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Synergetic Roadmap

The 2023 report of the synergetic roadmap on carbon neutrality and clean air for China: Carbon reduction, pollution mitigation, greening, and growth☆

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A B S T R A C T

The response to climate change and air pollution control demonstrates strong synergy across scientific mechanisms, targets, strategies, and governance systems. This report, based on a monitoring indicator system for coordinated governance of air pollution and climate change, employs an interdisciplinary approach combining natural and social sciences. It establishes 20 indicators across five key areas: air pollution and climate change, governance systems and practices, structural transformation and technologies, atmospheric components and emission reduction pathways, and health impacts and co-benefits. This report tries to provide actionable insights into the interconnectedness of air pollution and climate governance. It highlights key policy gaps, presents updated indicators, and offers a refined monitoring framework to track progress toward China's dual goals of reducing emissions and improving air quality. Compared to previous editions, this year's report has updated four key indicators: meteorological impacts on air quality, climate change and its effects, governance policies, and low-carbon building energy systems. The aim is to further refine the monitoring framework, track progress, and establish a comprehensive theory for collaborative governance while identifying challenges and proposing solutions for China's pathway to carbon neutrality and clean air. The report comprises six chapters. The executive summary chapter is followed by analyzing air pollution and climate change interactions. Governance systems and practices are discussed in the third chapter, focusing on policy implementation and local experiences. The fourth chapter addresses structural transformations and emission reduction technologies, including energy and industrial shifts, transportation, low-carbon buildings, carbon capture and storage, and power systems. The fifth chapter outlines atmospheric component dynamics and emission pathways, presenting insights into emission drivers and future strategies. The sixth chapter assesses health impacts and the benefits of coordinated actions. Since 2019, China Clean Air Policy Partnership has produced annual reports on China's progress in climate and air pollution governance, receiving positive feedback. In 2023, the report was co-developed with Tsinghua University's Carbon Neutrality Research Institute, involving over 100 experts and multiple academic forums. The collaboration aims to continuously improve the indicator system and establish the report as a key resource supporting China's efforts in pollution reduction, carbon mitigation, greening, and sustainable growth.

1. Executive summary

In the new context of ecological civilization construction, China faces two major strategic tasks: achieving carbon peaking and carbon neutrality when building a Beautiful China. Promoting pollution reduction, carbon reduction, greening, and growth in a coordinated manner has become an essential strategy for the comprehensive green transformation of economic and social development. This approach addresses environmental challenges fundamentally and provides an effective path toward achieving the carbon peaking and carbon neutrality goals alongside the vision of a Beautiful China. The report from the 20th National Congress emphasized the importance of integrated conservation and systematic governance, balancing industrial restructuring, pollution control, ecological protection, and climate change response.

Scientific studies and practical investigations reveal that emissions of greenhouse gases and air pollutants originate from similar sources and exhibit distinct interactions. This intrinsic connection between climate change and air pollution significantly impacts both ecosystems and public health. Thus, there is a strong synergy between climate change mitigation and air pollution control in terms of mechanisms, targets, governance, measures, and overall benefits. The Ministry of Ecology and Environment's "Synergistic Efficiency Plan for Pollution and Carbon Reduction" marked the beginning of practical exploration in this area. The Ministry has

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made progress by integrating pollution and carbon reduction efforts, improving policies, and reinforcing mechanisms, contributing to a win-win outcome of environmental, climate, economic, and social benefits.

To comprehensively evaluate the progress of coordinated climate change and air pollution governance, since 2021, Tsinghua University and other institutions, supported by the Energy Foundation and the China Clean Air Policy Partnership (CCAPP), have compiled the "Annual Report on China's Carbon Neutrality and Clean Air Synergy Pathways". This initiative facilitates interdisciplinary exchange among experts in atmospheric science, environmental engineering, energy, public health, and management, aiming to form a closed-loop process for policy-making, evaluation, and optimization.

This year, CCAPP collaborated with Tsinghua University's Institute for Carbon Neutrality for the first time, engaging top experts to produce the third edition of the report, themed "Carbon Reduction, Pollution Mitigation, Greening, and Growth". The report refines the monitoring indicator system, establishing 20 indicators across five areas (summarized in Table 1): air pollution and climate change, governance systems and practices, structural transformation and technologies, sources and sinks of atmospheric components, and health impacts and co-benefits. By tracking these indicators, the report analyzes obstacles and provides solutions to advance China's path toward carbon neutrality and clean air.

(1) Air Pollution and Climate Change: In 2022, the concentrations of major air pollutants declined compared to 2021. The average $PM_{2.5}$ concentration across 339 cities was 29 μg m^{-3}, a 35.6% reduction from 2015. The number of cities meeting the national $PM_{2.5}$ standards increased significantly. However, ozone concentrations showed mixed trends, highlighting ongoing challenges in pollution control. Meteorological conditions in 2022 influenced pollution levels, with regional variations in $PM_{2.5}$ and ozone trends.
(2) Governance Systems and Practices: Coordinated efforts in air pollution control and carbon reduction have deepened. Policies, such as the "Synergistic Efficiency Plan", emphasize integrated governance, innovation in policy tools, and establishing transparent and participatory governance systems. Efforts at both national and local levels have shown progress, but more work is needed to ensure consistent outcomes across regions.
(3) Structural Transformation and Technologies: Energy and industrial shifts are crucial for achieving carbon neutrality. In 2022, renewable energy generation increased significantly, while coal use still played a substantial role. Innovations in energy efficiency and clean technologies are advancing, but challenges remain in balancing economic growth with emissions reductions.
(4) Sources, Sinks, and Emission Reduction Pathways: China's carbon emissions have shown varied trends, driven by key sectors like energy and industry. Land use changes, including forest expansion, have contributed significantly to carbon sequestration. However, maintaining high carbon sink levels requires scientific forest management.
(5) Health Impacts and Co-benefits: $PM_{2.5}$ exposure continues to decline, improving public health. However, ozone and nitrogen dioxide remain concerns, with significant health risks. Climate change, particularly extreme heat, exacerbates health issues, emphasizing the need for adaptive measures and stricter air quality standards.

Overall, China's efforts in pollution and carbon reduction are evolving, but continued integration, structural transformation, and precise governance strategies are necessary. Meeting dual goals requires innovative solutions, regional cooperation, and policies prioritizing public health and environmental quality. This report presents the synergetic roadmap for carbon neutrality and clean air, showing a comprehensive assessment of the country's progress in reducing emissions and improving air quality, highlighting the strong synergy between climate change mitigation and air pollution control. The significant health co-benefits of greenhouse gas mitigation and air quality improvement are emphasized, underscoring the potential for achieving carbon neutrality goals while enhancing public health outcomes.

2. Air pollution and associated weather-climate interactions

Changes in air quality and the intensity of associated weather-climate interactions serve as prominent indicators that directly illustrate the environmental impacts of air pollution and carbon co-control. With that, this section reviews the changes in air quality

Table 1
Summary of 20 indicators in the monitoring system of this report.

Areas	Indicators
1. Air pollution and associated weather-climate interactions	1.1. Changes in air quality
	1.2. Variations in adverse meteorological conditions
	1.3. Climate change and its impact on energy
2. Synergetic governance system and practices	2.1 Construction of a synergetic governance system
	2.2. Economic policies for synergetic governance
	2.3. Local practices
3. Structural Transformation and Governance Technologies	3.1 Transformation of the energy mix
	3.2 Transformation of the industrial structure
	3.3 Transformation of the transportation structure
	3.4 Low-carbon transition of building energy systems
	3.5 CCUS technologies
	3.6 New electricity system
	3.7 Pollution control
4. Sources, sinks, and mitigation pathway of atmospheric composition	4.1. Anthropogenic CO_2 emissions
	4.2. Land use change and land carbon sinks
	4.3 Progress in emissions of air pollutants and progress of synergistic control
	4.4. Future mitigation potentials and synergetic pathway
5. Health impacts and benefits of coordinated control	5.1 Air pollution and related health impacts
	5.2 Climate change and health effects
	5.3 Health co-benefits of greenhouse gas mitigation and air quality improvement

and variations in adverse meteorological $PM_{2.5}$ conditions in 2022, as well as climate change and its impacts on air pollution.

2.1. Changes in air quality

Air quality has continuously improved in China over the past decade. In 2022, the average $PM_{2.5}$ concentration in 339 cities at or above the prefecture level was 29 μg m^{-3}, 35.6% lower than the 2015 level (Fig. 1a). During 2021–2022, the $PM_{2.5}$ concentrations in the Beijing–Tianjin–Hebei and its surrounding regions (BTHs) and Pearl River Delta region (PRD) declined much more than in other regions, while it rebounded slightly in the Fen–Wei Plain (FWP) and the Sichuan Basin (SCB). Although $PM_{2.5}$ concentrations continued to decrease from 2015 to 2022 in China, there were still 86 cities exceeding the National Ambient Air Quality Standard Grade II for annual $PM_{2.5}$ concentration in 2022, implying that $PM_{2.5}$ pollution is still severe in China.

In 2022, the 90th percentile of the maximum daily 8-h average (MDA8) O_3 concentrations ranged from 90 μg m^{-3} to 184 μg m^{-3} across Chinese cities, with an average concentration of 145 μg m^{-3}, which was 5.8% higher than the 2021 average level (Fig. 1c). Compared to 2021, the O_3 concentrations in the SCB, BTHs, YRD (Yangtze River delta), FWP, and PRD increased by 15.0%, 6.3%, 7.3%, 1.2% and 14.5%, respectively. Measuring the three-year running average, the O_3 concentrations in China and key regions continued to increase from 2015 to 2019, while they remained flat or decreased slightly during 2020–2022.

The ratio of severely $PM_{2.5}$ polluted days across the country was 0.7% in 2021, which was 75.0% lower than that in 2015 (2.8%), indicating the remarkable effects of the control of heavy $PM_{2.5}$ pollution in air pollution control. Among the key regions, the ratio of severely $PM_{2.5}$ polluted days in BTHs and FWP was 1.7% and 1.6% in 2021, which decreased by 83.0% and 68.0%, respectively, compared with the 2015 levels. By 2022, the PRD region will be free of severe pollution for four consecutive years. After nearly ten years of air pollution control, the spatial pattern of air quality in China has changed significantly. In 2022, cities in Hebei Province have dropped out of the top 10 most polluted $PM_{2.5}$, and the pollution center has shifted to Shaanxi and Henan Province.

2.2. Variations in adverse meteorological conditions

The formation, accumulation, and diffusion of aerosol pollutants are closely related to various meteorological conditions [1]. In China, a positive correlation was observed between pollutant concentrations and temperature, while an inverse relationship was noted with wind speed and boundary layer height, except for ozone. The primary pollutant concentrations demonstrated a positive correlation with relative humidity predominantly in North and Northeast China, contrasting with a negative correlation in other geographical areas. Conversely, ozone concentrations were negatively associated with relative humidity across China. The evaluation on meteorological condition index of $PM_{2.5}$ pollution (EMI) indicated that the national average $PM_{2.5}$ meteorological conditions in 2022 were slightly unfavorable compared to 2021 (Fig. 1b). Notably, atmospheric diffusion conditions in the BTHs, FWP, and SCB regions in 2022 were worse than those in the past five years and 2021, leading to an increase in $PM_{2.5}$ concentrations by about 8.3%, 7.9%, and 0.9% compared with 2021 levels, and 2.2%, 1.8%, and 0.8% compared with the average of the previous five years.

The meteorological variations also play a crucial role in influencing the formation and depletion of O_3, as well as the emissions of its precursors [2]. The evaluation of the meteorological condition index of O_3 pollution showed that meteorological conditions nationwide from May to September 2022 were more unfavorable than the previous year, which led to the increase in O_3 concentration in BTHs, YRD, FWP and SCB by 8.5%, 8.1%, 3.0%, and 11.0%, respectively, compared with the same period in 2021, and by 2.7%, 6.4%, 2.1% and 10.7%, respectively, compared with the average of the previous five years (Fig. 1d).

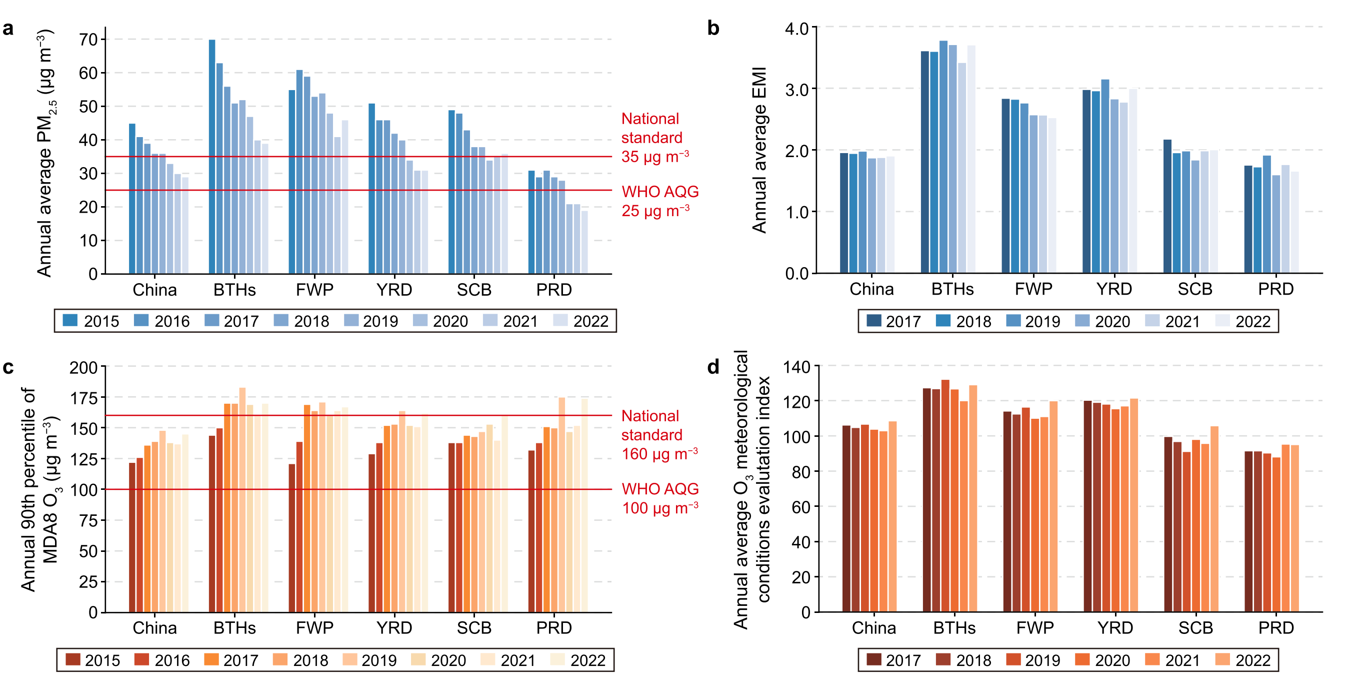

Fig. 1. Variations in air quality and the associated meteorological condition index over China and key regions from 2015 to 2022. **a**, Annual average $PM_{2.5}$ concentration. **b**, Annual average EMI. **c**, Annual 90th percentile of MDA8 O_3. **d**, Meteorological condition index of O_3 pollution. WHO AQG: World Health Organization's Air quality guidelines. EMI: Evaluation on meteorological condition index of $PM_{2.5}$ pollution. BTHs: Beijing–Tianjin–Hebei and its surrounding regions; FWP: Fen–Wei Plain; YRD: Yangtze River Delta; SCB: Sichuan Basin; PRD: Pearl River Delta. This figure is adapted from Ref. [27, 28].

In 2022, China experienced a total of 10 dust weather events [3], 3 times fewer than in 2021 and 2.2 times fewer than the average of the previous five years. The dust events in 2022 were characterized by late onset, weak intensity, and limited impact [3], with meteorological conditions overall favoring fewer and weaker dust weather in the spring of 2022.

The fluctuations in meteorological conditions significantly contribute to the increase or decrease of air pollution concentrations, particularly influencing severe pollution events. When formulating air pollution control measures, it is essential to consider the variation in meteorological conditions and make comprehensive plans to consolidate the improving air quality trend.

2.3. Climate change and its impact on energy

Due to the warming climate, China exhibited pronounced warm and dry climate characteristics in 2022, with severe drought and flood disasters, which might affect the impacts of the weather variation on air pollution [4]. In 2022, the national average temperature was 0.62 °C higher than the long-term average (1991–2020). Additionally, the average precipitation was 5.0% less than the long-term average. China saw a range of extreme weather and climate events throughout the year, including the highest summer temperature since 1961 in central and eastern China [5], severe summer-autumn drought in southern China [6], and frequent rainstorms in northeast and southern China [7], showing the characteristics of long time, high intensity and strong extremes [8]. These events underscore the increasing risk of extreme weather and disasters in China within the context of global climate change [9].

In the future, extreme climate changes will be more dramatic than average. Compared with the current climate, the annual average temperature in China will increase by about 1.3 °C by 2030 and about 2.1 °C by 2060 [10]. As global warming intensifies, extreme warm events will significantly increase, and cold events will significantly decrease in China [11]. The average annual precipitation will rise by about 8% by 2030 and by about 10% by 2060 [12,13]. Extreme precipitation events are expected to show a significant increase and enhanced trend on the whole, but the regional differences are large. The increasing areas will be mainly in northern and northeast China [14,15].

In 2022, the wind energy resources in China were slightly smaller than normal, and the annual average wind speed at a 10-m high was 0.82% smaller than the average in the past 10 years. The solar energy resources were relatively larger than normal, and the annual average horizontal plane total irradiance was the highest in the past 30 years. Under the emission reduction scenario of "carbon neutral", wind and solar energy resources in eastern China tend to increase from 2040 to 2049, with decreasing temporal variability, indicating the stability of solar and wind power generation will be enhanced [16]. However, for predicting future changes in wind and solar resources, significant differences and uncertainties exist among simulations based on different regions and emission scenarios [17].

3. Synergetic governance system and practices

3.1. Construction of a synergetic governance system

Following introducing the concept of "synergetic pollution reduction and carbon emission decrease," research on the theory and practice of synergistic management has emerged. On the one hand, the academic community, considering the "same root and source" nature of greenhouse gases and atmospheric pollutants, has systematically assessed the synergistic effects of various emission reduction actions, thereby promoting the gradual formation of societal consensus. On the other hand, from a practical standpoint, the industry has proposed that deepening structural adjustments and green transformation in the context of ultra-low emission of pollutants is the fundamental approach to achieving synergy in pollution reduction and carbon lowering. Additionally, a substantial body of research has identified several significant challenges that China's construction of a synergistic governance system must confront.

Synergetic governance, addressing both climate change and air pollution, demands a holistic approach due to their distinct mechanisms and spatial-temporal characteristics (Fig. 2). This governance requires policy summation and a deep synergy among ecological, energy security, and industrial transformation goals. China's socio-economic transformations and the evolution of industrial structures foster heterogeneous development needs. The effectiveness of policies aimed at pollution and carbon reduction varies significantly across sectors like economics, environmental health, energy, and technology, as well as between different regions and developmental stages. Moreover, issues like income disparity and energy poverty can arise as secondary effects of climate and environmental governance, potentially hindering high-quality socio-economic development [18]. Thus, achieving a synergistic effect necessitates systematically assessing socio-economic benefits tailored to regional specifics to plan pollution and carbon reduction strategies scientifically.

Policy design for synergetic governance must balance long-term and immediate objectives. Climate governance emphasizes long-term low-carbon innovation to optimize carbon budgets over time, whereas pollution control focuses on immediate, strict control measures to manage current environmental risks. Spatially, while climate change has global impacts, air pollution affects local environments, requiring coordinated approaches between national carbon markets and regional emission trading to balance broad and localized control strategies. Practically, continuous reinforcement of joint controls on pollutants and greenhouse gases is crucial. This includes unified emission standards and coordinates industrial layouts to prevent new "pollution havens" from emerging due to "carbon leakage" [19]. Innovative models for cross-compliance of carbon and pollution quotas through market mechanisms are necessary to enhance the effectiveness of synergetic governance [20].

Empirical studies suggest that while market mechanisms like quota trading and taxes are effective for short-term, low-cost emission reductions, they are less impactful for long-term, high-investment actions such as technological innovation [21]. Therefore, enhancing synergetic governance involves improving carbon

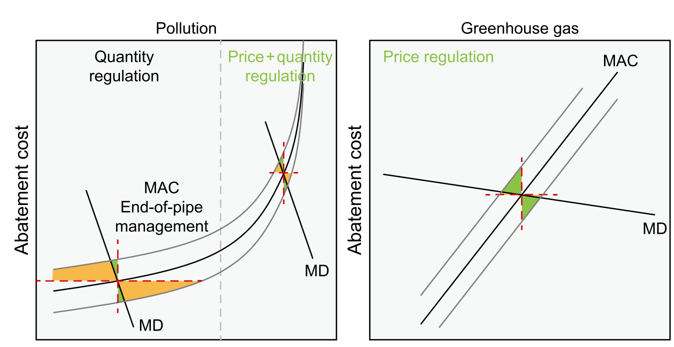

Fig. 2. Diagram of policy tools for environmental and climate governance. MAC: marginal abatement cost; MD: marginal damage.

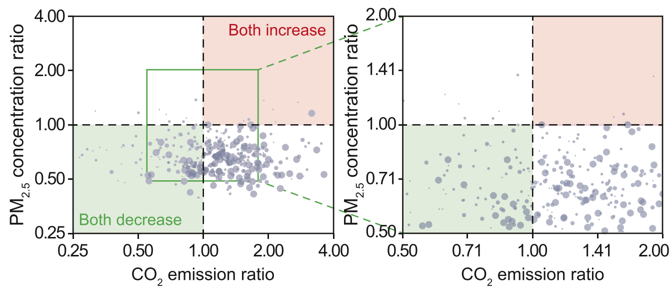

Fig. 3. Progress in city-level CO_2 emission and $PM_{2.5}$ pollution co-control. **a**, Changes in annual $PM_{2.5}$ concentrations and CO_2 emissions in Chinese cities from 2015 to 2021. **b**, Details of the area bounded by solid green lines in panel **a**. The size of the dots depicts CO_2 emissions in 2021. Data sources: Cai et al., 2018, 2019 [25,26]; China National Environmental Monitoring Center, http://www.cnemc.cn/. This figure is adapted from Fig. 10 in Zhang et al., 2023 [27] and Fig. 1 in Lei et al., 2024 [28], with data updated to 2015–2021.

market operations, linking emission trading systems, and promoting technological regulations and monitoring. Additionally, optimizing fiscal, tax, and financial incentives, particularly through transformative financial systems, can boost market-driven transformation and innovation.

3.2. Economic policies for synergetic governance

The incentive policy of the market economy with the carbon market as the main body has been continuously improved and innovated in practice. China's carbon market has become the world's largest carbon trading market regarding greenhouse gas (GHG) emissions. The national carbon market, functioning as a pivotal policy instrument for GHG control, has demonstrated its crucial role in fostering emissions reduction among enterprises and expediting the shift towards green and low-carbon practices. By the end of 2022, the cumulative trading volume of carbon emission quotas reached 230 million tons, with a total transaction value of CNY 10.5 billion, 28.5% and 36.7% higher than that of 2021, respectively. At the same time, climate-related investment and financing have solved the financial needs of the green and low-carbon transition stage. In 2022, China organized 23 localities to carry out climate investment and financing pilot projects, issued reference standards for storing local climate investment and financing projects, and guided pilot regions to build information docking platforms for "government, bank and enterprise". By the end of 2022, a total of more than 1500 projects have been collected or reserved in 23 pilot areas, involving about CNY 2 trillion of funds.

Furthermore, efforts such as voluntary GHG reduction trading and carbon finance have advanced further. Transition finance has attracted the attention of scholars and governments.

3.3. Local practices

Following the release of the Implementation Plan for synergizing the reduction of both pollution and carbon emissions, numerous regions, such as Jilin, Zhejiang, Fujian, Jiangxi, Shaanxi, and Ningxia, have proactively tailored and implemented the plan to align with their unique characteristics and needs, advancing practical efforts at the local level.

Based on the city-level air pollution and carbon emissions data, cities with high carbon emissions exhibit a more pronounced trend of $PM_{2.5}$ pollution. In 2021, the average CO_2 emissions of 99 cities with $PM_{2.5}$ concentrations that fell below the National Ambient Air Quality Standard (56.79 million tons) were roughly 55% higher compared to the other 236 cities with $PM_{2.5}$ concentrations that met the standard (36.65 million tons). By 2021, approximately 12% of cities have peaked their carbon emission, of which roughly 59% have met the $PM_{2.5}$ standard (using statistical evaluation method) [22–24]. Additionally, about 16% and 72% of cities are in the plateau and growth period, respectively. Interestingly, there appears to be no significant correlation between a city's carbon peak status, economic level, carbon emissions, and $PM_{2.5}$ compliance. Furthermore, substantial potential remains for enhancing synergy between air quality improvement and CO_2 abatements at a city level. Between 2015 and 2021, only 31% of the cities achieved a co-reduction in CO_2 emissions and $PM_{2.5}$ concentrations (dots in the third quadrant in Fig. 3). Conversely, both CO_2 emissions and $PM_{2.5}$ concentrations increased simultaneously in 9 cities, a decrease of 8 compared to 2015–2020.

4. Structural transformation and governance technologies

4.1. Transformation of the energy mix

New changes have occurred in the adjustment of the energy mix. By promoting clean and low-carbon energy transition while speeding up the system's development for new energy sources, coal and new energy grew under the stimulus of energy security and energy transition. In 2022, China's total energy consumption involved 5.41 billion tonnes of standard coal (up 2.9% year-on-year) (Fig. 4c), while in the past decade, China has supported its annual 6.2% gross domestic product (GDP) growth with an annual energy consumption growth rate of 3%. In 2022, coal consumption accounted for 56.2%, up 0.3 percentage points year-on-year, which constituted an increase instead of a decrease for the first time over the past decade. In the first two years of the 14th Five-Year Plan period, coal consumption increased by some 390 million tonnes, 7 times more than the cumulative increase during the previous period. Non-fossil energy consumption accounted for 17.5%, an increase of 1.6 percentage points over 2020 and 0.8 percentage points over 2021. The capacity for diverse clean energy supplies such as wind, photovoltaic (PV), hydro, biomass, nuclear, and hydrogen energy has continued to improve (Fig. 4).

Renewable energy development has increased its share in the energy mix. In 2022, China's nationwide power generation reached 8.7 trillion kWh, of which 36.2% came from non-fossil energy, up 8.6% year-on-year. Grid-connected solar, wind, nuclear, and hydropower generation grew by 31.2%, 16.2%, 2.5%, and 1.0%, respectively, with the first two exceeding 1 trillion kWh for the first time to reach 1.19 trillion kWh (up 21% year-on-year) and accounting for 13.8% of total power consumption. Increased power generation in the first two years of the 14th Five-Year Plan period took up 92% of that during the 13th Five-Year Plan. In 2022, China's installed renewable energy capacity topped 1.2 billion kW, exceeding the installed capacity of coal power and accounting for 47.3% of the country's total power capacity. Specifically, 125 million kW of additional wind and PV power capacity was installed, topping 100 million kW for the third year in a row. Additional capacity installed in the first two years of the 14th Five-Year Plan period reached 62% of that during the previous period. By the first half of 2023, China's installed renewable energy capacity exceeded 1.3 billion kW to reach 1.322 billion kW, accounting for 48.8% of the country's total. In 2022, over 51 million kW of new distributed PV power generation projects were connected to the grid, accounting for around 58% of the total new installed PV power capacity that year and 1.4 times the capacity of new centralized PV power stations integrated into the grid. Pilot programs of rooftop distributed PV systems at the county (city/district) level continued to progress steadily.

Conversely, coal power, as the “ballast” for energy security and the "backbone" of reliable power supply, witnessed a new surge,

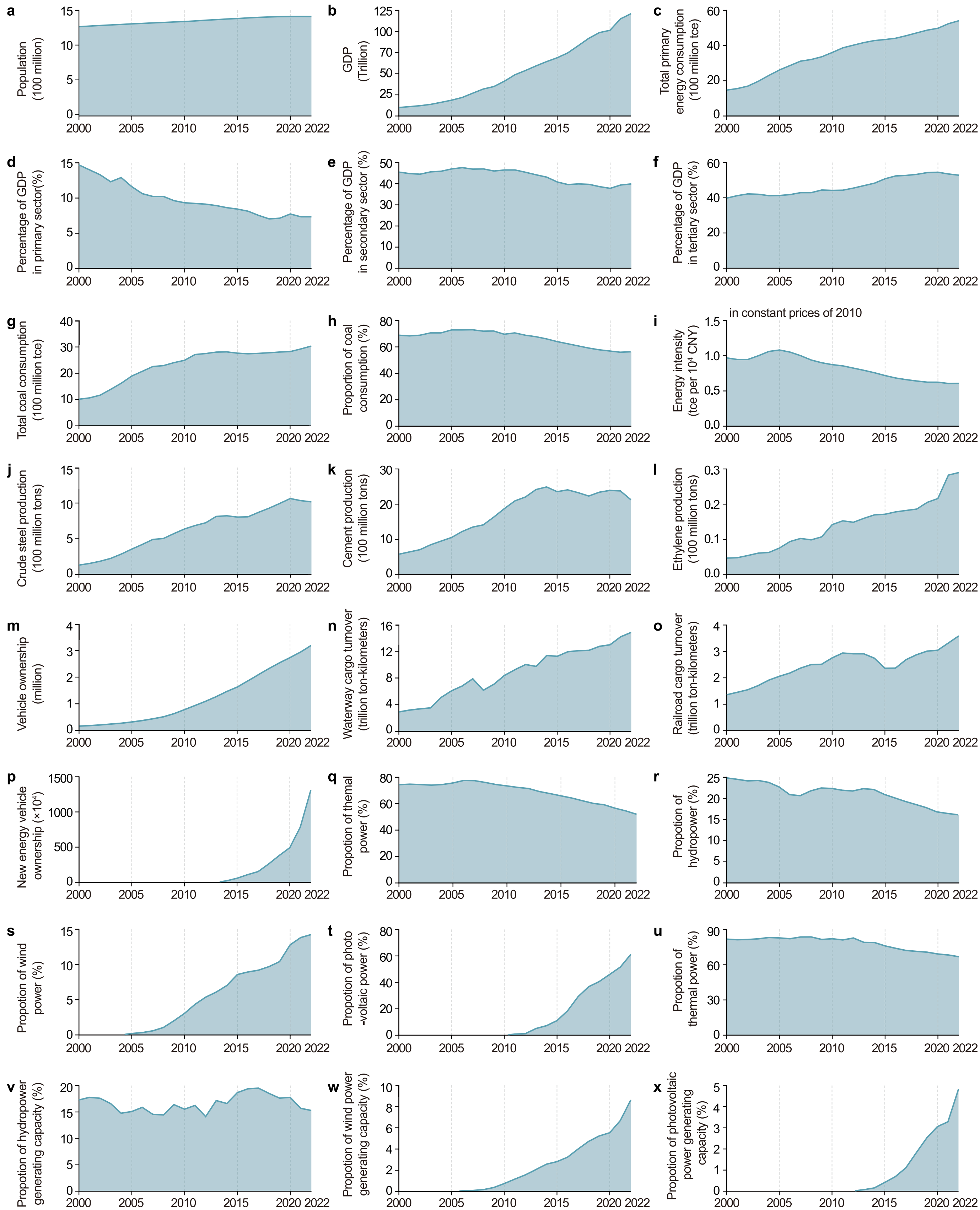

Fig. 4. Progress in structural transformation from 2000 to 2022. **a**, Total population; **b**, Gross domestic product (GDP); **c**, Total Primary energy consumption; **d**, Proportion of GDP from the primary sector; **e**, Proportion of GDP from the secondary sector; **f**, Proportion of GDP from the 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 Ref. [27,28].

with 52 GW of additional installed coal power capacity approved in the first half of 2023, which was more than half of that approved in 2022 alone and about 2.7 times that approved throughout 2021. The newly approved coal power projects were mainly built in provinces such as Hebei, Jiangsu, Shandong, Guangdong, and Hubei, accounting for more than 65% combined, of which around 72% were large generating units with a capacity of more than 1 million kilowatts.

Petroleum and natural gas consumption continues to fluctuate. In 2022, crude oil production was 204.67 million tonnes, up 2.9% over the previous year, with 71.2% imported. Natural gas production was 217.8 billion cubic meters, up 6.4% over the previous year, of which 41.2% was imported. In 2022, petroleum and natural gas accounted for 17.9% and 8.4% of the total primary energy consumption, down 0.7 and 0.5 percentage points year-on-year. With the post-pandemic economic development, China's consumption of crude oil and oil products is expected to see a short-term compensatory rebound; while natural gas demand will tend to grow, but with large fluctuations due to factors such as growing transportation demand and an increase in the use of natural gas for power generation [29].

As a basic component of the new electricity system, renewable energy has been developed and accommodated on a large scale, and new types of energy storage are also growing rapidly. In 2022, the installed capacity of new types of energy storage projects in China reached 8.7 million kW, with an average power storage period of 2.1 h, an increase of over 110% from the end of 2021. Lithium-ion battery energy storage is the mainstream technology for the time being. While corporate capital is flooding into the energy storage sector, it still faces problems such as low demand, far higher capacity than shipments, and low-price competition. Utilization of the energy storage sector's capacity fell to 60.5% in the first half of 2023 from 83.4% in 2022. Alongside this temporary surplus of energy storage battery capacity, the absence of unified safety standards has also led to a high number of safety incidents.

4.2. Transformation of the industrial structure

New industries, new forms of business, and new models have grown rapidly. From 2021 to 2022, China's GDP grew from 114.4 trillion yuan to 121.0 trillion yuan (Fig. 4b). The value added from the primary industry accounted for 7.3% (on par with the previous year) (Fig. 4d); that of the secondary industry increased to 39.9% from 39.4% (Fig. 4e), and that of the tertiary industry dropped from 53.5% to 52.8% (Fig. 4f). High-tech manufacturing output increased by 7.4% over the previous year, and its share in value-added industrial output increased from 15.1% to 15.5%. New energy vehicle output throughout the year exceeded 7 million, up 90.5% from the previous year, and PV cell output was 340 million kW, up 46.8%.

Vigorous efforts have been made to improve energy efficiency in key sectors and upgrade industry quality. In 2022, the State Council issued the Comprehensive Work Plan for Energy Conservation and Emission Reduction for the 14th Five-Year Plan Period, and the National Development and Reform Commission (NDRC) promulgated the Implementation Guidelines for Energy-Saving and Carbon-Cutting Transformation and Upgrading in Key Areas of Energy-Intensive Industries (2022). The same year, six ministries, including the Ministry of Industry and Information Technology (MIIT), issued the Action Plan for Industrial Energy Efficiency Improvement to promote energy-saving transformation and further pollutant control, with a focus on steel, non-ferrous metals, building materials, and petrochemical industries. By promoting energy-saving technologies such as efficient distillation systems, high-temperature and high-pressure coke dry-quenching (CDQ), and oxygen-enriched smelting, these documents encouraged the transformation of the long-process blast furnace-basic oxygen furnace (BF-BOF) steelmaking into the short-process electric furnace steelmaking. By 2025, more than 30% of production capacity and data centers in key industries such as steel, electrolytic aluminum, cement, flat glass, oil refining, ethylene, synthesis ammonia, and calcium carbide will have reached the energy efficiency benchmarks, and production capacity below the benchmarks will be no more.

Green transition and high-quality manufacturing development have been accelerated amid China's efforts to peak carbon emissions in key industries. In 2022, MIIT, NDRC, and the Ministry of Ecology and Environment (MEE) issued the Implementation Plan for Carbon Peaking in the Industrial Sector, which promoted positive progress in the optimization of the industrial structure and energy use structure during the 14th Five-Year Plan period, with a 13.5% reduction in energy consumption per unit value added of industrial enterprises above a designated size over 2020, and a dramatic decline in carbon intensity in key industries by 2025. During the 15th Five-Year Plan period, industrial energy intensity and carbon intensity will continue to fall, and efforts will be made to peak carbon emissions and cut peak loads, strengthen the capacity for carbon neutrality, and ensure that CO_2 emissions from the industrial sector will peak by 2030. Meanwhile, several ministries jointly issued guidelines for the high-quality development of steel and petrochemical industries and an implementation plan for carbon peaking in building materials and non-ferrous metals industries, providing clearer roadmaps for carbon peaking in key industries. The guidelines require continuous declines in energy consumption and carbon intensity per unit production of cement, glass, and ceramics in the building material industry and more than a 3% reduction in the comprehensive energy consumption per unit cement clinker production during the 14th Five-Year Plan period. According to the document, the industrial structure and energy use structure of non-ferrous metals will be remarkably improved, with the supply of recycled metals reaching more than 24%. The technical structure of the steel industry will be optimized, with the proportion of electric furnace steel production in the total crude steel production increasing to more than 15%, and the comprehensive energy consumption per tonne of steel will be reduced by more than 2%. Energy consumption and carbon emissions per unit production of staple products in the petrochemical industry will drop significantly, with a more than 10% decline in total volatile organic compound (VOC) emissions over the 13th Five-Year Plan period.

Presently, policy documents issued by different ministries have unveiled clear implementation plans for energy conservation and carbon reduction, and roadmaps for transforming specific industries. However, such transformation still faces difficulties and challenges due to the drain of resources caused by the large-scale production of industrial products in China. For example, the green and low-carbon development of many heavy industries is faced with the realities of adjusting to the industrial structure and energy mix, as well as the transformation of production modes. To transform the energy use structure, creating synergy with the clean energy supply system is essential. The transformation of the steel industry from the steelmaking process dominated by the BF-BOF process to the electric furnace steelmaking process requires a sufficient supply of steel scrap. However, the current availability of steel scrap resources is still at a low level, indicating the need to further increase the supply of steel scrap resources.

4.3. Transformation of the transportation structure

In 2022, China's rail cargo volume registered 4.93 billion tonnes, up 4.5% year-on-year; waterway freight volume was 8.55 billion tonnes, up 3.8%; highway freight volume was 37.12 billion tonnes, down 5.5%. The volume of intermodal rail-water container transportation at China's ports reached 8,747,000 TEUs (Twenty-foot Equivalent Units), up 16% year-on-year. In total, 2.68 billion tonnes of coal were transported via railways, up 3.9% from the previous year, and 736 million tonnes of containers were shipped by rail. The fourth batch of 46 multimodal transport demonstration projects and the third batch of 31 urban green freight transportation demonstration projects were launched, and 15 cities worked to shore up weak links in national integrated freight hubs. China saw 1.67 billion railway passenger trips, down 35.9% from the previous year, and 3.55 billion highway passenger trips, down 30.3%.

Green travel continues to make progress. In 2022, a total of 117 cities across China joined the national program to improve public transport, and 46 were recognized as model cities for transit metropolis construction; bus and tram services handled 16.62 billion passenger trips, and urban rail transit systems 18.59 billion trips; 97 cities reached the standards of green travel initiatives, with green trips accounting for more than 70% of all the trips made and green travel service satisfaction rate reaching more than 80%. Green trips in Beijing and Ningbo accounted for about 73.4% and 76.7% respectively.

Energy efficiency in the transportation sector continues to increase. In 2022, two national standards were released, namely the Fuel Consumption for Passenger Vehicles in Operation (GB/T 4353—2022) and the Fuel Consumption for Trucks in Operation (GB/T 4352—2022). The average fuel consumption of passenger vehicles dropped to 4.10 L per 100 km, down 19.6% from a year ago, moving up the timeline for the 2025 target of 4.60 L per 100 km. The comprehensive energy consumption per unit transport workload fell to 3.91 tonnes of standard coal/million converted tonne-kilometer, down 4.2% year-on-year; the fuel consumption per tonne-kilometer for civil aviation was 0.302 kg, down 11.4% from 2005.

Steady progress has been made in clean energy substitution. In 2022, China's new energy vehicle (NEV) ownership reached 13.1 million, of which 79.78% were battery electric vehicles (BEVs); NEV production and sales were 7,058,000 and 6,887,000 respectively, up 96.9% and 93.4% year-on-year, with a market share of 25.6%. Driven by a cleaner electricity mix, more optimized power consumption for electric car drives, a lower carbon footprint of key vehicle materials, and a higher energy density of batteries, BEVs' lifecycle carbon emissions were 40% less than traditional gasoline cars in 2020 and is expected to improve to 53% by 2030. China's charging infrastructure saw nearly 100% year-on-year growth, bringing the total number to 5.2 million units, and 17,581 charging piles had been installed in 4145 expressway service areas. The proportion of electrified railways in China was 73.8%, with 14,200 electric locomotives accounting for 64.2%. Airports across the country were equipped with 12,000 electric vehicles, accounting for 24% of the total, and 5200 recharging facilities, with electricity, natural gas, and purchased heat accounting for 82.8% of all the energy used; all the airports with an annual passenger throughput of more than 5 million had installed and put into use APUs (Auxiliary Power Units) as an alternative. Power-receiving facilities were installed on nearly 5200 ships, leading to a significant increase in shore power consumption; pilot programs such as inland river battery-powered ships and ocean-going methanol-powered ships continued to emerge.

Management toward the "dual carbon goals" continues to intensify. In 2022, China further perfected its transportation policy management system, covering policies, standards, and monitoring. For example, policy documents such as the Implementation Opinions of the Ministry of Transport, the National Railway Administration, the Civil Aviation Administration of China, and the State Post Bureau on Implementing the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy, and the 14th Five-Year Plan for the Green Development of the Postal Industry were issued. The Green Transportation Standards System (2022) was promulgated, and standards such as the Limits and Measurement Methods of Fuel Consumption for Natural Gas Commercial Vehicle for Passenger Transportation and the Energy Efficiency Grade and Evaluation Method of Main Electric Equipment for Highway Mechanism and Electrical Facilities were released. Statistical systems were also introduced, including the Administrative Measures for Energy Consumption Data and Carbon Intensity of Ships and the Interim Measures for the Administration of Monitoring, Reporting, and Verification of Carbon Dioxide Emissions from Civil Aviation Flights.

Moving forward, China should continue to work to promote the high-quality development and green and low-carbon transformation of transportation, further optimize the structure of energy consumed in the transportation sector, improve the energy efficiency of transportation equipment, optimize the transportation structure, and increase the efficiency of transportation organizations. In addition, efforts should be made to enhance the effective supply of infrastructure and accelerate the establishment of green and low-carbon modes of transportation. It is also necessary to further step up the development of a comprehensive national transport network, facilitate a shift in bulk cargo transportation and mid-long distance freight transportation from highways to railways and waterways, apply new energy and clean energy, raise the energy efficiency standards for fuel-powered transportation equipment; implement the national program to improve public transport; guide green travel, and build and adapt to an infrastructure system for electrified transportation.

4.4. *Low-carbon transition of building energy systems*

In 2021, carbon emissions from buildings in operation totaled 2.2 billion tCO_2, of which direct carbon emissions from fossil fuel combustion in buildings maintained a downward trend, accounting for 23% of the total (Fig. 5). In 2021, electricity consumed in the operation of buildings in China increased significantly to 2.2 trillion kWh, and indirect CO_2 emissions from power consumption grew to 1.24 billion tonnes, accounting for 57%. Total energy consumption by heating in northern cities peaked around 2017, and in recent years, with the adjustment of the energy mix, indirect carbon emissions from heat have shown a downtrend year by year, which accounted for 20% in 2021.

To realize carbon peaking and carbon neutrality goals, the

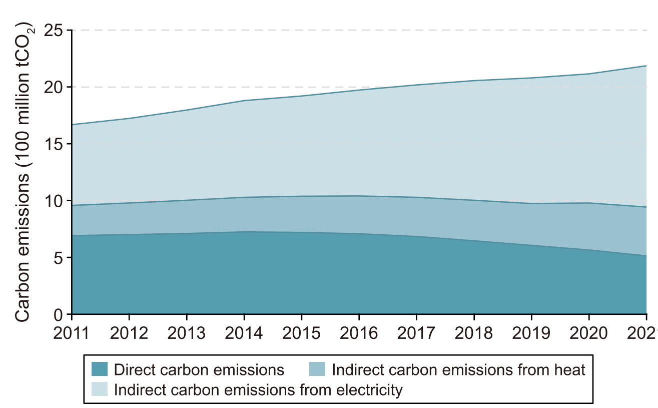

Fig. 5. Annual carbon emissions from the operation of buildings in China (2011—2021).

building sector should not only focus on improving building energy efficiency but gradually shift its priority from "energy-efficient buildings" to "lower-carbon buildings" in line with the changes in the circumstances. The CO_2 reduction targets and tasks set out in the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy, the Action Plan for Carbon Dioxide Peaking Before 2030, as well as the Implementation Plan for Carbon Dioxide Peaking in Urban-Rural Development and other documents issued by the Ministry of Housing and Urban-Rural Development (MOHURD) and NDRC, are generally divided into two parts: elimination of direct emissions and reduction of indirect emissions.

First, fully electrified design will be promoted in new buildings to eliminate direct emissions from buildings. Full electrification can be implemented first in public buildings and then residential buildings, first in cities and then in rural areas, to eradicate direct emissions from the source. By 2030, 20% of the new public buildings in cities will be fully electrified. Secondly, electric energy substitution will be promoted in existing buildings, including heating, domestic hot water, and cooking. Domestic hot water, gas water heaters, and steam heating systems will be replaced with distributed electric water heaters and efficient electric heat pumps. Thirdly, electric energy substitution in cooking. Focusing on public buildings, efforts will be made to develop and promote efficient electric cooking appliances and carry out active publicity and guidance so that residents can gradually change their cooking habits and get to know, accept, and use electric cooking appliances. By guiding the electrification of heating, domestic hot water, and cooking in buildings, China will increase the proportion of electricity consumption in building energy consumption to more than 65% by 2030.

To reduce indirect emissions from buildings, efficiency will first be improved, thus minimizing the energy consumption and carbon emissions required to meet the functional requirements of buildings and living quality. Second, the energy mix will be optimized for low-carbon electricity and heat consumption. Developing a new electricity system dominated by wind and PV power is mainly restricted by spatial resources, dispatching & storage, and flexible energy use resources. Hence, it is essential to tap the spatial resources in buildings fully to develop and utilize distributed PV systems. Thirdly, the mode of development will be changed. It is necessary to fully recognize the importance of buildings in the low-carbon transition of energy, give way to the role of buildings as a producer, dispatcher, storehouse, and consumer in the new electricity system, and take into account the entire power source-grid-load-storage-consumption chain.

4.5. CCUS technologies

Breakthroughs have been made in CCUS technologies with China transitioning to the next generation carbon capture technologies and conducting beneficial exploration in negative emission technologies such as biomass energy capture (BEC) and direct air capture (DAC), and achieving results in the R&D of key technologies such as high-performance adsorbents and preparation of absorbing materials. Carbon transportation technologies are transitioning from conventional tanker and ship transportation to onshore and submarine pipeline transportation. For example, Sinopec is building China's first long-distance supercritical CO_2 transportation pipeline as part of its Qilu Petrochemical-Shengli Oilfield CCUS Project. New CO_2 utilization technologies, such as the one-step synthesis of ethanol from CO_2 developed by a research team from Jiangnan University [30], are also emerging. In terms of CO_2 storage, China has begun to explore the feasibility of offshore CO_2 storage. For example, CNOOC has completed China's first offshore CO_2 storage demonstration project, enabling key devices for offshore CO_2 storage to be fully homemade.

While progressing, China's CCUS technologies are also experiencing rapid demonstration and application, with marked improvements in quantity, size, and industry coverage. They are transitioning from application in a single area to comprehensive demonstration in different areas. According to available statistics, as of the end of 2022, CCUS demonstration projects put into use and under planning or construction amounted to nearly 100, almost double the number in the previous year. Of these projects, about half had been put into use, with a capture capacity of some 4 million tonnes year^{-1} and an injection capacity of some 2 million tonnes year^{-1}, an increase of around 1/3 and 2/3, respectively, from the previous year. The scale of such projects has also increased; for example, China's first million-tonne CCUS project, the Qilu Petrochemical-Shengli Oilfield Project, was officially put into operation in August 2022; China Huaneng Group and CNPC are also building or planning million-tonne demonstration projects. In terms of industry applications, CCUS demonstration projects put into operation or under planning or construction in China have covered electricity, oil & gas, petrochemicals, building materials, steel, and various other industries. For example, the first CCUS demonstration project in China's steel industry commenced at Baogang Group, and the world's first glass furnace CO_2 capture demonstration project, built by China National Building Material Group Co., Ltd., has been completed and put into service.

Given the demonstration projects that have been put into operation, although China's CCUS technologies are still costly, they show a certain cost advantage over their foreign counterparts, which is growing amid China's practice of "learning by doing". Integrated oil displacement demonstration projects in China's coal, chemical, and petrochemical sectors feature relatively low capture costs, which can be as low as CNY 105 per tonne of CO_2. The electricity and cement industries in China see high capture costs, standing at CNY 200–600 and CNY 305–730 per tonne of CO_2, respectively, both generally below the average of foreign countries. With ongoing technological improvements, CO_2 capture costs are expected to decline further. For instance, CHN Energy reduced the total capture costs to CNY 300 tonne^{-1} and the comprehensive capture energy consumption to 2.35 GJ tonne^{-1} in the "150,000 tonne year^{-1} post-combustion CO_2 capture demonstration project" of Jinjie Power Plant, and the costs and energy consumption are expected to be further reduced in the subsequent 500,000 tonne year^{-1} coal power CCUS project of CHN Energy's Taizhou Power Plant.

With the establishment of a "1+N″ policy system for carbon peaking and carbon neutrality, CCUS technologies have received much attention [31]. Apart from support for the R&D and demonstration of CCUS technologies, there are a growing number of policies involving related technical standards. For example, the *Implementation Plan for Accelerating the Establishment of a Unified and Standardized Carbon Emissions Measuring and Counting System* and the *Action Plan to Standardize Carbon Peaking and Carbon Neutrality in Energy* propose to improve and push forward the standards system for CCUS technologies and related research. Meanwhile, the application of CCUS technologies in industrial sectors with difficulty cutting emissions has been given greater emphasis. For example, documents such as the Implementation Plan for Carbon Peaking in the Industrial Sector and the Implementation Plan for Synergizing the Reduction of Pollution and Carbon Emissions have set CCUS application targets for industrial sectors with difficulty cutting emissions, including steel and cement.

Despite the rapid development of CCUS technologies and demonstration and related policies in China, challenges such as high application costs, lack of effective business models, and difficulty in matching sources and sinks have put a certain distance between these technologies and large-scale commercial operations. Future planning and deployment should consider technologies, policies, and markets, among other factors.

4.6. New electricity system

The share of installed new energy capacity continued to increase at the end of 2022; China's installed capacity of wind and PV power was 365 and 393 million kW, respectively, both ranking first in the world. The provinces of Shandong, Jiangsu, and Zhejiang witnessed a sharp increase in the installed capacity of distributed PV power projects, and Nei Mongol and Xinjiang saw rapid growth in installed new energy capacity, at 39% and 36%, respectively. It is worth mentioning that since NDRC proposed a plan for the construction of massive wind and solar power projects in the Gobi Desert and other arid regions in 2021, projects with a combined capacity of over 200 GW are currently under construction there. It is estimated that by 2030, China's total installed capacity of wind and PV power will top 1.2 billion kW, or 50% of the total installed capacity, and provide 20–26% of the country's total electricity output, which was 13.8% in 2022. In Nei Mongol, the installed new energy capacity will exceed 200 million kW, or 70% of the total, and provide more than 50% of the region's total electricity output.

The level of new energy accommodation continues to improve. In 2022, China's average consumption rate of wind power was 96.8%, and that of solar PV power was 98.3%, while the nationwide wind and PV power curtailment was 23.4 and 64.1 billion kWh respectively. The figures are down 8.8% and 4.3%, respectively, from 2017, indicating a significant improvement in new energy accommodation. To meet the needs of building a new electricity system and the large-scale and high-proportion development of new energy, the share of pumped storage hydropower (PSH) and other flexible power sources in the electricity system will be significantly increased. As of the end of 2022, the cumulative installed capacity of PSH reached 45.19 million kW, up 24.18% from 2021. According to the Mid- and Long-term Development Plan for Pumped Storage Hydropower (2021–2035), China's installed capacity of PSH is expected to reach 120 million kW by 2030. Moreover, new energy storage technologies, such as advanced compressed air energy storage, sodium-ion battery energy storage, lithium-ion battery energy storage, and flow battery energy storage, are expected to further enhance the system's ability to accommodate new energy.

The structure of China's power system has been gradually optimized. Based on China's national conditions and resource endowments, the electricity flow distribution to transmit electricity from the west to the east and from the north to the south continues to intensify. New energy development will combine centralized and distributed projects. Regarding grid construction, 101.17 million kW of newly installed power capacity was put into operation nationwide in 2022, including 9.71 million kW of hydropower, 90.48 million kW of thermal power, and 0.92 million kW of wind power. Furthermore, 35,100 km of transmission line circuits of 220 kV or above and 155.31 million kVA of power transformation equipment of 220 kW or above were put into service, enabling large-scale optimal allocation of energy resources in China.

4.7. Pollution control

(1) Upgrading of coal-fired power plants to ultra-low emissions. Since 2015, China has implemented upgrading coal-fired power plants to ultra-low emissions on a large scale to bring their pollutant emissions to the levels of gas-fired power plants. As of the end of 2022, 94% of coal-fired generating units were upgraded to ultra-low emissions, with a combined capacity of 1.05 billion kW, an increase of nearly 20 million kW from 2021 (Fig. 6, the following seven sections the same).

(2) Intensified management of non-power sectors. Since 2013, China has developed and revised emission standards for cement, petrochemical, coating and ink, pharmaceutical, and other sectors; stepped up the management of industrial furnaces and kilns; and launched the retrofitting of the steel sector to achieve ultra-low emissions. As of the end of 2022, a total of 207 million tonnes of crude steel production capacity was upgraded to ultra-low emissions in the whole process of steel production, and 480 million tonnes of capacity was upgraded for key links of the production process, such as desulfurization and denitrification of sintering and pelletizing, and enclosed raw material yards, together taking up two-thirds of China's total crude steel production.

(3) Control of volatile organic compounds. Since the beginning of the 13th Five-Year Plan period, China has quickly advanced its work on VOC prevention and control by successively unveiling and improving a range of industry and product emission standards and related policy documents for controlling such emissions. As of the end of 2022, China had rectified more than 46,000 prominent problems concerning VOCs.

(4) Improvement of coal-fired boilers. From 2013 to 2022, the number of coal-fired boilers across the country declined from 520,000 to less than 100,000, and coal-fired boilers below 35 $t\ h^{-1}$ were obsoleted.

(5) Rural clean heating. Since 2017, China has vigorously implemented pilot clean winter heating in its northern part. As of the end of 2022, pilot clean winter heating had covered 88 cities nationwide, and bulk coal control was completed among 35 million rural households; clean heating covered an area of 17.9 billion square meters in northern China, with a clean heating rate of 75%.

(6) Control of emissions from mobile sources. China has gradually tightened emission standards for motor vehicles and phased out high-emission vehicles. Since July 1, 2020, the national VI emission standards have been enacted nationwide; gasoline and diesel for vehicles meeting the national VI emission standards have been supplied; and diesel for vehicles, regular diesel, and fuel oil for some ships have been regulated uniformly. Since July 1, 2021, the national VI emission standards for heavy-duty diesel vehicles have been fully implemented nationwide. Since 2012, more than 30 million high-emission and old vehicles have been removed from the roads, and more than 47,000 inland river ships have been dismantled and retrofitted. The regulation over whether diesel vehicles meet environmental protection standards has been fully strengthened with random inspections by randomly selected staff and prompt release of inspection results having been carried out among vehicle inspection and testing organizations for five consecutive years, resulting in six auto enterprises being urged to recall vehicles for environmental purposes.

(7) Comprehensive management of agriculture. Since China explicitly proposed vigorously promoting soil testing and formula fertilization, the technology has been applied to 1.93 billion mu of land. Open-air burning of straw has been effectively controlled. In 2022, 662 million tonnes of crop stalks were utilized comprehensively nationwide, up 2.3% year-on-year.

(8) Comprehensive dust control. With the gradual intensification of urban and rural environmental management, dust

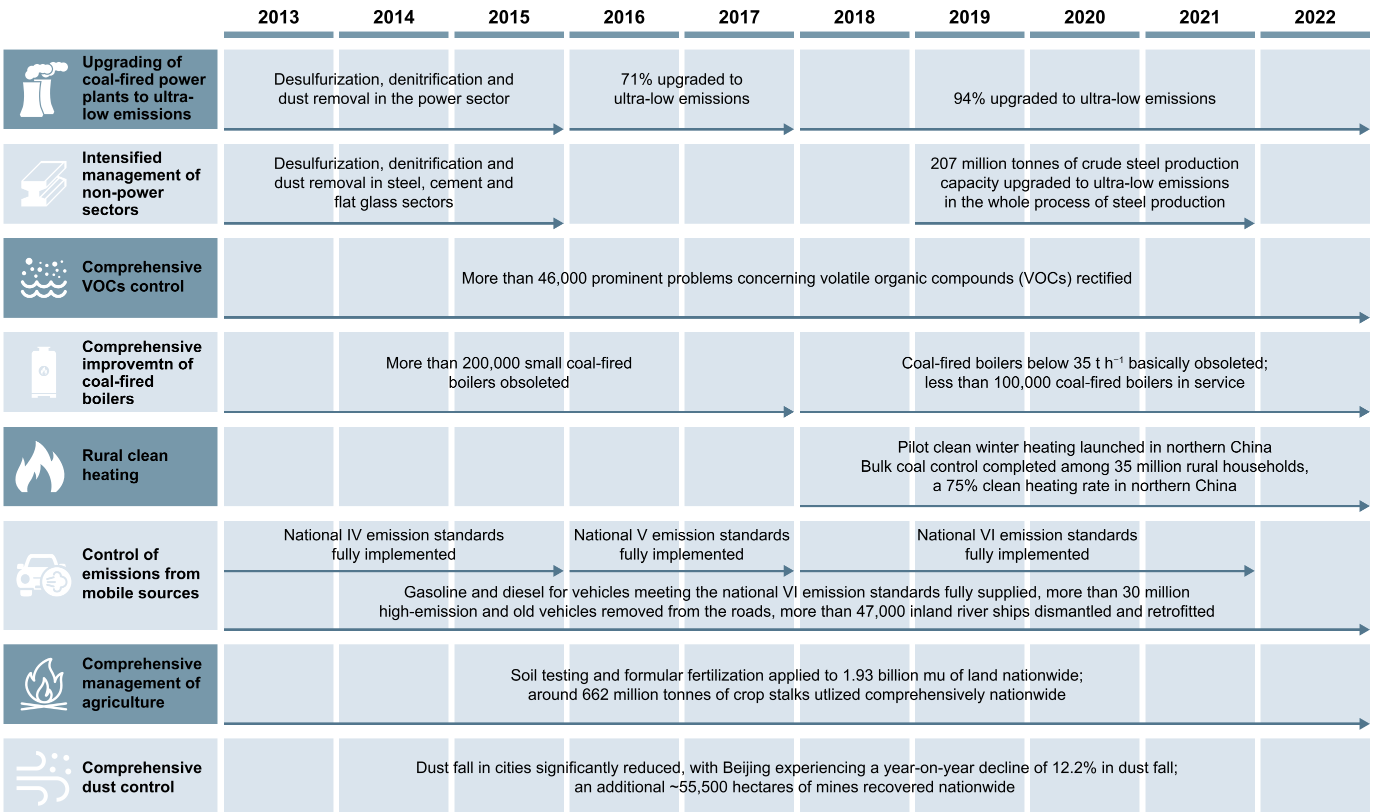

Fig. 6. Progress in pollution control indicators from 2013 to 2022. This figure is adapted from Ref. [27, 28].

control has been included as one of the key areas of atmospheric pollution prevention and control. It has been pushed ahead in areas such as construction, roads, storage yards, bare land, and mines. In 2022, dust fall in cities was significantly reduced nationwide, with Beijing experiencing a year-on-year decline of 12.2% in dust fall; an additional 55,500 ha of mines were recovered nationwide.

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

Since air pollutants and CO_2 emissions originate from similar sources, implementing policies to address climate change would improve air quality and provide considerable health co-benefits. In the future, the structural transformation of energy, industry, and transportation will become the focus of the synergistic governance for carbon neutrality and clean air in China. This section examines the current progress of synergistic abatement of pollutants and CO_2 emissions across various regions and sectors in China and assesses the potential contributions of carbon sequestration by terrestrial ecosystems to achieving carbon peak and carbon neutrality goals. Additionally, regional and sectoral disparities in synergies between carbon control and pollution abatement are analyzed to highlight the need to identify key sectors and develop a strategic synergetic roadmap tailored to each region.

5.1. Anthropogenic CO_2 emissions

Estimating anthropogenic CO_2 emissions plays an important role in the synergistic abatement of pollution and carbon emissions. Most provinces in China exhibited a fluctuating but overall upward trend in CO_2 emissions from 2005 to 2020 (Fig. 7). The power sector was the leading contributor to emission increases in most provinces, especially in northwest provinces (e.g., Xinjiang, Nei Mongol, Ningxia, and Shanxi). The industrial sector played a key role in the increase in emissions in central provinces (e.g., Hebei, Henan, and Sichuan). The decline of carbon emission intensity in China reflected the decoupling of carbon emissions from economic growth to achieve carbon neutrality [32]. For most provinces, the CO_2 emission intensity continuously declined from 2005 to 2020, except for Ningxia and Xinjiang. Over 80% of provinces (25 in total) met their targets of CO_2 emission intensity reductions. At the city level, from 2005 to 2015, 31 Chinese cities achieved strong decoupling (i.e., achieving economic growth accompanied by a decline in CO_2 emissions), while 185 cities achieved weak decoupling, where the growth rate of CO_2 emissions was lower than the economic growth rate [33]. This underscores the critical role of prior decarbonization efforts and further endeavors to reverse CO_2 emissions and meet future climate targets.

5.2. Land use change and land carbon sinks

Enhancing the carbon sequestration capacity of terrestrial ecosystems is considered an effective measure to reduce atmospheric CO_2 concentrations and mitigate climate change. Land use changes (e.g., forest area expansion) contributed to ~44% of China's terrestrial ecosystem carbon sinks, which have cumulatively sequestered about 8.9 ± 0.8 Pg C during 1980–2019 and still shows an increasing trend [37–39]. Currently, the majority of forest areas are composed of middle-aged and young forests, with a stronger carbon sequestration capacity compared to mature forests [40,41]. The maximum potential of China's terrestrial carbon sinks is about 0.16

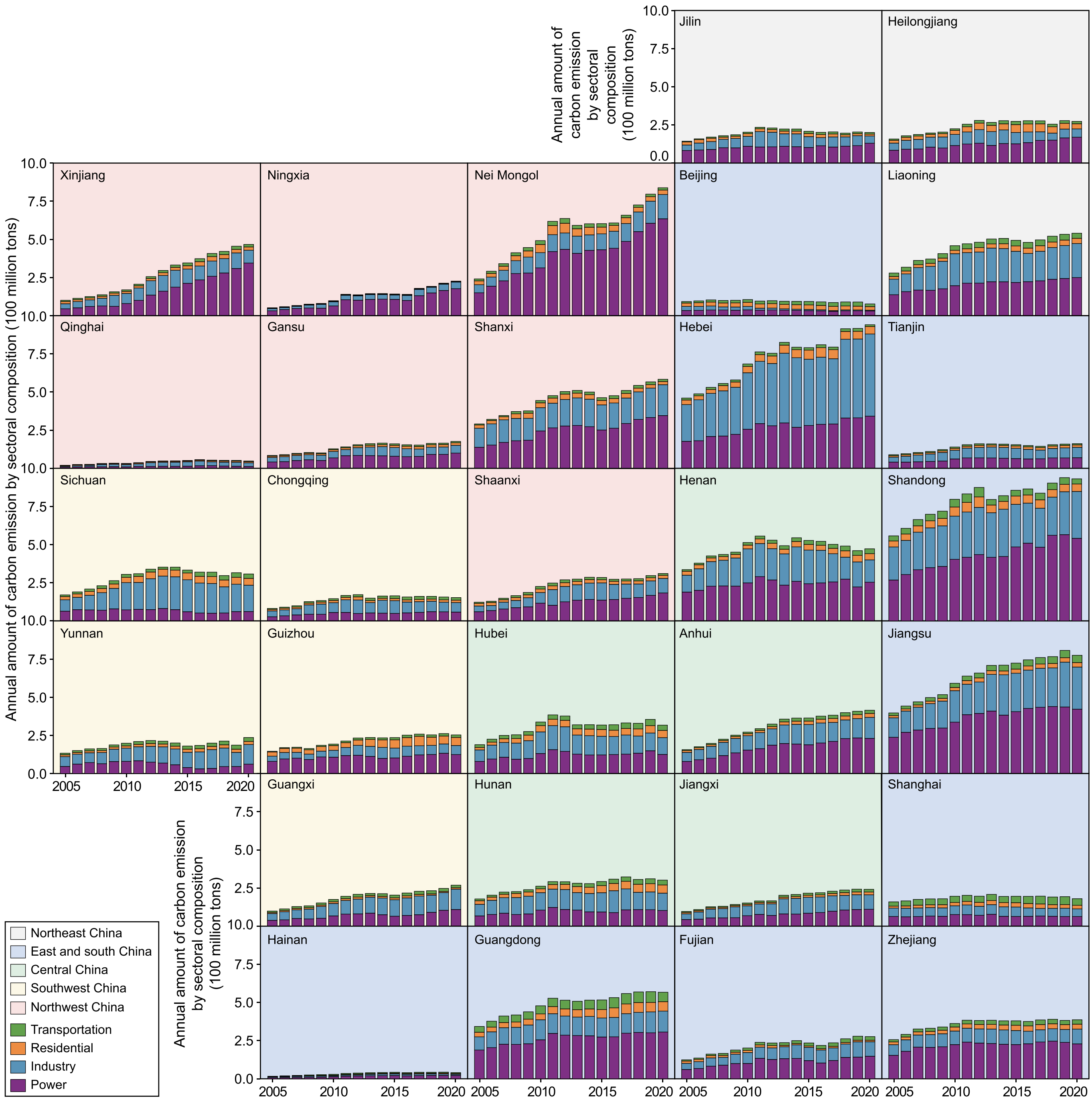

Fig. 7. China's regional carbon emissions and sectoral composition from 2005 to 2020 [33–36].

(0.08–0.27) Pg C $year^{-1}$ between 2020 and 2030 and is about 0.27 (0.16–0.38) Pg C $year^{-1}$ between 2020 and 2060 [42], which could be achieved by comprehensive land use planning based on precise land survey data and ecological principles. There is a pressing need to enhance the monitoring of terrestrial ecosystems and their carbon sinks, improve ecosystem management processes in land carbon models, and advance integrated systems for remote sensing and data fusion.

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

The synergistic abatement of CO_2 emissions and $PM_{2.5}$ air pollution exhibited substantial heterogeneity across various sectors and processes. For example, the coal combustion process in industrial and residential sectors showed notably positive synergistic effects in CO_2 emissions and $PM_{2.5}$ pollution reductions between 2015 and 2021 due to implementing the "coal-to-gas" policy. For the transportation sector, non-road machinery showed synergies between carbon control and $PM_{2.5}$ abatements from energy efficiency improvements, while road traffic decreased $PM_{2.5}$ pollution but increased CO_2 emissions by around 17%. When it comes to the power and heating sectors, the rising generation of coal power increased CO_2 emissions from the power and heating sector by over 30% (about 130 Mt), despite stringent emission standards that succeeded in air quality improvement.

Disparities exist in the synergies between carbon control and $PM_{2.5}$ abatements across different provinces during 2015–2021 (Fig. 8). As for the coal combustion process, over one-third of provinces achieved positive synergies in CO_2 emissions reductions and $PM_{2.5}$ pollution mitigation (Fig. 8a). Benefitting from the implementation of coal substitution, most provinces (other than Jiangsu, Jiangxi, and Xinjiang) have seen positive synergistic effects in the residential sector (Fig. 8g). However, the power and heating sector in most provinces showed negative synergies, marked by a sharp rise in CO_2 emissions (Fig. 8d). As for the coal combustion process of the industrial sector, an average rise of ~15% in CO_2 emissions was observed in the heavily industrialized provinces. When it comes to the gas combustion process, most provinces are experiencing increased CO_2 emissions in the power and heating, industrial and residential sectors, with a slight rise (~0.01 μg m^{-3}) in $PM_{2.5}$ pollution as gas becomes a substitute for coal to achieve carbon peak and air quality standards (Fig. 8e–h, and k). This suggests that future synergistic control of the gas combustion process is necessary to achieve long-term carbon neutrality goals as its usage expands.

5.4. Future mitigation potentials and synergetic pathway

Due to disparities in energy and industrial structures, the synergetic effects of air pollutant emissions reductions vary across regions under the carbon neutrality goal [43]. Beijing–Tianjin–Hebei and the surrounding regions would face challenges in synergistic pollutant emissions controls due to the large proportion of hard-to-abate industry (e.g., iron and steel, cement). The fossil energy share in this region is projected to remain at 75.2%

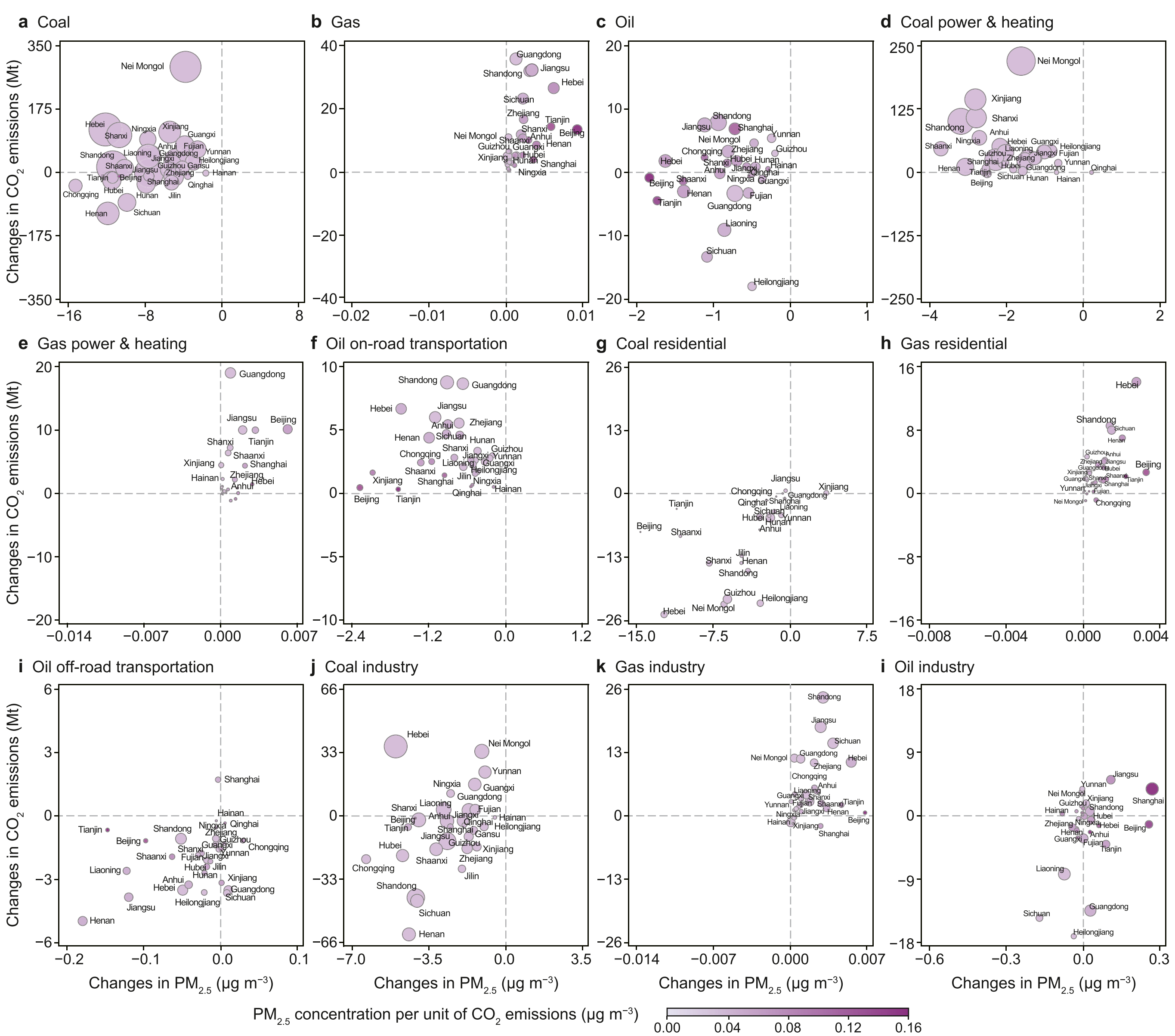

Fig. 8. Coordinated control of CO_2 emissions and $PM_{2.5}$ pollution in each sector of each province from 2015 to 2021.

and 43.6%, with $PM_{2.5}$ exposures at 35.0 and 14.4 μg m^{-3} by 2030 and 2060, respectively. In contrast, the Pearl River Delta (PRD) region, with lower fossil energy share and carbon intensity currently, will have fossil energy shares of 43.9% and 15.9%, with $PM_{2.5}$ exposure levels reduced to 11.3 and 4.5 μg m^{-3} by 2030 and 2060, respectively [44].

Similarly, the potential for synergies between carbon control and $PM_{2.5}$ abatement differs among various sectors. SO_2 and NO_x emissions from thermal power plants in the eastern and southern regions will be reduced by over 50% if renewable and nuclear energy penetration rate increases to 80% by 2050 [45]. Strategic retirements and pollution controls for thermal power plants could avoid more than 200,000 premature deaths due to air pollution from power generation in a 1.5 °C scenario [46]. For other sectors, increasing terminal electrification levels helps achieve positive synergistic effects. Taking the iron and steel industry as an example, the application of electric arc furnaces in the green power grids can remarkably improve energy efficiency and reduce the emissions of major air pollutants (i.e., NO_x, SO_2, and $PM_{2.5}$) by more than 80% before 2060 [47]. Therefore, the power sector needs to shift to low-carbon sources and expand its capacity and flexibility to promote a green transition towards carbon neutrality, considering potential increases in power demand due to electrification.

6. Health impacts and benefits of coordinated control

6.1. Air pollution and related health impacts

The long- and short-term exposure levels of $PM_{2.5}$ for residents in China have been decreasing. According to data from TAP (http://tapdata.org.cn/), the national population-weighted annual average $PM_{2.5}$ exposure concentration was 31.2 μg m^{-3} in 2022, similar to 2021, and down 40.8% from 52.8 μg m^{-3} in 2015. Key areas showed $PM_{2.5}$ levels between 19.7 and 44.7 μg m^{-3}, a 31.9–49.1% decrease from 2015. The Beijing–Tianjin–Hebei region had the most significant improvement, followed by the Yangtze River Delta (43.1%). In 2022, about 38.3% of the population lived in areas exceeding the national secondary $PM_{2.5}$ standard, a decrease of 37.5 percentage points from 2015. The percentage of people in Beijing–Tianjin–Hebei exposed to excessive $PM_{2.5}$ dropped from 94% in 2021 to 88%, while the proportions increased in Fenwei Plain, the Yangtze River Delta, and Chengdu–Chongqing areas. Short-term $PM_{2.5}$ exposure has also improved, with the national population-weighted days of $PM_{2.5}$ exceedance (daily $PM_{2.5}$ > 75 μg m^{-3}) at 24 days in 2022, 50.5 days fewer than in 2015 (Fig. 9). However, long- and short-term O_3 exposure increased in some regions. The national population-weighted average long-term O_3 exposure (annual maximum 8-h concentration for the peak 6 months) rose by 6.2 μg m^{-3} (6%) in 2022 compared to 2021. Key regions saw O_3 exposure rise by 15.6–24.3% from 2015, with the Fenwei Plain showing the most significant increase (12.3 μg m^{-3}). Short-term O_3 exposure, defined as days with a maximum 8-h O_3 concentration above 160 μg m^{-3}, averaged 21.9 days in 2022, 14.9 days more than in 2015 (Fig. 9). NO_2 exposure levels in China continued to decline. In 2022, the national population-weighted annual average NO_2 concentration was 25.73 μg m^{-3}, down 43.38% from 2013 to 25.77% from 2017, though still above the World Health Organization's Air quality guidelines (WHO's AQG) benchmark (10 μg m^{-3}). Daily NO_2 concentrations exceeded the WHO's AQG (25 μg m^{-3}) for 132 days, 169 days fewer than in 2017. Nonetheless, NO_2 remains a primary air pollutant affecting public health.

$PM_{2.5}$ exposure is a significant health risk factor, increasing the risk of diseases like stroke, ischemic heart disease, COPD (chronic obstructive pulmonary disease), lung cancer, type 2 diabetes, and respiratory infections, leading to premature mortality [48]. Due to reduced $PM_{2.5}$ exposure, adult premature deaths linked to $PM_{2.5}$ declined, with 1.2 million (95% CI: 1.07–1.34 million) long-term exposure deaths and 60,000 (95% CI: 40,000–80,000) short-term exposure deaths in 2022—a decline of 17.5% and 35.6% from 2015 [49] (Fig. 10). Research suggests that O_3 exposure poses independent health risks, with 150,000 (95% CI: 70,000–230,000) premature deaths from long-term exposure and 80,000 (95% CI: 50,000–120,000) from short-term exposure in 2022. While lower in total than $PM_{2.5}$, O_3-related deaths have increased since 2021 by 11.1% for long-term and 9.7% for short-term exposure (Fig. 10).

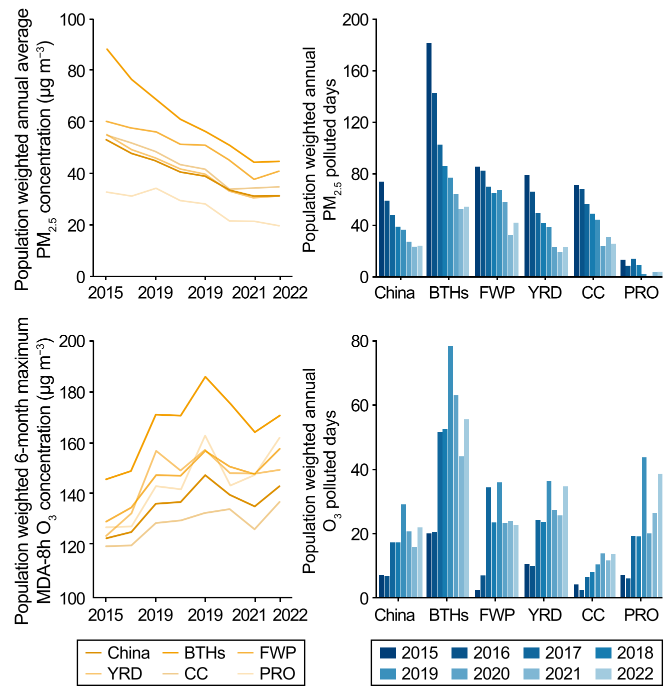

Fig. 9. The changes in long-term and short-term exposure levels of $PM_{2.5}$ and O_3 pollution in China from 2015 to 2022. BTHs Beijing–Tianjin–Hebei and its surrounding regions; FWP: Fen–Wei Plain; YRD: Yangtze River Delta; CC: Chengdu–Chongqing area; PRD: Pearl River Delta. This figure is adapted from Ref. [27].

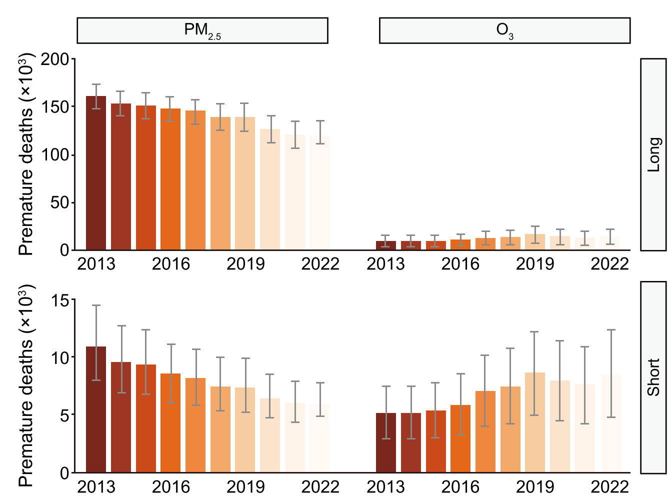

Fig. 10. The number of premature deaths among adults in China attributed to short-term and long-term exposure to $PM_{2.5}$ and O_3 from 2013 to 2022. This figure is adapted from Ref. [28].

Meta-analyses and global multicenter studies demonstrate that short-term exposure to NO_2 is associated with increased risks of daily all-cause mortality and mortality from cardiopulmonary disease [50,51], and that short-term NO_2 exposure poses an independent acute health hazard to residents [50]. To mitigate the impact of NO_2 on public health, effective air pollution prevention and control measures should be implemented in China. Based on the results of a study on the exposure-response relationship in 272 major cities in China [52], the estimated number of non-accidental deaths, deaths from cardiovascular diseases, and deaths from respiratory diseases in 2022 are 50,400 (95% CI: 39,200–61,600), 24,800 (95% CI: 19,300–33,100), and 5700 (95% CI: 4300–7200), respectively. Compared to the period from 2013 to 2020, the number of deaths associated with short-term NO_2 exposure exhibited a decreasing trend in 2022.

6.2. Climate change and health effects

The increase in frequency and intensity of extreme weather events directly results from climate change, posing significant health risks. In July 2017, a nationwide heatwave raised overall mortality risk by 23% (95% CI: 14–32%), and in 2021, heatwave exposure in China increased by 7.85 days, causing 13,185 additional deaths and economic losses equal to 1.68% of GDP [53]. Heat exposure contributed to 2.71% of non-accidental deaths from 2013 to 2015 and increased accidental mortality risk by 0.50% for every 1 °C rise between 2013 and 2019 [54,55]. In July 2017, heatwaves caused over 16,000 deaths and economic losses of 61.3 billion yuan [56,57]. Long-term heat exposure raises mortality risk by 2.93% (95% CI: 2.68–3.18%), disproportionately affecting low-urbanization areas [58].

Extreme weather events like cold spells, typhoons, and dust storms also increase mortality risk. Cold spells raise accidental death risk by 15.5%, causing 57,783 deaths and 229.1 billion yuan in losses [59], while typhoon exposure increases all-cause mortality by 7% [60]. Dust storms in Gansu elevate ischemic heart disease risk, with relative risks ranging from 1.105 to 1.183 [61]. Ozone pollution causes over 90,000 deaths annually in China and threatens food security, potentially reducing wheat and rice yields by up to 32.6% [62].

Adaptive measures are essential. Programs like the Heat Wave Intervention Program (HWIP) in Jinan City lowered heat-related disease prevalence (odds ratio, OR $= 0.495$, $p < 0.01$) [63]. Adaptation measures could offset 10% of future heat-related labor losses [64]. Successful global strategies, like the French heat warning system, saved 4388 lives in 2006 [65]. In 2022, Jinan's heat warnings prevented health losses worth 106 million yuan [66]. Urban green spaces also improve health, reduce pollution, and support "Healthy China" goals [67].

Future scenarios predict worsening impacts. Without mitigation (RCP8.5), heat-attributable deaths will rise to 2.4% by 2030, 3.2% by 2050, and 5.5% by 2090, with faster growth in southern, eastern, and central China [68]. Even under low-emission scenarios, deaths could be 1.6 times higher than historical levels [69]. Air pollution will also worsen, with $PM_{2.5}$ and ozone increasing by 3% and 4%, causing 12,100 and 8900 additional deaths by 2050 [70]. By the end of the century, compound events involving heatwaves and ozone pollution will become more frequent, increasing exposure days by 36.7 in China, affecting eastern areas the most [71].

6.3. Health co-benefits of greenhouse gas mitigation and air quality improvement

The carbon neutrality goal profoundly influences the joint governance of greenhouse gases and air pollutants. It emphasizes the potential of energy policies to reduce emissions and improve public health by scientifically addressing health benefits and economic impacts.

Climate change and rising ozone levels increase extremely high temperatures and heatwaves, heightening mortality risks, particularly for susceptible populations with underlying health conditions [72,73]. This evidence suggests that coordinated ozone and climate change management could yield considerable health benefits.

A study of 9727 hypertensive deaths in Jiangsu (2016–2017) found that high summer temperatures shortened life spans by 1474 years, with 77.9% due to hypertensive heart disease [72]. In Pudong, Shanghai (2008–2017), COPD mortality risk rose in summer, with a risk ratio of 1.02 (95% CI: 1.00–1.03) for every 10 $\mu g\ m^{-3}$ increase in ozone concentration [73].

Current mitigation policies are projected to reduce $PM_{2.5}$ levels to 27.6 $\mu g\ m^{-3}$ by 2030. Stricter policies could decrease concentrations by 10.2–16.3 $\mu g\ m^{-3}$ by 2030 and 12.5–25.4 $\mu g\ m^{-3}$ by 2050 [74], potentially avoiding up to 210,000 premature deaths by 2030 and 537,000–880,000 by 2050 [74–76]. Acute myocardial infarction cases could drop by 10.6–46.2%, reducing to 5880–9760 cases [77]. Despite $PM_{2.5}$ reductions, population aging will increase premature deaths by 125% (1.69 million cases) by mid-century as the over-70 population grows from 10% to 30% [78].

Rising vehicle ownership will increase emissions. Policies promoting electric vehicles, emission standards, and green transport could avoid 6400–18,500 premature deaths by 2050. Decarbonizing the power sector alongside clean vehicle initiatives could prevent 100 additional deaths [79]. Clean vehicle policies alone would reduce $PM_{2.5}$ and O_3 by 9.4% and 4.4% by 2035, avoiding 68,000 and 33,000 premature deaths [80]. Electric vehicle adoption combined with decarbonized power could prevent 15,500 premature deaths by 2030, yielding health benefits of 70–170 billion yuan [81].

High temperatures will also drive economic burdens. By 2050, labor loss in the Yangtze River Delta could exceed 7%, costing 0.20–0.25% of GDP from 2050 to 2100 (He et al., 2022). Adaptive strategies could reduce labor loss and offset 10% of these economic costs, particularly in the Yangtze River and Pearl River Deltas.

7. Summary and recommendation

The report outlines China's progress in integrating carbon neutrality and clean air strategies under a synergetic governance framework. Key achievements include significant reductions in $PM_{2.5}$ levels and advances in renewable energy adoption. However, challenges remain, such as rising ozone levels and regional disparities in achieving synergies between carbon reduction and air pollution control. Efforts in structural transformation across energy, industry, transportation, and building sectors are noted, with innovations in renewable energy, green transportation, and carbon capture, utilization, and storage (CCUS) technologies playing pivotal roles. The report highlights the health co-benefits of reduced air pollution but stresses the need for ongoing adjustments to address persistent pollutants like ozone and nitrogen dioxide.

To address the integration of carbon neutrality and air quality goals, China should focus on aligning climate and pollution control policies, ensuring mutual reinforcement rather than trade-offs. Tailored strategies should address regional disparities, emphasizing local industrial and energy structures. Accelerating renewable energy deployment and improving grid stability are critical, alongside fostering innovation in CCUS and sectoral electrification to reduce reliance on fossil fuels. Efforts should prioritize public health by mitigating $PM_{2.5}$, ozone, and nitrogen dioxide exposure while enhancing monitoring systems to track progress. Transparent decision-making and stakeholder engagement will be essential for achieving sustainable and inclusive outcomes.

CRediT authorship contribution statement

Jicheng Gong: Writing - Review & Editing, Writing - Original Draft, Methodology, Formal Analysis, Conceptualization. **Zhicong Yin:** 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. **Tong Zhu:** Supervision. **Huijun Wang:** Supervision. **Jinnan Wang:** Supervision. **Kebin He:** Supervision. All the other co-authors contributed to the original draft and revisions of the article.

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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