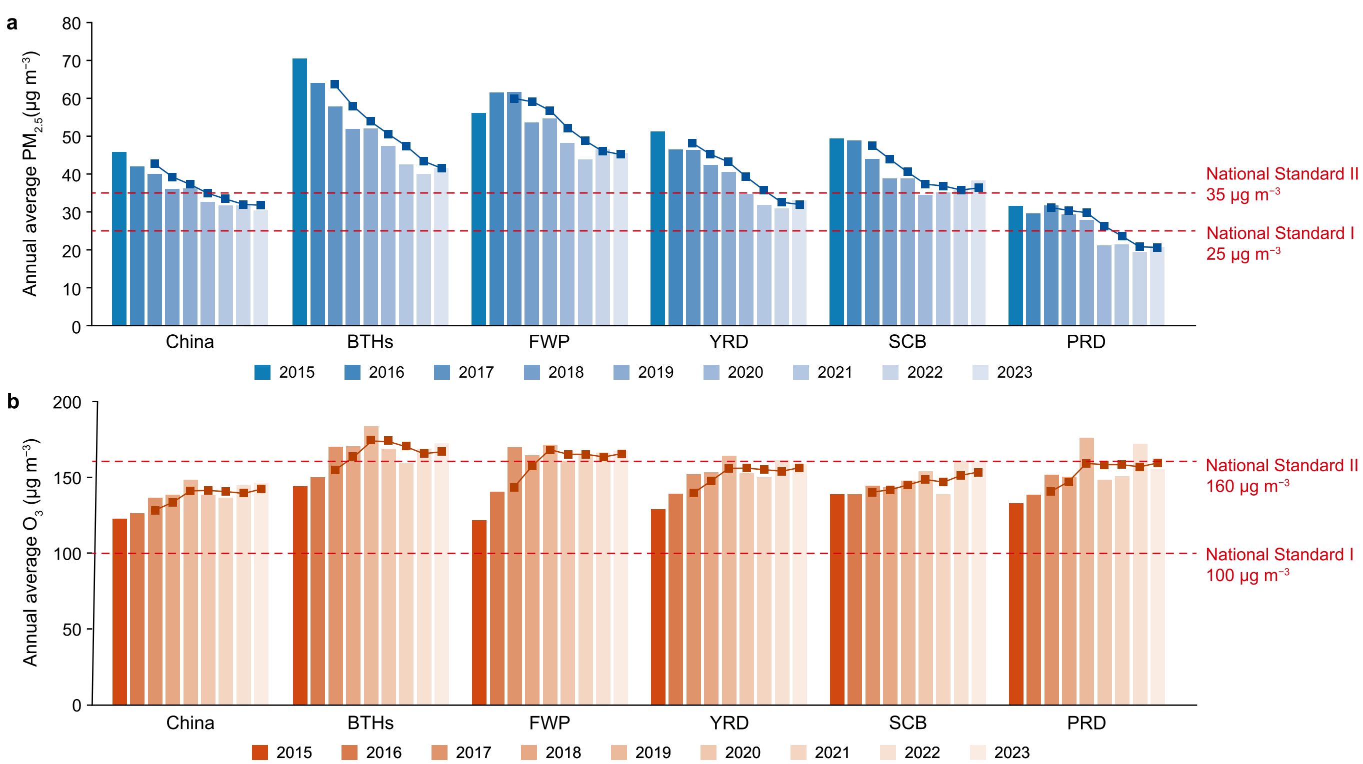

Fig. 1. Variations of the annual average $PM_{2.5}$ and O_3 concentrations (bars) and the three-year moving average concentrations (block dotted lines) over China and key regions from 2015 to 2023. **a**, Annual average $PM_{2.5}$ concentration. **b**, Annual 90th percentile of the maximum 8-h average O_3 concentrations. This figure is adapted from Fig. 1 in Ref. [14], with data updated to 2015–2023. China comprises a total of 339 cities: 333 prefecture-level cities, 4 municipalities directly under the central government (Beijing, Shanghai, Tianjin, and Chongqing), and 2 special administrative regions (Hong Kong and Macau). Five key urban clusters are highlighted: BTHs (Beijing–Tianjin–Hebei and its surrounding areas, 54 cities), FWP (Fen–Wei Plain, 11 cities), YRD (Yangtze River Delta, 41 cities), SCB (Sichuan Basin, 7 cities), and PRD (Pearl River Delta, 9 cities).

reported no severe $PM_{2.5}$ pollution days for five consecutive years. The proportion of days with severe O_3 pollution was substantially lower than that of $PM_{2.5}$, accounting for only 0.02% across the 339 cities in 2023. All key regions recorded a proportion below 0.06%.

Regarding the influence of meteorological conditions on pollution, compared to 2022, the YRD, PRD, and SCB experienced meteorological conditions more conducive to elevated pollutant concentrations in 2023, consistent with the increased annual average $PM_{2.5}$ concentrations in these regions. Conversely, meteorological conditions in the BTHs, as well as the FWP, were more favorable for pollutant dispersion compared to those in 2022 [15]. Consequently, clean air action plans in the BTHs and FWP regions should prioritize addressing changes in anthropogenic emissions. Thus, the slight increase in $PM_{2.5}$ concentrations in some key regions in 2023 may be attributed to (1) changes in pollution sources (e.g., industrial and traffic emissions): driven by economic recovery and (2) less favorable meteorological dispersion conditions in 2023.

Compared to the rest of the world, $PM_{2.5}$ concentrations in India—although decreasing—remain at relatively high levels, whereas those in South Korea, Japan, the United States, and the United Kingdom are lower and exhibit smaller variations. Japan, the United States, and the United Kingdom have maintained values below 15 $\mu g\ m^{-3}$, reflecting relatively stable air quality. For warm-season O_3 concentrations, the United States and South Korea have exhibited an overall rising trend. In Japan and European regions, O_3 fluctuations predominate, with no clear upward trend. Since 2017, China's warm-season O_3 concentrations have exceeded those of these countries, which warrants attention.

2.2. Climate change and extreme weather climate

Climate change can affect air pollution by altering meteorological conditions, while air pollutants, such as GHGs, can accelerate global warming. Therefore, tracking the characteristics of climate change globally and in China in 2023 is highly important. The climate system is experiencing pronounced changes characterized by global warming [16]. According to the World Meteorological Organization, 2023 was the warmest year on record, around 1.4 ± 0.1 °C warmer than the pre-industrial period (1850–1900) [17]. In China, the 2023 annual mean surface temperature was 10.7 °C, 1.8 °C higher than pre-industrial levels (before 1750), and 0.84 °C above the 1991–2020 average, marking the highest recorded since 1901 [18]. In the context of global warming, extreme weather and climate events have exhibited emerging new characteristics [19,20], resulting in substantial social, economic, and ecological losses. For instance, record-breaking extreme heatwaves occurred concurrently across multiple Northern Hemisphere regions [21,22]. High temperatures led to a widespread increase in energy consumption for cooling, while also reducing wind power generation due to insufficient wind speeds, placing considerable pressure on the energy sector to ensure supply [23,24]. Prolonged high temperatures also created favorable conditions for the spread of wildfires. Wildfires in Canada burned over 13 million hectares, more than seven times the long-term average [17], severely compromising the carbon sink capacity of forest ecosystems.

Climate change has intensified tropical cyclones, increasing their strength and duration [25,26]. The landfall and northward progression of Tropical Cyclone Doksuri triggered extreme rainfall events in North China, with a maximum cumulative rainfall of 1003 mm over three days, equivalent to two years of local precipitation. Tropical Cyclone Freddy set a record for the longest duration, persisting for 36 days and causing approximately USD 481 million in economic losses. Additionally, numerous regions worldwide experienced extreme drought conditions. In China, Yunnan Province experienced its most severe winter–spring drought since 1961 [27], with a meteorological drought lasting 102.9 days, resulting in water shortages, ecosystem degradation, and affecting 4 million people. In the Amazon rainforest [27], central regions recorded the lowest rainfall in 40 years, with river levels reaching historic lows, causing Brazil's fourth-largest hydroelectric plant to cease operations.

Extreme weather exacerbates air pollution, posing remarkable threats to human health [28–30]. Prolonged heatwaves during extremely hot summers intensify ozone accumulation through physical and chemical processes [31], with quantitative studies indicating that heatwaves can increase urban ozone pollution by over 30% [32]. In spring 2023, China experienced dust weather characterized by higher frequency, greater intensity, earlier onset, and broader spatial impact compared to historical norms, linked to the recent deterioration of climate and environmental conditions in dust source regions. In 2023, China experienced 17 dust events, the highest number since 2011, covering approximately 5.1 million square kilometers and affecting 940 million people [33]. The most severe dust event (March 19–24) caused air quality in over 60 northern Chinese cities to reach severe or worse pollution levels.

2.3. Greenhouse gases in the atmosphere

Given that the increase in atmospheric GHGs is the primary driver of global warming, this section examines changes in atmospheric GHGs globally and in China in 2023, using observational and satellite data. In 2023, the global annual average atmospheric CO_2 concentration reached 420 mg L^{-1}, a 151% increase compared to pre-industrial levels, and a 2.3 mg $L^{-1}\ yr^{-1}$ rise from 2022 [34]. Data from China's Waliguan baseline observatory indicates that the average annual absolute increment over the past decade (2013–2022) was 2.2 mg $L^{-1}\ yr^{-1}$, slightly below the global average. Satellite data (2010–2023) reveal that China's CO_2 concentrations and trends are consistent with those of the Northern Hemisphere. High CO_2 concentration zones in China are primarily located in the North China region and parts of Central China, largely due to North China's status as a major coal-producing and centralized heating region. Additionally, certain areas of Central China, with dense populations, exhibit increased CO_2 emissions from anthropogenic activities. The Pearl River Delta is China's largest regional source of CO_2 emissions, driven by substantial energy consumption, dense industrial emissions, and transportation-related emissions. In contrast, regions with vast areas and minimal human activity, such as Xinjiang, Xizang, and Qinghai, show lower CO_2 concentrations.

In 2023, the global annual average atmospheric methane (CH_4) concentration reached 1934 $\mu g\ L^{-1}$, a 265% increase compared to pre-industrial levels, and a 11 $\mu g\ L^{-1}$ rise from 2022. Over the past decade (2014–2023), the average growth rate was 10.7 $\mu g\ L^{-1}\ yr^{-1}$, with the period from 2020 to 2022 recording the highest growth rate (15.4 $\mu g\ L^{-1}\ yr^{-1}$). Key drivers include the rapid increase in wetland emissions and the reduction in anthropogenic NO_x emissions during the COVID-19 pandemic. Data from China's Waliguan baseline observatory indicates that the average annual absolute increment over the past decade (2013–2022) was 9.8 $\mu g\ L^{-1}\ yr^{-1}$, slightly below the global average. The global annual average atmospheric N_2O concentration reached 336.9 $\mu g\ L^{-1}$, a 125% increase compared to pre-industrial levels, and a 1.1 $\mu g\ L^{-1}$ rise from 2022. Over the past decade (2014–2023), the average growth rate was 1.1 $\mu g\ L^{-1}\ yr^{-1}$, with the highest recorded growth rate (1.3 $\mu g\ L^{-1}\ yr^{-1}$) occurring between 2021 and 2022. Data from

China's Waliguan baseline observatory indicates that the average annual absolute increment over the past decade (2013–2022) was 1.1 μg L^{-1} yr^{-1}, slightly above the global average.

Frequent extreme weather and climate events have exhibited notable feedback on GHG emissions. Extreme precipitation markedly increases wetland areas, thereby enhancing CH_4 emissions [35]. Global high temperatures enhance soil bacterial activity, resulting in increased CH_4 and N_2O emissions [36]. The increasing frequency of heatwaves and droughts has led to a rise in wildfires. Between 2001 and 2022, the global annual average forest fire area was 46.95 million hectares, 11 times the annual average increase in plantation forest area during the same period. In China, effective forest fire management has kept wildfire carbon emissions low, despite accounting for 5.4% of the global forest area; China's wildfire carbon emissions constitute only 0.6% of the global total.

3. Synergetic governance system and practices

3.1. Construction of a synergetic governance system

Since 2021, the Ministry of Ecology and Environment (MEE) has been progressively establishing a synergetic governance system aimed at reducing pollution and carbon emissions. This system is guided by ecological environment zoning controls, leverages environmental impact assessments as a core approach for controlling emissions at their sources, and is underpinned by robust capabilities in integrated carbon and pollution emission inventory and integrated carbon-pollution monitoring. At the macro level, the General Office of the State Council issued the “Opinions on Strengthening Ecological Environment Zoning Control” in March 2024. Several provinces and cities have initiated pilot projects to promote synergy from a spatial management perspective. Regarding source control, research and pilot initiatives focused on the management system for environmental impact assessments of GHG emissions have been systematically implemented. Specifically, nine provinces, including Zhejiang and Chongqing, have targeted six key industries—power, steel, building materials, nonferrous metals, petrochemicals, and chemicals—and conducted environmental impact assessments on GHG emissions across more than 500 construction projects and seven industrial parks since 2021. To support governance capabilities, MEE released the “Technical Guidelines for the Compilation of Integrated Emission Inventory of Air Pollutants and Greenhouse Gases (Trial)”, which guides local governments in compiling integrated carbon and pollution emission inventories tailored to local conditions. Additionally, the MEE introduced the “Pilot Work Plan for Carbon Monitoring and Assessment” and has been rolling out pilot projects for carbon monitoring and assessment at regional, city, and key industrial levels, thereby enhancing collaborative governance at the emission source level.

As environmental management practices increasingly seek to incorporate GHG control into the existing environmental governance framework for synergetic effects, the academic community has primarily concentrated on two areas: the selection of management targets and the design of management structures. The first area focuses on the “same root and source” nature of GHGs and air pollutants, evaluating the cost-effectiveness of synergetic control across various management targets and recommending priorities for such integrated governance. The second area emphasizes a governing approach, exploring how to harmonize existing GHG and air pollution management systems by examining governance methods and tools, thereby effectively reducing overall social management costs.

3.2. Economic policies for synergetic governance

The policy framework for synergetic governance has been progressively refined through the exploration and application of various policy tools in administrative management, economic incentives, and social participation. In the realm of administrative management, the government has established a comprehensive top–down approach to synergetic governance. Following the issuance of the “Implementation Plan for Synergizing Reduction of Pollution and Carbon Emission” in June 2022, all provinces in China had released working plans for synergetic control by the end of 2023, thereby facilitating a collaborative working framework between central and local departments. Moreover, the release of the policy to promote the transition from dual control over the amount and intensity of energy consumption to dual control over the amount and intensity of carbon emissions has reinforced the policy shift from an emphasis on energy intensity and total energy consumption to a focus on carbon reduction. Additionally, various policy pilot programs have been implemented.

In terms of economic incentives, the policies centered around the carbon market have been continually enhanced. The efficacy of carbon market trading policies in expediting the green and low-carbon transition is becoming increasingly evident. By the end of 2023, the cumulative trading volume of China's carbon market reached 440 million tons, with a total transaction value of approximately CNY 24.9 billion, covering around 5.1 billion tons of carbon emissions, thereby establishing the world's largest carbon market based on GHG emission coverage. The implementation of the “Management Measures for Voluntary Emission Reduction Transactions (Trial)” has further diversified the carbon market system. Concurrently, multiple tax incentive policies have continued to support green and low-carbon development, with these policies set to remain in effect until the end of 2027. Furthermore, the price mechanisms aligned with green development requirements have been enhanced, with the ongoing execution of tiered electricity pricing for high-energy-consuming industries and sewage treatment charges. Continuous innovation in climate-related investment and financing has addressed the financial needs associated with the green and low-carbon transition. Banking institutions are actively directing financial resources toward eco-friendly, green, and low-carbon sectors. By the end of 2023, the balance of domestic and foreign currency green loans reached CNY 30 trillion, establishing the world's largest green credit market. Pilot programs for climate investment and financing have also been advanced, with the total credit limit in 23 pilot areas attaining CNY 455 billion.

Policies system aimed at boosting social participation have been further refined. The central government has introduced policies supporting technological innovation and the application of green and low-carbon technologies across society. A mechanism to incentivize green and low-carbon consumption has also been established. For example, a national green consumption points system has been explored by a new group standard. Furthermore, cities such as Beijing, Shenzhen, Shanghai, and Tianjin have consecutively unveiled implementation plans pertaining to carbon inclusion. Moreover, continuous efforts to enhance the disclosure of environmental information and carbon emissions have culminated in the establishment of a national environmental information disclosure system platform, prompting more than 80,000 enterprises to legally disclose environmental information.

3.3. Local practices

Following the release of the implementation plan for pilot projects aimed at implementing synergetic management practices to reduce both environmental pollution and carbon emissions in cities and industrial parks, 21 cities and 43 industrial parks had launched localized innovation pilots by March 2024. The participating cities include resource-based, industry-dominated, and ecology-prioritized cities, and the industrial parks span a range of leading sectors, including petrochemicals, resource recycling, equipment manufacturing, steel and coking, agriculture, new materials, new energy, and coal chemicals.

To evaluate city-level co-control progress, emissions of air pollutants and CO_2 spanning from 2015 to 2022 are analyzed. The findings suggest that cities with higher carbon emissions tend to have more severe $PM_{2.5}$ pollution levels. Specifically, in 2022, the average CO_2 emissions of 84 cities with $PM_{2.5}$ concentrations below the National Ambient Air Quality Standard were approximately 50% higher than those of 251 cities that met the standard. Moreover, nearly 31% of the cities are currently at the peak of their carbon emissions (as determined by statistical tests of carbon peak phases), with roughly 74% of them having achieved the $PM_{2.5}$ standard [37]. The remaining 14% and 54% of cities are currently in the plateau and growth periods of carbon emissions, respectively. However, progress in city-level co-control is trending downward. Between 2015 and 2022, 88 cities realized a simultaneous reduction in both $PM_{2.5}$ concentrations and CO_2 emissions (represented as dots in the third quadrant of Fig. 2), which is 17 fewer than in the previous period (2015–2021). This decline is primarily attributed to ongoing growth in CO_2 emissions in approximately 72% of the cities during 2015–2022. In contrast, only five cities demonstrated an increase in both $PM_{2.5}$ concentrations and CO_2 emissions, which is 45% lower than the figure recorded for the period 2015–2021.

4. Structural transformation and control technologies

In 2023, China's economic and social development has accelerated into a high-quality stage of green and low-carbon transformation (Fig. 3). While new momentum industries have developed steadily, significant progress has been made in high-tech manufacturing and the transition to green, low-carbon practices. To fully advance the “dual carbon" goals, strengthen foundations, and enhance momentum, China must continue to focus on innovation and high-end manufacturing to build a modern industrial system and achieve higher-level development.

4.1. Transformation of the energy structure

Driven by ambitious national decarbonization targets, technological cost reductions, and policy incentives, new changes have unfolded in the transformation of the energy mix. The year 2023

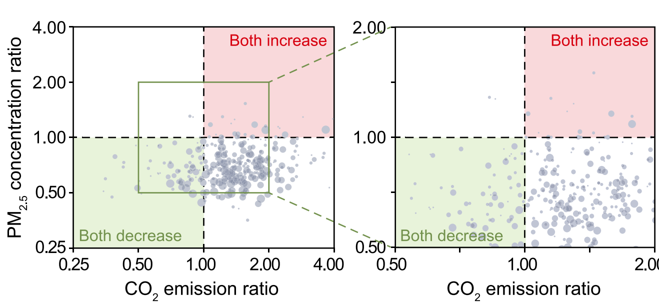

Fig. 2. Progress in co-control of city-level CO_2 emissions and $PM_{2.5}$ pollution in China, 2015–2022. Left panel: changes in annual $PM_{2.5}$ concentrations and CO_2 emissions in Chinese cities from 2015 to 2022. Right panel: details of the area bounded by solid green lines in the left panel. The dot size in both panels depicts CO_2 emissions in 2022. This figure is adapted from Fig. 1 in Ref. [14], Fig. 1 in Ref. [8], and Fig. 3 in Ref. [9], with data updated to 2015–2022.

witnessed steady improvements in both energy supply and clean energy transition within the energy system, striking a balance between development and security imperatives. There has been a sustained growth in both fossil energy and new energy, driven by a persistent growth in energy demand. The total annual energy consumption in 2023 increased by 5.7% year-on-year to reach 5.7 billion tons of coal equivalent (tce), marking the largest incremental rise since 2005 and the highest growth rate since 2012. During the 14th FYP period, China's energy consumption elasticity coefficient has exhibited an upward trend, reaching 1.1 in 2023, which surpassed 1.0 for the first time since the 11th FYP period.

The growth in electricity use has accelerated. In 2023, electricity consumption surged due to the increasing electrification of end-use consumption, particularly the ongoing electricity substitution in major sectors such as industry, transportation, and construction. The electricity consumption elasticity coefficient was 1.3, remaining above 1.0 for four consecutive years. The total electricity consumption of the entire society reached 9.2 trillion kWh, representing a 6.7% year-on-year increase, which is 3.1 percentage points (pps) higher than the previous year. Meanwhile, per capita electricity consumption set a record high of 6539 kWh. Electricity use in emerging industries continued to grow rapidly. Notably, the high-tech and equipment manufacturing industries saw a year-on-year increase of 11.3% in electricity use, outpacing the manufacturing sector overall by 3.9 pps. The proportion of electricity in end-use energy consumption increased to approximately 28%, with specific shares of 27.6%, 48.1%, and 4.3% in the industrial, construction, and transportation sectors, respectively.

Challenges remain in reducing fossil fuel consumption. In 2023, the production of crude coal, crude oil, and natural gas increased due to intensified efforts within the energy system to secure coal, electricity, and gas supplies. Although the share of coal in total energy consumption continued to decline, coal consumption increased by 5.6% in 2023, marking a rise of over 4% for the third consecutive year. The power sector accounted for more than 80% of the national increase in coal consumption. Oil and gas storage and production have risen. In 2023, crude oil and natural gas consumption expanded by 9.1% and 7.2%, respectively [38]. The newly added production capacity reached 22.5 million tons for crude oil and 42 billion m^3 for natural gas, which increased annual crude oil production to over 200 million tons and natural gas production to above 230 billion m^3, reflecting a year-on-year growth of more than 4.5%.

The installed capacity of renewable energy has soared. By the end of 2023, China's full-caliber installed capacity stood at 2.9 billion kW, up 13.9% year-on-year. For the first time in history, per capita installed capacity exceeded 2.0 kW per person, reaching 2.1 kW per person. The installed capacity of non-fossil energy sources surpassed that of thermal power for the first time in 2023, accounting for over 50% of the total installed capacity, while the share of coal in the installed capacity fell below 40% for the first time. Specifically, the installed capacity of thermal power was 1.39 billion kW, an increase of 4.1% year-on-year. The installed capacities of hydropower and nuclear power reached 420 and 56.91 GW, while the installed capacities of grid-connected wind and solar power attained 440 and 610 GW, increases of 1.8%, 2.4%, 20.7%, and 55.2%, respectively [38].

The improvement in energy efficiency has decelerated. In 2023, the reduction in energy intensity in China tended to contract. Within major energy-intensive industrial enterprises, comprehensive energy consumption decreased by 0.8% per unit of calcium carbide production and by 0.1% for electrolytic aluminum, whereas it increased by 0.9% per unit of ammonia and by 1.6% per ton of steel. Energy use (tce Kw^{-1}) for thermal power generation declined by 0.2%. Preliminary estimates indicate that, after deducting energy

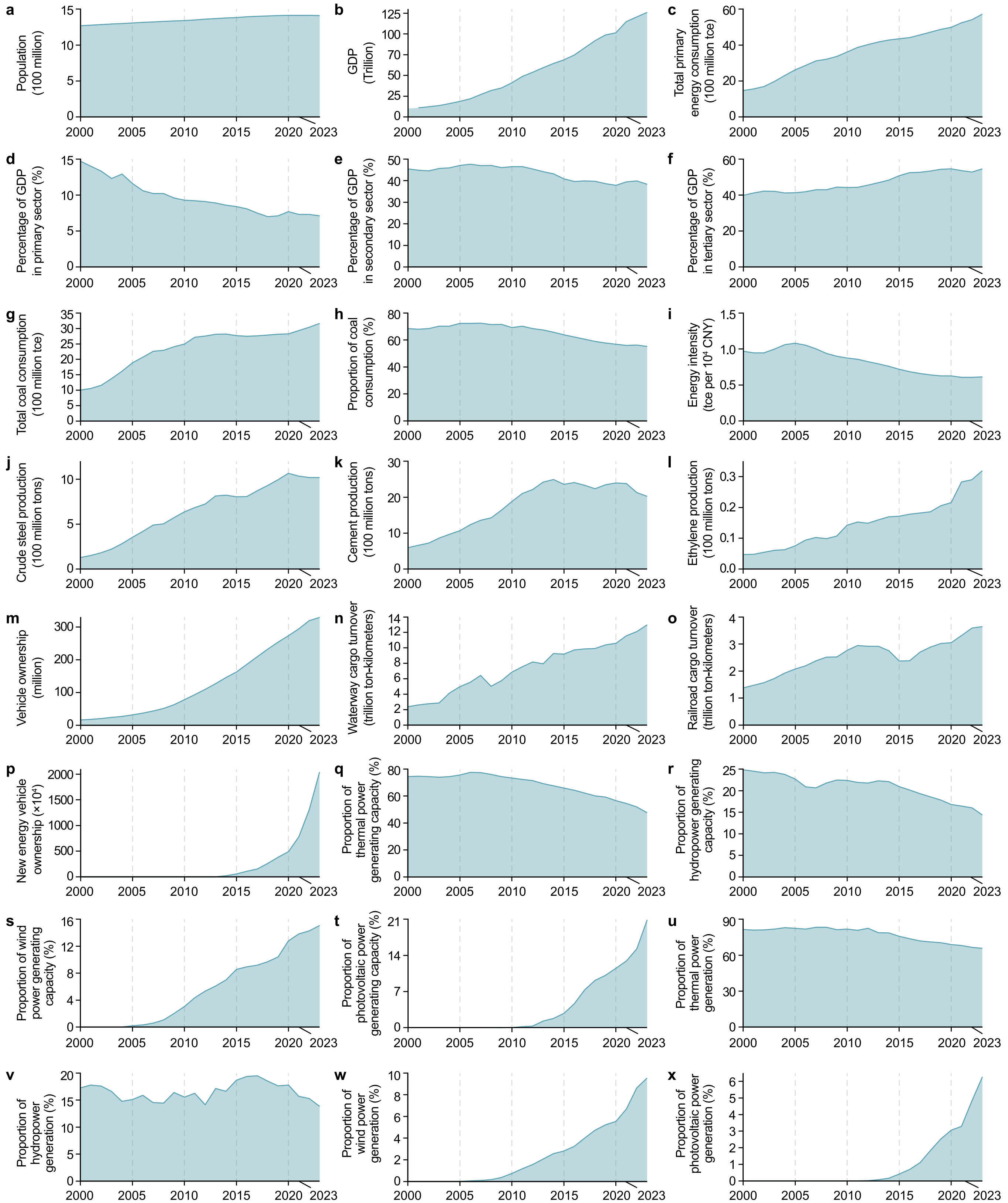

Fig. 3. Progress in structural transformation from 2000 to 2023. **a**, Total population; **b**, Gross domestic product (GDP); **c**, Total primary energy consumption; **d**, Proportion of GDP from the primary sector; **e**, Proportion of GDP from the secondary sector; **f**, Proportion of GDP from the tertiary sector; **g**, Total coal consumption; **h**, Share of coal in total energy consumption; **i**, Energy intensity; **j**, Crude steel production; **k**, Cement production; **l**, Ethylene production; **m**, Vehicle ownership; **n**, Waterway freight turnover; **o**, Railway freight turnover; **p**, New energy vehicle ownership; **q**, Proportion of thermal power installed capacity; **r**, Proportion of Hydroelectric power installed capacity; **s**, Proportion of wind power installed capacity; **t**, Proportion of photovoltaic power installed capacity; **u**, Share of thermal power generation; **v**, Share of hydroelectric power generation; **w**, Share of wind power generation; **x,** Share of photovoltaic power generation. This figure is adapted from Fig. 4 in Ref. [14], Fig. 2 in Ref. [8], and Fig. 4 in Ref. [9], with data updated to 2000–2022.

use related to raw materials and non-fossil sources, the national energy consumption per CNY 10,000 of gross domestic product (GDP) decreased by 0.5% compared to the previous year [38]. From 2021 to 2023, energy-saving and carbon-reduction renovations, as well as flexibility and heating retrofits, were completed for more than 700 GW across China, resulting in a 0.9% reduction in the average coal consumption of thermal power plants for coal power supply. Furthermore, the proportion of production capacity exceeding energy efficiency benchmarks increased by an average of 6 pps in industries such as steel, electrolytic aluminum, cement, oil refining, ethylene, and ammonia [39].

The installed capacity of coal power has continued to grow rapidly. This is primarily due to short-term energy security concerns amid surging electricity demand and the intermittency of renewable energy supply. In 2023, the installed capacity of coal power experienced a robust increase compared to the previous year. The newly approved installed capacity of coal power projects reached 106 GW, raising the approved installed capacity to 73.5% of the total approved installed capacity during the 13th FYP period, which was larger than the figures of 18.6 GW in 2021 and 90.7 GW in 2022. Cumulatively, coal power generation in 2023 totaled 5.4 trillion kWh, representing a 6.1% increase from 2022.

In November 2023, the National Development and Reform Commission and the National Energy Administration issued the “Circular on Establishing a Capacity Tariff Mechanism for Coal Power,” which stipulates the implementation of two-part tariffs for coal power starting from 2024. The recovery of fixed costs through the capacity tariff may reach 30–50% across the provinces. This regulation marks a significant milestone in repositioning coal power from a base-load source to a flexible power source.

Gaps remain in the energy mix and emission intensity with developed economies. While China has continued to optimize its energy mix, gaps still exist relative to developed economies. In 2023, the proportion of coal consumption remained above 50%, which is lower than that of South Africa but comparable to India's, while the levels were only 12% and 10% in the European Union and the United States, respectively. The proportion of renewable energy consumption is on the rise, driven by the rapid development of renewable energy sources. In 2023, the proportion of non-hydro renewable energy consumption was 0.9 pps above the world average, yet 0.2 and 0.4 pps below the levels of Japan and the United States, respectively. GHG emissions from the power sector are expected to peak in the short term, with the long-term changes depending on whether the coal phase-out can be accelerated after 2025. China exhibits significantly higher carbon intensity and GHG emission intensity than developed economies, though it has outperformed South Africa since 2016. The carbon intensity in 2022 exceeded the levels of the United States and the European Union by 54% and 72%, respectively [40]. Despite a lower growth rate, per capita carbon emissions and GHG emissions are still expanding and have surpassed the levels of most developed economies and large developing countries.

4.2. Transformation of the industrial structure

Emerging industries have developed steadily. Between 2022 and 2023, China's GDP grew from 121.0 trillion yuan to 126.1 trillion yuan, an increase of 5.2% year-on-year. The added value of the primary industry accounted for 7.1% of the GDP. The added value of the tertiary industry as a share of the GDP rose from 52.8% to 54.6%, in contrast to the decline of the secondary industry from 39.9% to 38.3%. The high-tech manufacturing sector recorded a year-on-year growth of 2.7% in added value, raising its share in the added value of industries above designated size from 15.5% to 15.7%. The production of new energy vehicles (NEVs) reached 9.4 million units, representing a 30.3% increase over the previous year. The production of solar photovoltaic (PV) cells surged by 54.0% to reach 540 GW. Exports of the “new three” products, namely electric passenger vehicles, lithium batteries, and solar cells, totaled 1.1 trillion yuan, exceeding the trillion-yuan threshold for the first time [38].

Efforts have been undertaken to promote the continued improvement of energy efficiency in key areas and facilitate the high-end development of traditional industries. In 2023, the State Council issued the “Opinions on Comprehensively Promoting the Development of a Beautiful China,” which emphasizes transformation across the board, encourages green scientific and technological innovation, and prioritizes green transition in key industries, including steel, petrochemicals, chemicals, and building materials. According to the guidelines, the proportion of NEVs among new automobiles will be raised to 45% by 2027, while old diesel locomotives will be eliminated. In September 2023, Chinese President Xi Jinping introduced the concept of “new quality productive forces”, which are “born out of in-depth industrial transformation and upgrading.” The new quality productive forces encompass high-tech and extensive frontier sectors, signifying a significant leap in productivity and reflecting industrial upgrading and transformation as their core hallmark.

The initiatives to build a quality-powered nation and a manufacturing powerhouse have spurred green and low-carbon industrial development. In 2023, the State Council issued the “Outline of Building a Quality-Powered Nation,” which proposes to accelerate the research and development of critical and core low-carbon, zero-carbon, and negative-carbon technologies, advance the low-carbon transformation of energy-intensive industries, comprehensively implement green design, green manufacturing, and green construction, and promote the upgrade of traditional building materials such as steel, glass, and ceramics. In the same year, the Ministry of Industry and Information Technology, in conjunction with seven other departments, issued the “Guiding Opinions on Accelerating the Transformation and Upgrading of Traditional Manufacturing Industries,” which emphasizes the need to strengthen green and low-carbon development and deepen energy-saving and carbon-reducing transformation. According to the guidelines, by 2027, China's traditional manufacturing industries are expected to make notable progress in their high-end, intelligent, green, and integrated development, thereby consolidating their position and competitiveness in the global industrial division of labor and cooperation. Meanwhile, the penetration rate of digital research and development and design tools should exceed 90%, while the numerical control rate of key processes should exceed 70% in industrial enterprises. Both the industrial energy consumption intensity and carbon dioxide emission intensity should continue to decline.

4.3. Transformation of the transportation structure

The transportation structure has been gradually optimized. In 2023, national freight transport reached 5.0 billion tons via railway, 9.4 billion tons via waterway, and 40.3 billion tons via roadway, marking year-on-year increases of 1.0%, 9.5% and 8.7%, respectively. Progress has been made in the “roadway to railway” and “roadway to waterway” transitions for freight transport, as well as in the “oil to electricity” and “oil to hydrogen” shifts for vehicles, contributing to the acceleration of a green, low-carbon transportation system. The national rail-water intermodal transport of containers through ports totaled 10,183,600 twenty-foot equivalent units, representing a 15.9% year-on-year increase. Railway transport of coal rose by 1.9% over the previous year to reach 2781 million tons, while railway transport of containers totaled 791 million tons with a year-on-year increase of 7.4%. The potential of railways in transporting bulk goods and containers has been gradually released. Green transport models accounted for more than 90% and 78% of coal and iron transport at major coastal ports, respectively [41,42].

Green travel has been further advanced. In 2023, a total of 76 cities across six batches were recognized as "Model Cities for Transit Metropolis Development," and 30 cities participated in the national program of transit metropolis development during the 14th FYP period. Passenger trips handled by bus and tram services were 18% more than the previous year to reach 38.1 billion, while those made via urban rail transit systems soared 52.2% year-on-year to reach 29.4 billion. There were 308 urban rail transit lines in operation nationwide, with a total length of 10,158.6 km. In 13 cities, rail transit systems accounted for more than 50% of all passenger trips. Major cities such as Beijing, Shanghai, Guangzhou, Shenzhen, and Chengdu have actively explored carbon-inclusive incentive mechanisms for public transportation. National railway traffic recorded 3.9 billion passenger trips, representing a 130.4% increase over the previous year and an average annual growth rate of over 6% in the past decade. Highway passenger traffic also experienced a 22.4% year-on-year rise to reach 11.0 billion passenger trips [41,42].

Energy efficiency in the transportation sector continues to improve. In 2023, a total of 22.502 million passenger vehicles were produced or imported by 119 enterprises located in China, with an average actual fuel consumption of 3.8 L per 100 km under the Worldwide Harmonized Light-duty Test Cycle (WLTC). Among them, 21.787 million passenger cars were manufactured domestically by 95 enterprises, while 716,000 were imported by 24 enterprises, exhibiting average actual WLTC fuel consumption of 3.7 and 7.3 L per 100 km, respectively [41]. The comprehensive energy consumption per unit of railway transport workload decreased by 3.3% year-on-year, reaching 3.8 tce per 10^6 converted tons–kilometers [42]. Fuel consumption in the civil aviation sector was 0.3 kg ton^{-1} km^{-1}, down 14.3% from 2005. The average energy consumption per passenger and CO_2 emissions per passenger at airports dropped by 38.4% and 60.5%, respectively, compared to the baseline (2013–2015 average) [43].

Clean energy substitution has made steady progress. As of 2023, there were 20.4 million NEVs in use nationwide, 76.0% of which were pure electric vehicles. NEVs production and sales reached 9.6 million and 9.5 million, up 35.8% and 37.9% year-on-year, respectively, securing a market share of 31.6%. Meanwhile, the deployment of charging infrastructure increased by 65% from the previous year, reaching 8.6 million units. Specifically, charging facilities were deployed in 6328 expressway service areas, accounting for 95% of the national total. All expressway service areas in 15 provinces and cities, including Beijing, Shanghai, Hebei, and Anhui, are now equipped to provide charging services. The national railway electrification rate stood at 75.2%, with 14,600 electric locomotives representing 65.2% of the total fleet [41]. Airports nationwide have integrated 127.9 million electric vehicles, accounting for 26.4% of all vehicles, alongside 5802 charging facilities, which contributed to 89.0% of the energy used from electricity, natural gas, and purchased heat [43]. Amid the efforts to accelerate the regular use of shore power, the consumption of shore power by ships at berth in the Yangtze River Economic Belt exceeded 124 GWh. In addition, China's first hydrogen fuel cell-powered vessel, "Qingzhou 1," completed its maiden voyage.

4.4. Low-carbon transition of building energy systems

In 2022, building operation carbon emissions totaled 2.2 billion Tco_2, of which direct carbon emissions from fossil fuel combustion continued to decline, accounting for 21%. Building operation electricity consumption increased markedly to over 2.3 trillion kWh, leading to a rise in associated indirect carbon emissions to 1.3 billion tons, which accounted for 58%. The total energy consumption for heating in northern cities peaked around the year 2017. With the recent adjustment of the energy mix, indirect carbon emissions from heating systems have declined year by year, with the share down to 21% in 2022 (Fig. 4).

Building operation carbon emissions are influenced by energy consumption, energy mix, and energy conversion efficiency in buildings. A comparative analysis was conducted on the amount and intensity of carbon emissions from buildings across countries. Due to lower energy consumption, China outperformed most of the developed countries in terms of building operation carbon emissions per capita and per unit of area. Specifically, China's per capita carbon emissions from buildings were less than one-third of those of the United States and one-half of those of Canada, Japan, and South Korea. Building carbon emissions per unit of area were also at a lower level in China. However, China exhibited a higher intensity of carbon emissions from buildings than France and Sweden, despite its lower intensity of energy use. France and Sweden have achieved low-carbon targets in the building sector, attributable to their low-carbon energy mix (which is dominated by nuclear power and hydropower, respectively). This further highlights the importance of the low-carbon transformation of the energy system and energy mix, alongside efforts in energy saving and energy efficiency, in developing an energy-efficient and low-carbon building sector.

Improving energy efficiency has long been a crucial aspect of building energy management in China. On the one hand, the design standards for energy efficiency of new buildings have been gradually raised. The energy efficiency requirements have increased from 30% to 50%, 65%, and 75% for newly constructed urban residential buildings, and from 50% to 65% and 72% for newly constructed urban public buildings. Meanwhile, ultra-low-energy-consumption and near-zero-energy-consumption buildings have been promoted nationwide, particularly in the colder northern provinces and cities. On the other hand, energy-saving operations and renovations of existing buildings have been identified as a key aspect of building energy management, particularly for existing public and residential buildings in northern urban areas. This creates a work pattern that places equal emphasis on "incremental" and "stock" construction rather than concentrating solely on the "increment."

4.5. Carbon capture, utilization, and storage technologies

China has made significant progress in carbon capture,

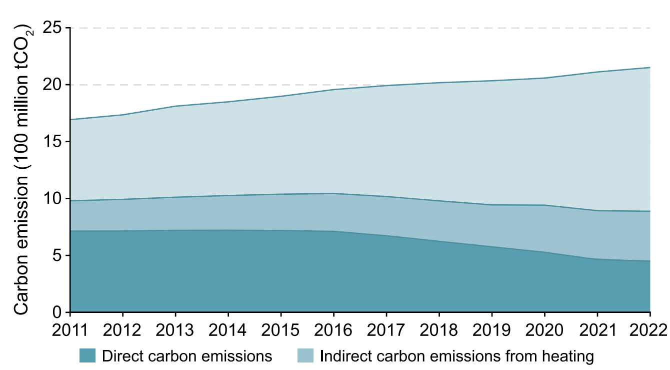

Fig. 4. Annual carbon emissions from building operations in China (2011–2022). This figure is adapted from Fig. 5 in Ref. [9], with data updated to 2011–2022.

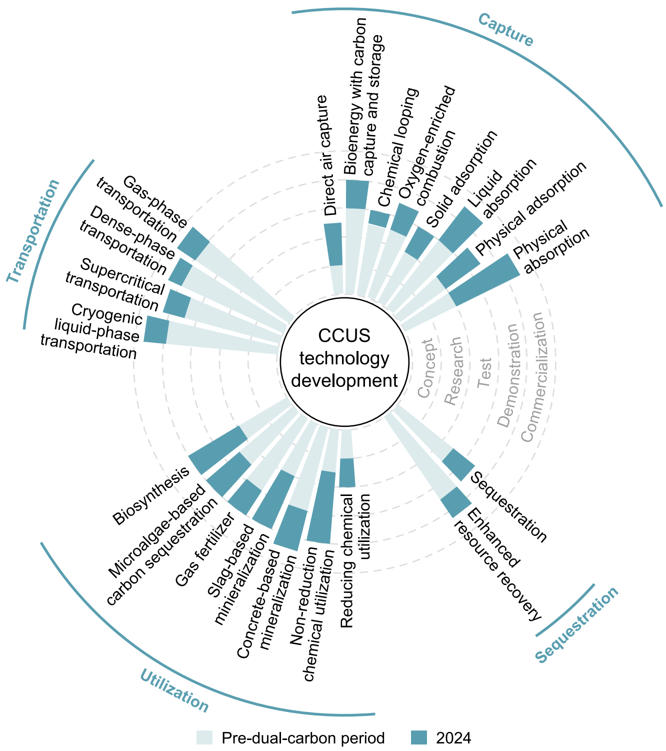

Fig. 5. Development of major carbon capture, utilization, and storage (CCUS) technologies in China across key dimensions before the adoption of the dual-carbon goals (light blue) and in 2024 (dark blue).

utilization, and storage (CCUS) technologies, approaching international standards while incorporating Chinese characteristics (Fig. 5). In terms of capture technologies, updates and iterations have been implemented to minimize energy consumption and reduce costs. While solid adsorption, chemical looping, and direct air capture remain in the test stage, many other technologies have advanced into demonstration or commercialization. In particular, significant breakthroughs have been achieved in liquid absorption, which has successfully reduced regeneration heat consumption by nearly 40% from 3.8 to below 2.4 GJ per Tco_2 in a demonstration project at a 500,000 t yr^{-1} coal-fired power plant. Regarding transportation technologies, both road tanker and ship transportation have been commercialized. With major technical bottlenecks cleared, pipeline transportation has progressed into the supercritical phase and gained momentum for large-scale operations. Pipelines for gas-phase, supercritical, and dense-phase transportation have been constructed and put into operation. Utilization technologies, including chemical and biological processes and mineralization, have matured to the point of industrial demonstration or commercial application, positioning China as a leader overall. Among geological utilization and storage technologies, CO_2 flooding and uranium leaching for enhanced resource extraction have reached an advanced international level, while a large-scale demonstration of storage in a deep saline aquifer has been implemented.

CCUS demonstration and application have progressed rapidly, with notable improvements in the number, size, and industrial scope of projects and a discernible trend towards clustering. According to incomplete statistics, over 100 CCUS demonstration projects have commenced operation or are under planning and construction in China. They collectively achieve a capture capacity of more than five million tons per year and an injection capacity of more than two million tons per year. Recent years have witnessed a marked increase in the size of CCUS demonstration projects. More than 50 projects with a capacity of 100,000 t yr^{-1} and above have been implemented, while several million-ton projects are under planning and construction. For instance, a coal power project with a capture capacity of 500,000 t yr^{-1} has been operating stably since its official launch in June 2023. Since 2022, a total of 45 projects have been commissioned across 12 industries. In addition to the expanded deployment in traditional industries such as power generation, steel, and cement, the first demonstration projects have been successfully initiated in glass, printing and dyeing, lime, and petrochemical industries and biomass power plants. Along with a leap in quantity and scale, China has begun to explore the development of CCUS clusters. Planning is underway for the establishment of several 10-million-ton CCUS clusters in regions such as the Ordos Basin, Junggar Basin, Daya Bay, and YRD.

Underpinned by increased demonstration and technology maturity, the cost of CCUS technologies in China has consistently declined, creating a cost advantage over international counterparts. Currently, the carbon avoidance costs of whole-chain CCUS technologies range from USD 20 to USD 190 per Tco_2 for major carbon capture sources globally (including coal-fired and gas-fired power plants, coal chemical plants, natural gas processing plants, steel and cement plants, etc.). In China, these costs are estimated at USD 60 per Tco_2 for conventional power plants and USD 80 per Tco_2 for integrated gasification combined cycle power plants, marking the lowest worldwide. The costs are reported at approximately USD 100, 70, 130, and 30 per Tco_2 for natural gas combined cycle power plants, steel plants, cement plants, and fertilizer plants, respectively, which are also at a relatively low level globally. In addition, there is a more substantial reduction in the costs of direct air capture. The costs have decreased by 60–80% over the past decade, from over USD 600 per Tco_2 in 2011 to USD 100–220 per Tco_2 in recent years. Nevertheless, they remain relatively high compared to the overall expenses of stationary emission sources.

4.6. New electric power system

Electricity generation has exhibited a steady growth. In 2023, national power generation totaled 9.5 trillion kWh, representing a 6.9% increase over the previous year. Among them, wind and solar power generation totaled 1.5 trillion kWh, accounting for approximately 15.5%. Thermal power generation increased 6.4% year-on-year to 6.3 trillion kWh, accounting for approximately 66.2%. Nuclear power generation reached 434.7 billion kWh, a 4.1% increase year-on-year. Renewable energy generation reached 3 trillion kWh, equivalent to nearly one-third of the total electricity consumption of society. The installed power generation capacity has consistently increased, reaching 2919.7 GW by the end of 2023, representing a 13.9% increase from the end of the previous year.

The proportion of installed renewable energy capacity continues to rise. By the end of 2023, the national installed capacity of renewable energy had exceeded 1.5 billion Kw, surpassing that of thermal power and raising its proportion in the national installed power generation capacity to over 50%. Specifically, the installed capacities of hydropower, wind, and solar power were 421 GW, 441 GW, and 609 GW, respectively [38]. China has maintained its leading position in renewable energy installed capacity for several consecutive years, contributing approximately 40% to the global total by the end of December 2023. In 2023, the installed capacity of renewable energy increased by 305 GW, representing 82.7% of the newly installed power generation capacity in China and 50% of the global total, surpassing the combined addition from the rest of the world.

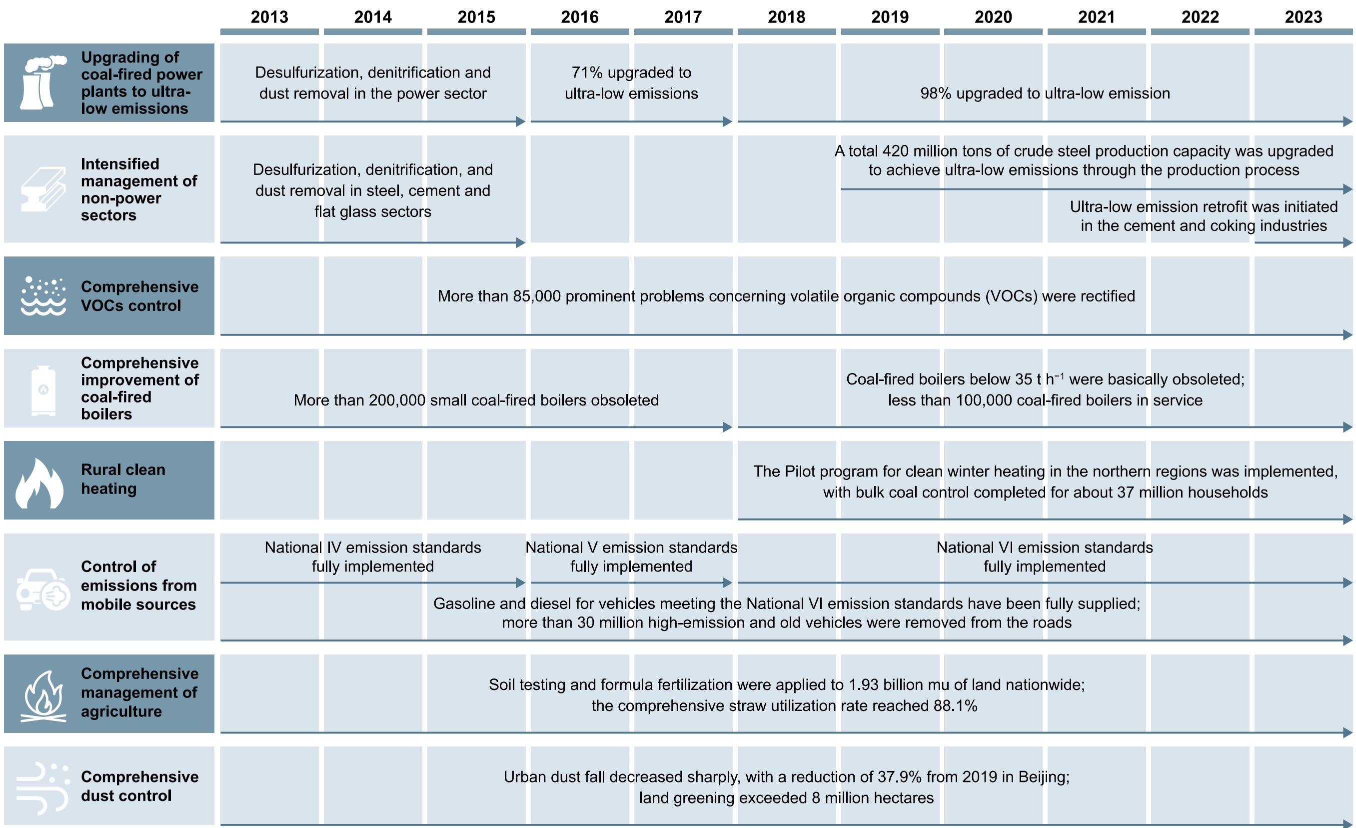

Fig. 6. Progress of pollution control indicators from 2013 to 2023. This figure is adapted from Fig. 5 in Ref. [14], Fig. 3 in Ref. [8], and Fig. 6 in Ref. [9], with data updated to 2013–2023.

The capacity to integrate new energy sources is continually improving. In 2023, China's average utilization rates reached 97.3% for wind power and 98.0% for PV power, while wind power curtailment decreased to 22.4 billion kWh, a 9.3% decline from the 2017 level. The capability to accommodate new energy sources has been significantly enhanced. To adapt to the construction of new electric power systems and the large-scale and high-proportion development of new energy, pumped storage hydropower and other flexible power sources will be meaningfully heightened in the power system. By the end of 2023, the cumulative installed capacity of pumped storage hydropower had reached 50.19 GW, representing a 44.2% increase from the 2021 level. It is expected to reach 120 GW by 2030, according to the "Medium- and Long-Term Development Plan for Pumped Storage (2021–2035)." Moreover, emerging energy storage technologies, including advanced compressed air energy storage, sodium-ion battery energy storage, lithium-ion energy storage, and liquid current battery energy storage, are expected to further enhance the power system's capacity to accommodate new energy sources.

The structure of the power system has been gradually optimized. In alignment with China's national conditions and resource endowments, electricity flow distribution has been intensified to facilitate power transmission from the west to the east and from the north to the south. Both centralized and distributed power generation have been advanced in new energy development. Regarding power grid construction, 220 kV and above transmission lines have been extended by 38,100 km, 220 kV and above substation equipment has increased by 257 million kVA, and direct current converters have been augmented by 16 GW, enabling the large-scale optimal allocation of energy resources in China.

4.7. Enhanced effectiveness of pollution removal technologies

Ultra-low emission retrofit of coal-fired power plants. Since 2015, China has implemented large-scale ultra-low emission retrofits to reduce pollutant emissions from coal-fired power plants to the level of those from gas-fired power plants. By the end of 2023, coal-fired power plants meeting ultra-low emission standards had reached 1.2 billion kW, representing 98% of the national total installed coal power capacity.

Intensified management of non-electricity industries. Since 2013, China has formulated and revised emission standards for cement, petrochemical, coating & ink, and pharmaceutical industries, and stepped up the management of industrial furnaces and kilns. In 2019, retrofit for ultra-low emissions was carried out in the steel sector. As of the end of 2023, a total of 420 million tons of crude steel production capacity was upgraded to achieve ultra-low emissions throughout the production process, and 400 million tons of capacity were upgraded for key links of the production process, such as desulfurization and denitrification of sintering and pelletizing, and enclosed raw material yards. In 2023, the ultra-low-emission retrofit was initiated in the cement and coking industries as part of a continued effort to reduce emissions from non-electricity industries.

Control of volatile organic compounds. Since the 13th FYP period, China has quickly advanced the work on volatile organic compounds (VOCs) control by issuing and improving a range of industry and product emission standards and related policy documents. By the end of 2023, a total of 85,000 prominent problems associated with VOCs were rectified.

Reduction of coal-fired boilers. Since 2013, the number of coal-fired boilers nationwide has declined from the original 520,000 to less than 100,000. Coal-fired boilers with an hourly steam capacity of less than 35 t h^{-1} have been eliminated.

Rural clean heating. Since 2017, China has vigorously implemented a pilot program for clean winter heating in the northern regions. By the end of 2023, bulk coal control had been completed for approximately 37 million households.

Control of mobile source emissions. Motor vehicle emission standards have been further tightened. Starting from July 1, 2023, National VI-b emission standards will be implemented for light-duty vehicles and heavy-duty diesel vehicles. Consequently, the production, import, and sale of models that don't comply with these standards will be banned. Moreover, research has been initiated on the development of National VII emission standards for motor vehicles. The vehicle inspection and testing mechanism, which features random inspections by randomly selected staff and prompt release of inspection results, has been carried out for six consecutive years. A total of 13 auto enterprises have been urged to recall vehicles for environmental purposes, involving 3.26 million vehicles.

Comprehensive management of agriculture. The campaign for the comprehensive utilization of straw has been implemented in depth, effectively controlling open-air burning and continuously improving comprehensive utilization nationwide. In 2023, the overall rate of straw utilization in China reached 88.1%, specifically 57.6%, 20.7%, 8.3%, 0.7%, and 0.8% utilized as fertilizers, fodder, energy sources, substrate, and raw materials, respectively.

Comprehensive dust control. With the gradual intensification of urban and rural environmental management, dust control has been prioritized as a key component in preventing and controlling air pollution since 2013. Consequently, urban dust fall has dropped sharply. In Beijing, the citywide dust fall was reduced to 3.6 t km^{-2} per month in 2023, down 37.9% from 2019. Since the 13th FYP period, a total of 320,000 ha of historically abandoned mines have been remediated under the project of ecological restoration, focusing on major areas and river basins. In 2023, land greening exceeded 8 million hectares, with 4.0 million hectares of forest planted, 4.4 million hectares of degraded grassland restored, and 1.905 million hectares of sandy and stony land reclaimed.

5. Source, sinks, and mitigation pathway of atmospheric composition

Carbon emission changes are a key indicator of regional low-carbon development progress [44]. Based on the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC), this indicator analyzes the dynamic trends and main drivers of China's CO_2 emissions from 2000 to 2023, with a focus on industry and energy perspectives. It further compares the carbon emission trends and differences between China and major global countries and regions over the past decade, examining China's characteristics and challenges in reducing carbon emissions.

5.1. Anthropogenic CO_2 emissions

Changes in carbon emissions reflected the low-carbon development process in different regions. Here, by deriving data from MEIC, we tracked the dynamic changes and driving forces of China's carbon dioxide emissions from 2000 to 2023 from sectoral and energy composition perspectives. China's CO_2 emissions and their sectoral contributions exhibit marked temporal variation from 2000 to 2023 (Fig. 7) [45]. Prior to 2020, China's CO_2 emissions underwent a transition from a phase of rapid growth to one of more moderate growth. The decline in China's CO_2 emission growth rate was primarily driven by a “new normal” development mechanism shifting from “quantity” to “quality,” as well as the synergistic emission-reduction effects of China's progressively deepened air-pollution control efforts. As a result, various sectors in China, along with the total volume of CO_2 emissions, gradually entered a moderate-growth stage. Following 2020, influenced by pandemic lockdowns and subsequent economic recovery and stimulus measures, China's CO_2 emission growth rate increased slightly. Between 2020 and 2023, total carbon emissions increased by approximately 1.2 billion tons, with an average annual growth rate of 3.5%.

Between 2020 and 2023, except for the residential sector, CO_2 emissions in all other sectors—power, heating, industrial, and transportation—showed increasing trends at varying degrees. China's electricity increased by 18%, and related CO_2 emissions rose by 701 million tons, contributing 60.9% of the increase in CO_2 emissions during the study period. Meanwhile, the CO_2 emissions share of the heating sector rose from 4.6% in 2000 to 8.9% in 2020, and further to 10.1% in the 2020–2023 period. The industrial sector experienced a relatively smaller increase in CO_2 emissions when compared to the power and heating sectors. CO_2 emissions from the transportation sector increased by 208 million tons between 2020 and 2023, accounting for 18.1% of the total increase. The transition to cleaner energy sources is a significant driving force behind the sustained decrease in carbon emissions from the residential sector.

Similar to the trend in China's carbon-emissions development, the increase in carbon emissions in India and other parts of Asia is primarily driven by emissions from the power and industrial sectors, with growth in coal consumption being the primary determining factor. In contrast, in the United States and the European Union, the reduction in CO_2 emissions from the power sector has been a key driver of the overall decline in emissions in these regions, primarily due to the increased share of renewables in the power sector and adjustments to the fossil-fuel structure.

5.2. Land use change and land carbon sinks

Sustaining and enhancing terrestrial carbon sinks is of critical significance for mitigating global climate change and represents a pivotal component of China's carbon neutrality strategy [46–48]. However, significant uncertainties persist in estimating CO_2 fluxes resulting from land-use change [49], and model-based assessments of China's terrestrial carbon sink exhibit considerable variability [50]. The recent China Land Carbon Budget provides a spatially explicit (10 km resolution) assessment of China's terrestrial carbon sink and its drivers from 1980 to 2023 [51]. Results indicate that China's terrestrial sink averaged approximately 0.34 Pg C yr^{-1} during the 2010s. Remarkably, despite occupying only 7% of the global land area, it contributed over 10% of the global terrestrial carbon sink during the same period. Between 2010 and 2021, terrestrial ecosystems offset 14.7% $\pm$ 2.5% of China's anthropogenic CO_2 emissions [51]. The Chinese government has announced ambitious targets for expanding forest coverage. Process-based modeling simulations further indicate that China's forest biomass carbon stock could increase by 13.6 $\pm$ 1.5 Pg C between 2020 and 2100 [52]. Some strategies, such as species substitution, extended rotation cycles, and enhancement of wood product carbon pools, offer substantial potential to further elevate China's terrestrial carbon stocks [53–56], thereby making more effective contributions to the carbon neutrality objective.

5.3. Progress in emissions of air pollutants and progress of synergistic control

CO_2 emissions share common sources with air pollution and

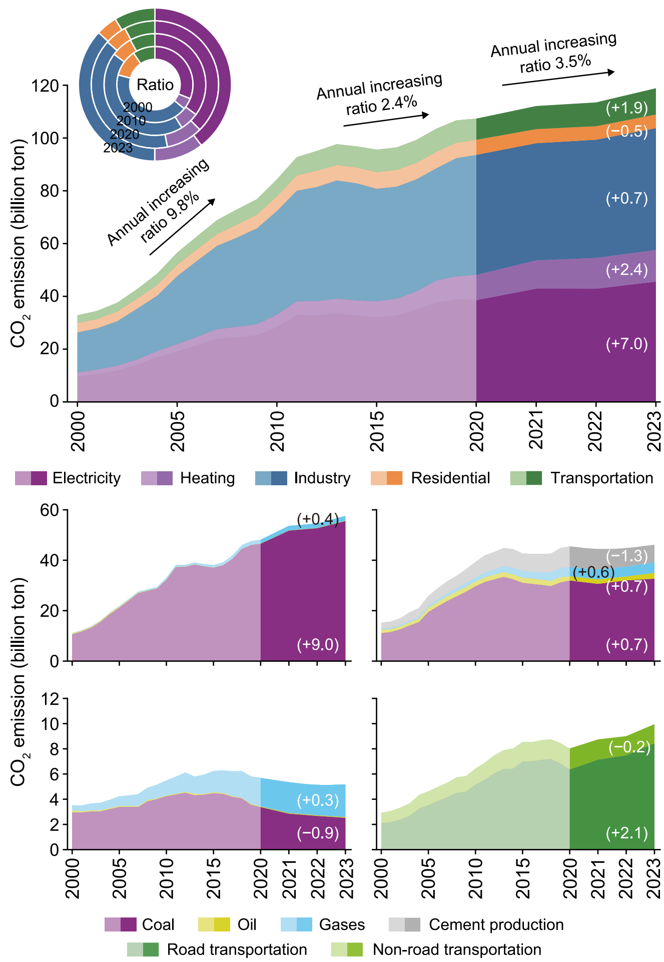

Fig. 7. Trends in CO_2 emissions and sectoral composition in China from 2000 to 2023. The annular chart in the upper right shows the proportions of CO_2 emissions by sector for each year. The light and dark shades represent CO_2 emissions before and after 2020, respectively. The numbers in parentheses represent the absolute change in 2023 relative to 2020.

have synergistic effects. From 2020 to 2023, CO_2 emissions in China increased by 12%, while SO_2, NO_x, primary $PM_{2.5}$, and VOCs decreased by 14%, 15%, 8%, and 8%, respectively, showing a negative synergy between CO_2 and air pollutant reductions (Fig. 8). Among all sectors, only the residential sector achieved coordinated reductions in CO_2 and major air pollutants. This is attributed to the implementation of bulk coal substitution, which has led to a reduction in coal consumption in the residential sector.

In the industrial sector, key air pollutants have generally decreased, while CO_2 emissions have increased, but at a slower rate. Among these, only the industrial process achieved synergistic reductions. This indicates that a series of measures related to industrial structure adjustment (such as eliminating backward production capacity and resolving excess capacity) have achieved good results. CO_2 and certain air pollutants have both increased during industrial coal, oil, and gas combustion processes, indicating remaining potential for synergistic emission reductions.

The power and heating sector, as the largest source of CO_2 emissions, has shown a “dual growth" trend in CO_2 and major air pollutants over the past three years, particularly in coal combustion processes (approximately 1.06 billion tons). Due to the rapid development of electrification in the industrial, residential, and transportation sectors, power and heating consumption continue to grow (with an average annual growth rate of approximately 7%). At the same time, the scale of coal-fired power continues to increase, resulting in relatively limited potential for synergistic CO_2 and pollutant emission reductions in this sector in the future.

In the transportation sector, with continuous improvements in energy efficiency, CO_2 and air pollutants from non-road mobile sources have achieved synergistic reductions. In the future, China needs to continue focusing on structural adjustments in key sectors, such as energy, industry, and transportation, to achieve a deep reduction in carbon and air pollutant emissions.

China has achieved historic success in air pollution control. Between 2013 and 2020, nationwide anthropogenic emissions of SO_2 and primary $PM_{2.5}$ decreased by 70% and 44%, respectively. This emission reduction rate is essentially equivalent to the emission reduction achievements achieved by major developed economies, such as the United States and the European Union, over the past twenty years (i.e., 2000–2020). While anthropogenic emissions of NO_x, NH_3, and non-methane volatile organic compounds declined by 29%, 14%, and 4%, respectively, this indicates considerable remaining reduction potential for these pollutants. Compared to the emission reduction rates during the first phase of the Clean Air Action (2013–2017), the reduction rates for most emission species slowed slightly during the second phase (2017–2020). This change is primarily attributed to China's air pollution control efforts entering a phase of deep-water implementation, where the emission reduction potential from end-of-pipe treatment measures in the power and industrial sectors has gradually diminished. In the future, China must continue to focus on structural adjustments in key sectors, such as energy, industry, and transportation, to achieve deep synergistic governance of carbon and air pollutants.

5.4. Future mitigation potentials and synergistic pathways

China's provinces exhibit pronounced spatial heterogeneity in their synergistic governance effectiveness for air pollution abatement and CO_2 mitigation [57,58]. The national population-weighted annual average $PM_{2.5}$ concentration is projected to decline from 33.4 μg m^{-3} in 2020 to 17.2 μg m^{-3} by 2035, and further to 12.1, 7.6, and 5.3 μg m^{-3} by 2060 [59–61]. From a regional perspective, provinces dominated by resource and energy supply, as well as basic industries, such as Shanxi, Hebei, Jiangxi, and Shaanxi, exhibit the greatest potential for coordinated pollution and carbon reduction (Supplementary Fig. S1). Compared to 2020, these provinces are expected to achieve over 80% reductions in both CO_2 emissions and $PM_{2.5}$ concentrations by 2060. However, due to limitations in technological maturity and cost, large-scale deployment of energy and industrial transformation measures will remain constrained in the near term; consequently, end-of-pipe control strategies will continue to predominate until about 2030. Thereafter, with the gradual rollout of structural transformations, carbon neutrality policies are expected to become the principal drivers of sustained air quality enhancement.

Maximizing synergistic co-benefits inevitably raises issues of reform cost-sharing and benefit allocation, with risks and rewards often misaligned. Going forward, it will be essential to leverage market mechanisms—such as targeting special transfer payments and air-pollution control funds toward central and western provinces—to support the development of high-efficiency energy technologies, share transition costs, and distribute benefits, thereby fostering balanced regional development [60]. At the same time, policymakers must ensure that instruments within the “policy toolbox” are calibrated and sequenced to generate coherent synergies, avoiding regulatory gaps or overlaps that could erode efficiency [62]. Emphasis should be placed on top-level design and comprehensive, system-wide governance reforms.

In summary, although China's overall co-benefits of pollution reduction and carbon abatement have improved markedly, significant spatiotemporal disparities persist across provinces due to differences in economic development stages and industrial structures. Tailoring co-governance measures to local conditions is thus vital to fully realize the advantages of synergistic mitigation. Deepening our understanding of the drivers behind these disparities will help identify mechanisms for joint atmospheric and carbon governance, stimulate local policy innovation, and provide critical guidance for dynamically adjusting and optimizing provincial co-mitigation pathways.

6. Health impacts and Co-benefits

6.1. Air pollution and health impacts

Fine particulate matter ($PM_{2.5}$) poses significant health risks, including increased incidence of stroke, ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, type 2 diabetes, and respiratory infections [63]. In 2023, China's population-weighted average $PM_{2.5}$ concentration increased slightly from 30.7 μg m^{-3} in 2022 to 30.9 μg m^{-3} (Fig. 9). Despite this marginal increase, the number of days with heavy $PM_{2.5}$ pollution decreased slightly. The premature mortality burden attributable to long-term $PM_{2.5}$ exposure was approximately 1.21 million (95% confidence interval [CI]: 1.09–1.35 million) deaths in 2023, a slight rise from 1.19 million in 2022 [64]. Conversely, deaths related to short-term $PM_{2.5}$ exposure saw a modest decline. Overall, between 2018 and 2023, premature deaths linked to long-term and short-term $PM_{2.5}$ exposure decreased by 12.4% and 26.2%, respectively.

It is noteworthy that ozone concentrations in some rural and remote areas can exceed those in urban areas, widening the scope of population exposure. Furthermore, Ozone exposure independently contributes to adverse health outcomes. In 2023, long-term and short-term ozone exposure were linked to approximately 150,000 (95% CI: 70,000–240,000) and 70,000 (95% CI: 40,000–110,000) premature deaths, respectively, comparable to those in 2022. Although the total number of ozone-related deaths is lower than that attributed to $PM_{2.5}$, short-term ozone exposure resulted in a similar or higher number of premature deaths compared to short-term $PM_{2.5}$ exposure.

NO_2 has been identified by the World Health Organization (WHO) as one of the risk factors for inducing acute respiratory diseases and asthma [65,66]. With respect to other pollutants covered by the WHO air quality guidelines, NO_2 exposure levels in China have decreased substantially, from 45.4 μg m^{-3} in 2013 to 23.2 μg m^{-3} in 2023, but still remain above the WHO guideline value. In 2022, the number of days exceeding the WHO's daily NO_2 standard decreased by 164 days compared to 2017. Nevertheless, NO_2 continues to pose a major health threat, with approximately 51,000 (95% CI: 39,700–62,400) non-accidental deaths attributed to short-term exposure in 2023 [67]. Notably, females and the elderly exhibited higher sensitivity to NO_2 exposure [68].

6.2. Climate change and health effects

In 2022, China's average annual heatwave exposure reached 21 days per capita, considerably above the historical baseline level (1986–2005) [69]. Increased extreme weather events attributable to climate change were associated with elevated health risks, including cardiovascular diseases, mental health disorders, and chronic disease exacerbation [70–72].

The compound effects of humidity and extreme temperatures demonstrated heterogeneous mortality impacts across seasons.

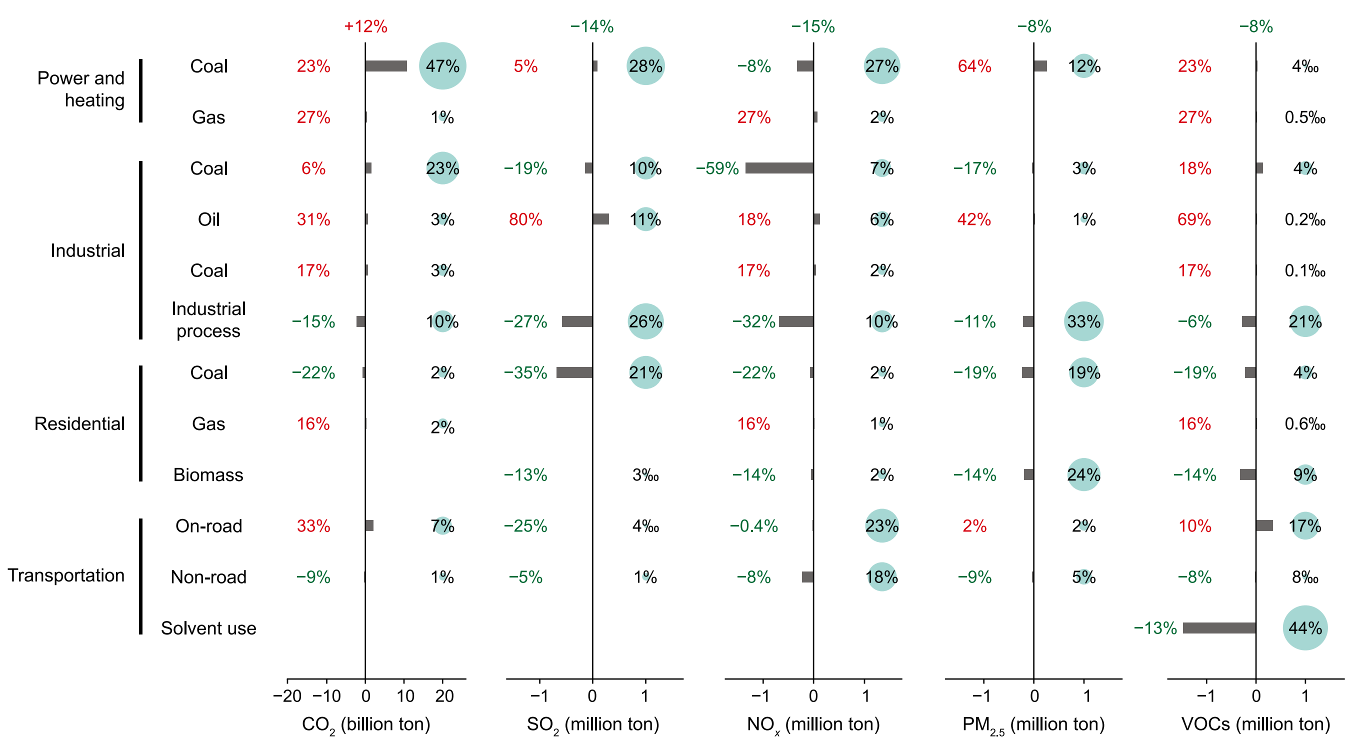

Fig. 8. Emission changes (bars) and proportions (filled circles) of air pollutants and CO_2 from different sectors in China, 2020–2023. Red numbers indicate an increase, green numbers indicate a decrease, and black numbers indicate the proportion of emissions in 2023.

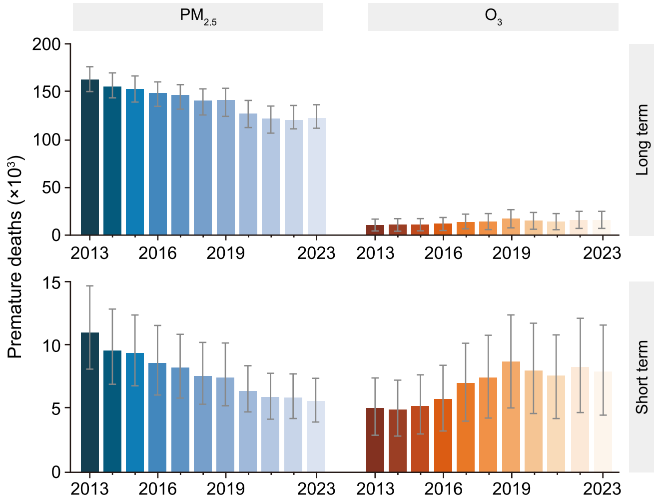

Fig. 9. The long-term and short-term $PM_{2.5}$ and O_3 exposure associated with premature deaths in China from 2013 to 2023. This figure is adapted from Fig. 7 in Ref. [8] and Fig. 1 in Ref. [9], with data updated to 2013–2023.

Dry-hot summer events were associated with higher non-accidental death risks (10.2%) compared to wet-hot events (3.2%) [70]. Conversely, in winter, wet-cold events showed slightly greater mortality risks (1.2%) than dry-cold events (1.1%) [73].

China is experiencing increased climate-sensitive health risks from extreme weather events (such as typhoons and sandstorms), affecting both inland and coastal regions [74,75]. Elderly and vulnerable populations, particularly those with daily living limitations, cognitive impairment, or social isolation, face elevated climate-related mortality risks.

Adaptive strategies, including early warning systems and resilient urban infrastructure [76,77], are critical for mitigating these health impacts, with a strong emphasis on protecting vulnerable populations.

6.3. Health Co-benefits of coordinated governance

Coordinated climate and air pollution governance significantly improves public health, though quantifying health benefits remains uncertain. Extreme heat and air pollution concurrently elevate mortality risks, notably ozone-related deaths during heatwaves, due to the nonlinearities of chemical interactions. The government must consider the impact of VOC/NO_x sensitivity regimes on changes in ozone concentration.

Carbon neutrality-driven energy transformations significantly reduce pollutants and offer substantial health benefits [78,79]. By 2060, $PM_{2.5}$ exposure could decrease by 14.5 μg m^{-3}, averting 29–50 million premature deaths cumulatively [8]. Low-carbon transitions, especially in rural and electricity sectors, significantly reduce $PM_{2.5}$ exposure and related deaths.

Regional disparities highlight the varying health benefits of carbon neutrality [80–82]. By 2030, China's eastern, central, and western regions could prevent approximately 86,771, 49,712, and 25,734 premature deaths, respectively [14]. Carbon trading policies significantly enhance health outcomes while reducing costs. For example, by 2050, achieving carbon neutrality in the Guangdong–Hong Kong–Macao region could notably reduce $PM_{2.5}$ and ozone levels, thereby significantly improving both health and economic outcomes.

7. Implications

In the future, air pollution control should be deeply integrated with the goals of carbon peaking and carbon neutrality, considering regional differences, industry characteristics, and emission-reduction pathways to enhance the effectiveness of synergistic reductions. On the one hand, efforts should be made to accelerate the establishment of a clean, low-carbon, intelligent, and efficient energy system, gradually moving toward zero-carbon energy. On the other hand, technological innovation and industrial upgrading should be advanced to develop and promote a new generation of synergistic technologies to prevent and control air pollution and carbon emissions, creating demonstrable, replicable models. At the same time, public health should remain central to governance, with a focus on strengthening health risk assessment and prevention, enhancing international exchanges and cooperation, and systematically adopting global best practices.

7.1. Policy implications

Climate change response policy. This analysis suggests that effective response measures should be developed and tailored to different types of extreme events, with particular attention to safeguarding the operational stability and infrastructure resilience in the renewable energy sector.

Ecosystem carbon sinks. Our findings indicate that afforestation practices should comprehensively account for ecological, climatic, social, and economic impacts, as well as potential trade-offs among these dimensions. The temporal pathway of forest carbon sink potential should be systematically integrated with emission reduction plans in the energy and industrial sectors.

Carbon market mechanisms. The evidence presented supports optimizing cross-industry pollution and carbon-reduction costs by adjusting the coverage of the carbon market. Cross-regional governance can be advanced by innovating carbon quota allocation mechanisms, emission offset rules, and an intertemporal quota banking system. Furthermore, developing financial products and services linked to carbon emission permits, together with strengthening policy coordination and harmonizing relevant institutional frameworks, is a critical priority.

Energy structures. This study underscores the need to gradually reduce reliance on fossil fuels, develop a green power system centered on wind and solar energy, and enhance grid flexibility and intelligence to efficiently integrate and utilize renewable energy. Simultaneously, the transition will require accelerated electrification of end-use energy, with priority given to low-carbon transitions in high-pollution industries— for example, replacing residential coal heating with clean energy sources and promoting the adoption of electric vehicles. Additionally, advanced distributed energy systems support local microgrid development and enhance storage technology to improve the stability and dispatchability of renewable energy sources.

Mitigate the health harms of climate change. Our results highlight the importance of strengthening multi-level prevention and response systems, including issuing early warnings before extreme weather arrives and deploying medical resources effectively while raising public health-risk awareness. Providing targeted, personalized climate-related health advice and decision support to vulnerable populations is likewise identified as a key measure.

7.2. Research implications

The impact of climate change on carbon emissions. Future research should deepen the understanding of the mechanisms underlying climate change and its effects on natural and anthropogenic carbon emissions. Particular emphasis should be placed on enhancing prediction and early warning capabilities for extreme weather events.

Research on maximizing the effectiveness of response policies. Further investigation is warranted into regionally differentiated strategies for urban spatial planning and greening intensity that minimize pollution and heat-island effects. Studies should also focus on selecting suitable tree species and planting schedules to maximize forest biomass carbon while ensuring ecological suitability.

CRediT authorship contribution statement

Zhicong Yin: Writing - Review & Editing, Writing - Original Draft, Methodology, Formal Analysis, Conceptualization. **Yu Lei:** Writing - Original Draft, Methodology, Formal Analysis, Conceptualization. **Xi Lu:** Writing - Review & Editing, Writing - Original Draft, Methodology, Formal Analysis, Conceptualization. **Qiang Zhang:** Writing - Review & Editing, Writing - Original Draft, Methodology, Formal Analysis, Conceptualization. **Jicheng Gong:** Writing - Original Draft, Methodology, Formal Analysis, Conceptualization. **Xin Liu:** Writing - Review & Editing. **Wei Li:** Writing - Review & Editing. **Cilan Cai:** Writing - Review & Editing. **Qimin Chai:** Writing - Review & Editing. **Renjie Chen:** Writing - Review & Editing. **Wenhui Chen:** Writing - Review & Editing. **Hancheng Dai:** Writing - Review & editing. **Zhanfeng Dong:** Writing - Review & Editing. **Jingli Fan:** Writing - Review & Editing. **Guannan Geng:** Writing - Review & Editing. **Cunrui Huang:** Writing - Review & Editing. **Jianlin Hu:** Writing - Review & Editing. **Shan Hu:** Writing - Review & Editing. **Moyu Li:** Writing - Review & Editing. **Tiantian Li:** Writing - Review & Editing. **Wei Li:** Writing - Review & Editing. **Yongsheng Lin:** Writing - Review & Editing. **Jun Liu:** Writing - Review & Editing. **Jinghui Ma:** Writing - Review & Editing. **Boyang Mao:** Writing - Review & Editing. **Yang Ou:** Writing - Review & Editing. **Yue Qin:** Writing - Review & Editing. **Lulu Shen:** Writing - Review & Editing. **Weiqi Tang:** Writing - Review & Editing. **Dan Tong:** Writing - Review & Editing. **Xuying Wang:** Writing - Review & Editing. **Jiaxing Wang:** Writing - Review & Editing. **Xuhui Wang:** Writing - Review & Editing. **Rui Wu:** Writing - Review & Editing. **Qingyang Xiao:** Writing - Review & Editing. **Yang Xie:** Writing - Review & Editing. **Xiaolong Xu:** Writing - Review & Editing. **Tao Xue:** Writing - Review & Editing. **Dongxu Yang:** Writing - Review & Editing. **Haipeng Yu:** Writing - Review & Editing. **Da Zhang:** Writing - Review & Editing. **Li Zhang:** Writing - Review & Editing. **Ning Zhang:** Writing - Review & Editing. **Shaojun Zhang:** Writing - Review & Editing. **Xian Zhang:** Writing - Review & Editing. **Zengkai Zhang:** Writing - Review & Editing. **Hongyan Zhao:** Writing - Review & Editing. **Bo Zheng:** Writing - Review & Editing. **Yixuan Zheng:** Writing - Review & Editing. **Tong Zhu:** Supervision. **Huijun Wang:** Supervision. **Jinnan Wang:** Supervision. **Kebin He:** Supervision.

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.

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Appendix A. Supplementary data

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References

[1] Y. Zheng, et al., Air quality improvements and health benefits from China's clean air action since 2013, Environ. Res. Lett. 12 (2017) 114020, https://doi.org/10.1088/1748-9326/aa8a32.
[2] Q. Zhang, et al., Drivers of improved PM2.5 and air quality in China from 2013 to 2017, Proc. Natl. Acad. Sci. 116 (2019) 24463–24469, https://doi.org/10.1073/pnas.1907956116.
[3] J. Zhang, et al., Impacts of compound extreme weather events on ozone in the present and future, Atmos. Chem. Phys. 18 (2018) 9861–9877, https://doi.org/10.5194/acp-18-9861-2018.
[4] J. Li, et al., Winter particulate pollution severity in north China driven by atmospheric teleconnections, Nat. Geosci. 15 (2022) 349–355.
[5] X. Zhang, et al., 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 (2019) 1885–1902.
[6] J. Xing, et al., The quest for improved air quality may push China to continue its CO2 reduction beyond the Paris commitment, Proc. Natl. Acad. Sci. 117 (2020) 29535–29542, https://doi.org/10.1073/pnas.2013297117.
[7] J. He, et al., Towards carbon neutrality: a study on China's long-term low-carbon transition pathways and strategies, Environ. Sci. Ecotechnol. 9 (2022) 100134, https://doi.org/10.1016/j.ese.2021.100134.
[8] Y. Lei, et al., The 2022 report of synergetic roadmap on carbon neutrality and clean air for China: accelerating transition in key sectors, Environ. Sci. Ecotechnol. 19 (2024) 100335.
[9] J. Gong, et al., The 2023 report of the synergetic roadmap on carbon neutrality and clean air for China: carbon reduction, pollution mitigation, greening, and growth, Environ. Sci. Ecotechnol. 23 (2025) 100517.
[10] J. He, et al., Air pollution characteristics and their relation to meteorological conditions during 2014–2015 in major Chinese cities, Environ. Pollut. 223 (2017) 484–496.
[11] C. Hong, et al., Weakening aerosol direct radiative effects mitigate climate penalty on Chinese air quality, Nat. Clim. Change 10 (2020) 845–850.
[12] Y. Zheng, Q. Zhang, D. Tong, S.J. Davis, K. Caldeira, Climate effects of China's efforts to improve its air quality, Environ. Res. Lett. 15 (2020) 104052.
[13] M. Guo, N.A.S. Hamm, B. Chen, Understanding air pollution reduction from the perspective of synergy with carbon mitigation in China from 2008 to 2017, J. Environ. Manag. 367 (2024) 122017, https://doi.org/10.1016/j.jenvman.2024.122017.
[14] Q. Zhang, et al., Synergetic roadmap of carbon neutrality and clean air for China, Environ. Sci. Ecotechnol. 16 (2023) 100280.
[15] Y. Xian, Y. Zhang, Z. Liu, H. Wang, T. Xiong, Characterization of winter PM2.5 source contributions and impacts of meteorological conditions and anthropogenic emission changes in the Sichuan basin, 2002–2020, Sci. Total Environ. 947 (2024) 174557, https://doi.org/10.1016/j.scitotenv.2024.174557.
[16] Z. Yin, et al., Traditional Meiyu-baiu has been suspended by global warming, Natl. Sci. Rev. 11 (2024), https://doi.org/10.1093/nsr/nwae166 nwae166.
[17] (WMO), W. M. O., State of the Global Climate 2023, 2024.
[18] L. Sun, et al., State of China's climate in 2023, Atmospher. Oceanic Sci. Lett. 17 (2024) 100519.
[19] Z. Yin, Y. Wan, Y. Zhang, H. Wang, Why super sandstorm 2021 in north China? Natl. Sci. Rev. 9 (2021) https://doi.org/10.1093/nsr/nwab165.
[20] W. Zhang, et al., Weather and climate extremes hitting the globe with emerging features, Adv. Atmos. Sci. 41 (2023) 1001–1016, https://doi.org/10.1007/s00376-024-4080-3, 2024.
[21] R. Dunn, et al., Global climate in 2023, Bull. Am. Meteorol. Soc. 105 (2024) S12–S155, https://doi.org/10.1175/bams-d-24-0116.1.
[22] Y. Sun, G. Jia, X. Xu, Extreme high temperatures and heatwave events across Europe in 2023, Environ. Res. Commun. 7 (2025) 021001, https://doi.org/10.1088/2515-7620/adae60.
[23] P. Sherman, X. Chen, M.B. McElroy, Wind-generated electricity in China: decreasing potential, inter-annual variability and association with changing climate, Sci. Rep. 7 (2017) 16294, https://doi.org/10.1038/s41598-017-16073-2.
[24] G. Akhmat, K. Zaman, T. Shukui, F. Sajjad, Does energy consumption contribute to climate change? Evidence from major regions of the world,

Renew. Sustain. Energy Rev. 36 (2014) 123–134, https://doi.org/10.1016/j.rser.2014.04.044.
[25] T. Chen, et al., Northward shift in landfall locations of tropical cyclones over the Western north Pacific during the last four decades, Adv. Atmos. Sci. 39 (2022) 304–319, https://doi.org/10.1007/s00376-021-1077-z.
[26] W. Mei, S.-P. Xie, Intensification of landfalling typhoons over the northwest Pacific since the late 1970s, Nat. Geosci. 9 (2016) 753–757, https://doi.org/10.1038/ngeo2792.
[27] J.A. Marengo, et al., The drought of Amazonia in 2023-2024, Am. J. Clim. Change 13 (2024) 567–597, https://doi.org/10.4236/ajcc.2024.133026.
[28] G. D'Amato, et al., Climate change, air pollution and extreme events leading to increasing prevalence of allergic respiratory diseases, Multidisciplinary Respiratory Medicine 8 (2013) 12, https://doi.org/10.1186/2049-6958-8-12.
[29] M. De Sario, K. Katsouyanni, P. Michelozzi, Climate change, extreme weather events, air pollution and respiratory health in Europe, Eur. Respir. J. 42 (2013) 826–843, https://doi.org/10.1183/09031936.00074712.
[30] H. Zhang, Y. Wang, T.-W. Park, Y. Deng, Quantifying the relationship between extreme air pollution events and extreme weather events, Atmos. Res. 188 (2017) 64–79, https://doi.org/10.1016/j.atmosres.2016.11.010.
[31] R. Wang, et al., The relationship between the intensified heat waves and deteriorated summertime ozone pollution in the beijing–tianjin–hebei region, China, during 2013–2017, Environ. Pollut. 314 (2022) 120256, https://doi.org/10.1016/j.envpol.2022.120256.
[32] M. Li, et al., Coping with the concurrent heatwaves and ozone extremes in China under a warming climate, Sci. Bull. 69 (2024) 2938–2947, https://doi.org/10.1016/j.scib.2024.05.034.
[33] Y. Chen, S. Chen, H. Bi, J. Zhou, Y. Zhang, Where is the dust source of 2023 several severe dust events in China? Bull. Am. Meteorol. Soc. 105 (2024) E2085–E2096, https://doi.org/10.1175/BAMS-D-23-0121.1.
[34] (WMO), W. M. O., The state of greenhouse gases in the atmosphere based on global observations through 2023. https://library.wmo.int/records/item/69057-no-20-28-october-2024, 2024.
[35] Z. Zhang, et al., Recent intensification of wetland methane feedback, Nat. Clim. Change 13 (2023) 430–433, https://doi.org/10.1038/s41558-023-01629-0.
[36] E.N. Koffi, P. Bergamaschi, R. Alkama, A. Cescatti, An observation-constrained assessment of the climate sensitivity and future trajectories of wetland methane emissions, Sci. Adv. 6 (2020), https://doi.org/10.1126/sciadv.aay4444 eaay4444.
[37] L. Zhang, et al., City-level pathways to carbon peak and neutrality in China, Cell Rep. Sustain. 1 (2024), https://doi.org/10.1016/j.crsus.2024.100102.
[38] NBS, Statistical Bulletin on National Economic and Social Development of the People's Republic of China in 2023, 2024.
[39] NDRC, Improve Energy Conservation and Carbon Reduction Work to a Higher Level and Quality, 2024.
[40] M. Crippa, D. Guizzardi, F. Pagani, M. Banja, M. Muntean, E. Schaaf, F. Monforti-Ferrario, W. Becker, R. Quadrelli, A. Risquez Martin, P. Taghavi-Moharamli, J. Köykkä, G. Grassi, S. Rossi, J. Melo, D. Oom, A. Branco, J. San-Miguel, G. Manca, E. Pisoni, E. Vignati, F. Pekar, GHG Emissions of all World Countries, Publications Office of the European Union, Luxembourg, 2024, https://doi.org/10.2760/4002897.
[41] MOT, Statistical Bulletin on the Development of the Transportation Industry, 2024.
[42] NRA, 2023 Railway Statistics Bulletin, 2024.
[43] CAAC, 2023 Civil Aviation Industry Development Statistics Bulletin, 2024.
[44] Q. Shi, et al., Co-benefits of CO2 emission reduction from China's clean air actions between 2013-2020, Nat. Commun. 13 (2022) 5061.
[45] R. Xu, et al., MEIC-global-CO2: a new global CO2 emission inventory with highly-resolved source category and sub-country information, Sci. China Earth Sci. 67 (2024) 450–465, https://doi.org/10.1007/s11430-023-1230-3.
[46] C. Chen, et al., China and India lead in greening of the world through land-use management, Nat. Sustain. 2 (2019) 122–129, https://doi.org/10.1038/s41893-019-0220-7.
[47] X. Wang, et al., The greenhouse gas budget for China's terrestrial ecosystems, Natl. Sci. Rev. 10 (2023), https://doi.org/10.1093/nsr/nwad274.
[48] Z. Yu, et al., Forest expansion dominates China's land carbon sink since 1980, Nat. Commun. 13 (2022) 5374, https://doi.org/10.1038/s41467-022-32961-2.
[49] P. Friedlingstein, et al., Global carbon budget 2023, Earth Syst. Sci. Data 15 (2023) 5301–5369, https://doi.org/10.5194/essd-15-5301-2023.
[50] S. Piao, Y. He, X. Wang, F. Chen, Estimation of China's terrestrial ecosystem carbon sink: methods, progress and prospects, Sci. China Earth Sci. 65 (2022) 641–651, https://doi.org/10.1007/s11430-021-9892-6.
[51] X. Xia, et al., The carbon budget of China: 1980–2021, Sci. Bull. 69 (2024) 114–124, https://doi.org/10.1016/j.scib.2023.11.016.
[52] Z. Yu, et al., Maximizing carbon sequestration potential in Chinese forests through optimal management, Nat. Commun. 15 (2024) 3154.
[53] J.J. Bukoski, et al., Rates and drivers of aboveground carbon accumulation in global monoculture plantation forests, Nat. Commun. 13 (2022) 4206.
[54] N. Lu, et al., Biophysical and economic constraints on China's natural climate solutions, Nat. Clim. Change 12 (2022) 847–853.
[55] H. Xu, C. Yue, Y. Zhang, D. Liu, S. Piao, Forestation at the right time with the right species can generate persistent carbon benefits in China, Proc. Natl. Acad. Sci. 120 (2023) e2304988120.
[56] L. Zhang, P. Sun, F. Huettmann, S. Liu, Where should China practice forestry in a warming world? Glob. Change Biol. 28 (2022) 2461–2475.
[57] X. Fu, et al., Co-benefits of transport demand reductions from compact urban development in Chinese cities, Nat. Sustain. 7 (2024) 294–304.
[58] Q. Zha, Z. Liu, J. Wang, Spatial pattern and driving factors of synergistic governance efficiency in pollution reduction and carbon reduction in Chinese cities, Ecol. Indic. 156 (2023) 111198.
[59] J. Cheng, et al., A synergistic approach to air pollution control and carbon neutrality in China can avoid millions of premature deaths annually by 2060, One Earth 6 (2023) 978–989.
[60] Y. Qin, et al., Amplified positive effects on air quality, health, and renewable energy under China's carbon neutral target, Nat. Geosci. 17 (2024) 411–418.
[61] Y. Sun, et al., Air quality, health, and equity benefits of carbon neutrality and clean air pathways in China, Environ. Sci. Technol. 58 (2024) 15027–15037.
[62] W. Peng, et al., Th e surprisingly inexpensive cost of state-driven emission control strategies, Nat, Clim. Change 11 (2021) 738–745.
[63] C.J. Murray, et al., 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 (2020) 1223–1249.
[64] Q. Xiao, et al., Tracking PM2. 5 and O3 pollution and the related health burden in China 2013–2020, Environ. Sci. Technol. 56 (2021) 6922–6932.
[65] X. Meng, et al., Short term associations of ambient nitrogen dioxide with daily total, cardiovascular, and respiratory mortality: multilocation analysis in 398 cities, Br. Med. J. 372 (2021).
[66] P. Orellano, J. Reynoso, N. Quaranta, A. Bardach, A. Ciapponi, Short-term exposure to particulate matter (PM10 and PM2. 5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: systematic review and meta-analysis, Environ. Int. 142 (2020) 105876.
[67] R. Chen, et al., Associations between ambient nitrogen dioxide and daily cause-specific mortality: evidence from 272 Chinese cities, Epidemiology 29 (2018) 482–489.
[68] H.H. Shin, et al., Sex-difference in air pollution-related acute circulatory and respiratory mortality and hospitalization, Sci. Total Environ. 806 (2022) 150515.
[69] S. Zhang, et al., The 2023 China report of the lancet countdown on health and climate change: taking stock for a thriving future, Lancet Public Health 8 (2023) e978–e995.
[70] W. Fang, et al., The joint and interaction effect of high temperature and humidity on mortality in China, Environ. Int. 171 (2023) 107669.
[71] W. Fang, et al., Heat exposure intervention, anxiety level, and multi-omic profiles: a randomized crossover study, Environ. Int. 181 (2023) 108247.
[72] R. Xu, et al., Extreme temperature events, fine particulate matter, and myocardial infarction mortality, Circulation 148 (2023) 312–323.
[73] M. Li, et al., The comparison of mortality burden between exposure to dry-cold events and wet-cold events: a nationwide study in China, Sci. Total Environ. 904 (2023) 166859.
[74] Y. Ma, et al., The threaten of typhoons to the health of residents in inland areas: a study on the vulnerability of residents to death risk during typhoon “lekima” in jinan, China, BMC Public Health 24 (2024) 606.
[75] Z. Soleimani, et al., An overview of bioaerosol load and health impacts associated with dust storms: a focus on the Middle East, Atmos. Environ. 223 (2020) 117187, https://doi.org/10.1016/j.atmosenv.2019.117187.
[76] J.S. Ji, D. Xi, C. Huang, Building resilience in heatwaves, Nat. Med. 29 (2023) 1613–1614, https://doi.org/10.1038/s41591-023-02409-1.
[77] J. Xu, Z. Su, C. Liu, Y. Nie, L. Cui, Climate change, air pollution and chronic respiratory diseases: understanding risk factors and the need for adaptive strategies, Environ. Health Prev. Med. 30 (2025), 7-7.
[78] Q. Luo, F. Garcia-Menendez, J. Lin, G. He, J.X. Johnson, Accelerating China's power sector decarbonization can save lives: integrating public health goals into power sector planning decisions, Environ. Res. Lett. 18 (2023) 104023.
[79] T. Ma, et al., Costs and health benefits of the rural energy transition to carbon neutrality in China, Nat. Commun. 14 (2023) 6101.
[80] Z.-Q. Guo, et al., Air quality and heath co-benefits of low carbon transition policies in electricity system: the case of beijing–tianjin–hebei region, Environ. Res. Lett. 19 (2024) 054039.
[81] Y. Xie, et al., Health and economic benefits of reducing air pollution embodied in GBA's green and low-carbon development, Urban Clim. 52 (2023) 101755.
[82] Y. Xie, et al., Large-scale renewable energy brings regionally disproportional air quality and health co-benefits in China, iScience 26 (8) (2023) 107459.