The 2023 Report of Synergetic Roadmap on Carbon Neutrality and Clean Air for China

EXECUTIVE SUMMARY

Cutting carbon Emissions Reducing Pollution Expanding Green Development Pursuing Economic Growth

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Executive Summary

The 2023 Report of Synergetic Roadmap on
Carbon Neutrality and Clean Air for China

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Executive Summary

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EXECUTIVE SUMMARY

China has articulated two strategic objectives, the attainment of "carbon dioxide emission peaking and carbon neutrality goals" and the pursuit of "building a beautiful China". This approach represents an effective path to fundamentally address ecological and environmental problems. Report to the 20th National Congress of the Communist Party of China emphasizes that China will advance the Beautiful China Initiative and take a holistic and systematic approach to the conservation and improvement of mountains, waters, forests, farmlands, grasslands, and deserts. China will carry out coordinated industrial restructuring, pollution control, ecological conservation, and climate response, and will promote concerted efforts to cut carbon emissions, reduce pollution, expand green development, and pursue economic growth. China will prioritize ecological protection, conserve resources and use them efficiently, and pursue green and low-carbon development to promote harmony between humanity and nature. In this context, the emphasis on promoting synergy between clean air and carbon emission reduction measures has shifted towards optimizing technical roadmaps and designing comprehensive policy portfolios. This focus has attracted attention and exploration across various sectors of its society.

Air pollutants and greenhouse gas (GHG) emissions share similar sources. Climate change and air pollution exert significant adverse effects on ecological environments and human health, with a clear and mutual interaction between the two. Consequently, a significant synergetic effect exists between climate change mitigation and air pollution control in terms of scientific mechanisms, governance targets, action plans, specific measures and comprehensive benefits. Carrying out the *Implementation Plan for Synergizing Reduction of Pollution and Carbon Emission* marks a new stage in China's synergetic governance of pollutant and carbon emission reduction. With the aim to cut carbon emissions, reduce pollution, expand green development, and pursue economic growth, the Ministry of Ecology and Environment advocates for enhanced integration and coordination of efforts to reduce carbon emissions and pollutants reduction. This strategic approach aims to propel the advancement of co-governance initiatives. Currently, an initial synergetic system has been established, featuring an enhanced policy mechanism that facilitates the implementation of effective pilot projects. This initiative is geared towards expediting the green transformation across all social and economic sectors, reinforced by robust support and guarantees.

To comprehensively and objectively track and assess the progress of China's synergetic governance on climate change mitigation and air pollution control, Energy Foundation China and China Clean Air Policy Partnership (CCAPP), in collaboration with Tsinghua University, Chinese Academy of Environmental Planning, Peking University and Nanjing University of Information Science & Technology, have undertaken the compilation of the "Synergetic Roadmap on Carbon Neutrality and Clean air for China" starting from 2021. Serving as a collaborative platform, a group of domestic scholars spanning disciplines such as atmospheric sciences, environmental engineering, energy engineering, public health, and management sciences engage in interdisciplinary exchanges and cooperation. They diligently track, review, summarise and analyse the engagement in interdisciplinary exchanges and cooperation, track, review, summarise and analyse the process of synergetic governance of air pollution and climate change in China. This collaborative effort aims to establish a closed loop for policy-making, evaluation, and optimization, thereby fostering the implementation of co-governance policies.

The 2023 edition of *Synergetic Roadmap on Carbon Neutrality and Clean Air for China* represents the third annual update, with a thematic focus on cutting carbon emissions, reducing pollution, and expanding green development while pursuing economic growth. Expanding upon findings from preceding years, the 2023 report refines the monitoring indicator system for synergetic governance, incorporating 20 indicators across five aspects: air pollution and associated weather-climate change; synergetic governance system and practices; progress in structural transition and governance technology; sources, sinks, and mitigation pathway of atmospheric composition; and health impacts and benefits of coordinated control. The report aims to present the challenges that China faces in its ongoing efforts toward synergetic governance for carbon neutrality and clean air and provide potential solutions to address.

Synergetic Roadmap of Carbon Neutrality and Clean Air for China Evaluation Indicator System

01 | Air pollution and associated weather-climate interactions

- Changes in air quality
- The impact of meteorological conditions on air quality index (AQI)
- Climate change and its impact

02 | Synergetic governance system and practices

- Construction of a synergetic governance system
- Synergetic governance policies
- Local practices

03 | Progress in structural transition and governance technology

- Transition of the energy structure
- Transition of the industrial structure
- Transition of the transportation structure
- Low-carbon transition of building energy use
- Promotion of CCUS technology
- Construction of new power system
- Progress in air pollution control

04 | Sources, sinks, and mitigation pathway of atmospheric composition

- Anthropogenic CO_2 emissions
- Land use change and terrestrial carbon sinks
- Emissions of air pollutants and progress of coordinated control
- Future mitigation potentials and synergetic pathway

05 | Health impacts and benefits of coordinated control

- Health impacts of air pollution
- Health impacts of climate change
- Health co-benefits of carbon reduction

01 AIR POLLUTION AND ASSOCIATED WEATHER-CLIMATE INTERACTIONS

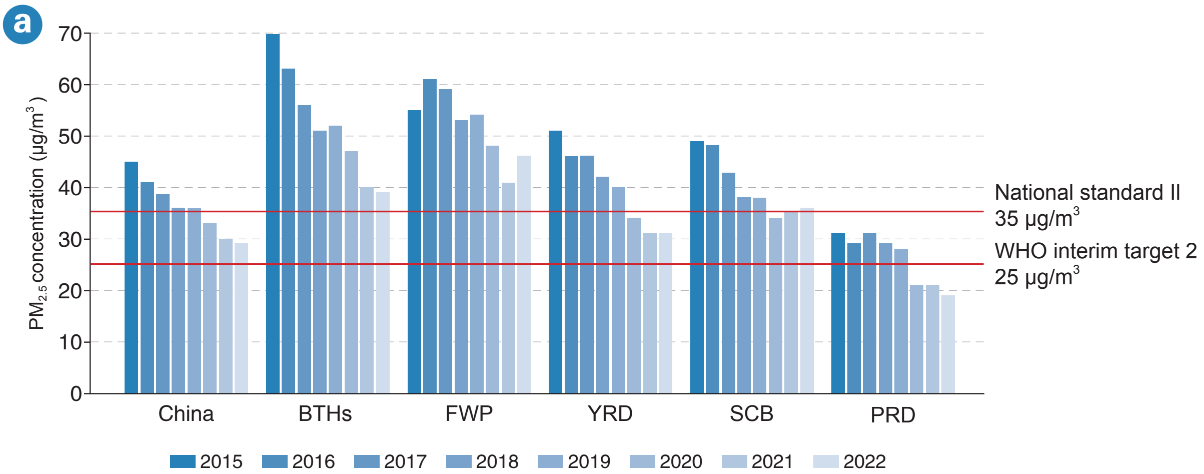
▶ **INDICATOR: Changes in Air Quality**

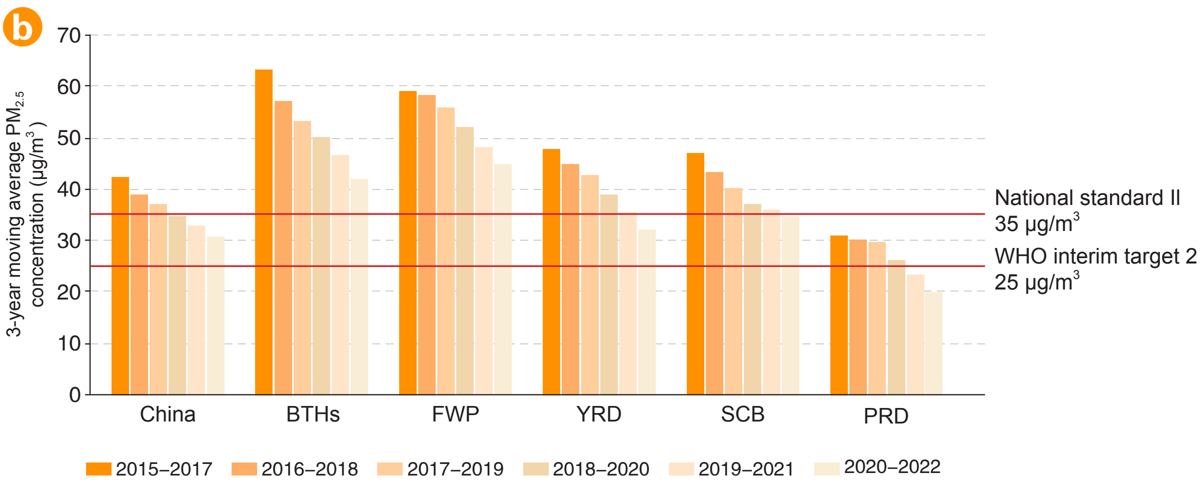
In 2022, both national and regional atmospheric pollutant concentrations decreased compared to the levels observed in 2021. The average $PM_{2.5}$ concentration in 339 cities at or above the prefecture level was 29 μg/m^3, marking a 35.6% reduction compared to the levels recorded in 2015 (Fig. 1). Notably,

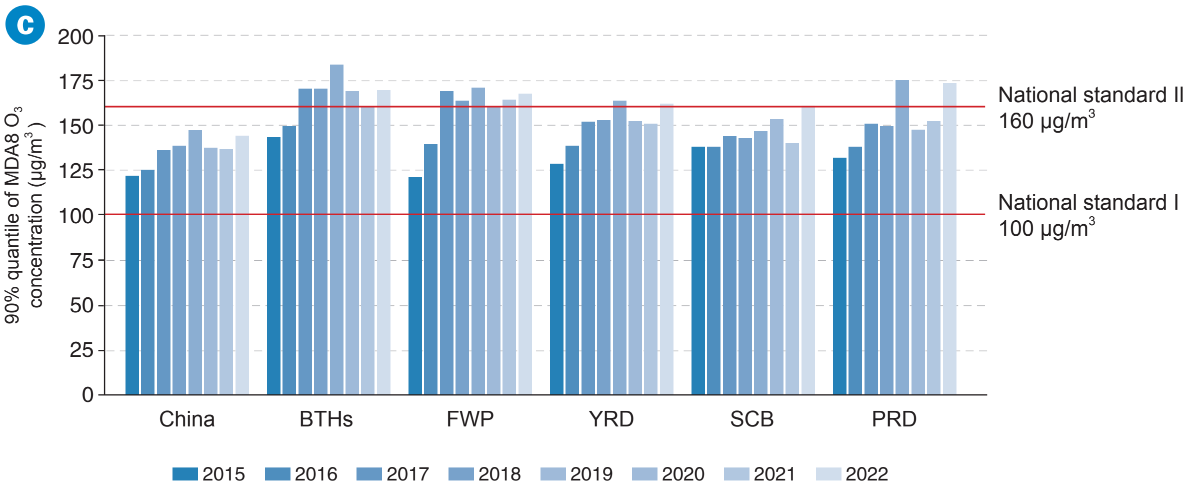
Fig. 1

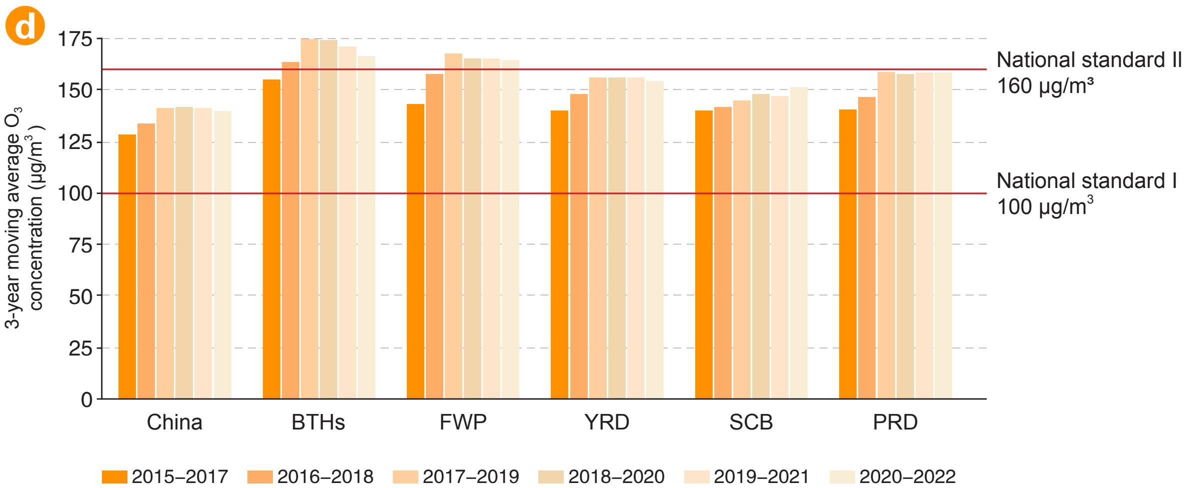
Annual average and the three-year moving average concentrations of $PM_{2.5}$ (a, b), and the 90% quantile of the MDA8 and the three-year moving average concentrations of O_3 (c, d) in China and key regions from 2015 to 2022.

BTHs: Beijing Tianjin Hebei and Surrounding Areas; **FWP:** Fenwei Plain; **YRD:** Yangtze River Delta; **SCB:** Sichuan Basin; **PRD:** Pearl River Delta









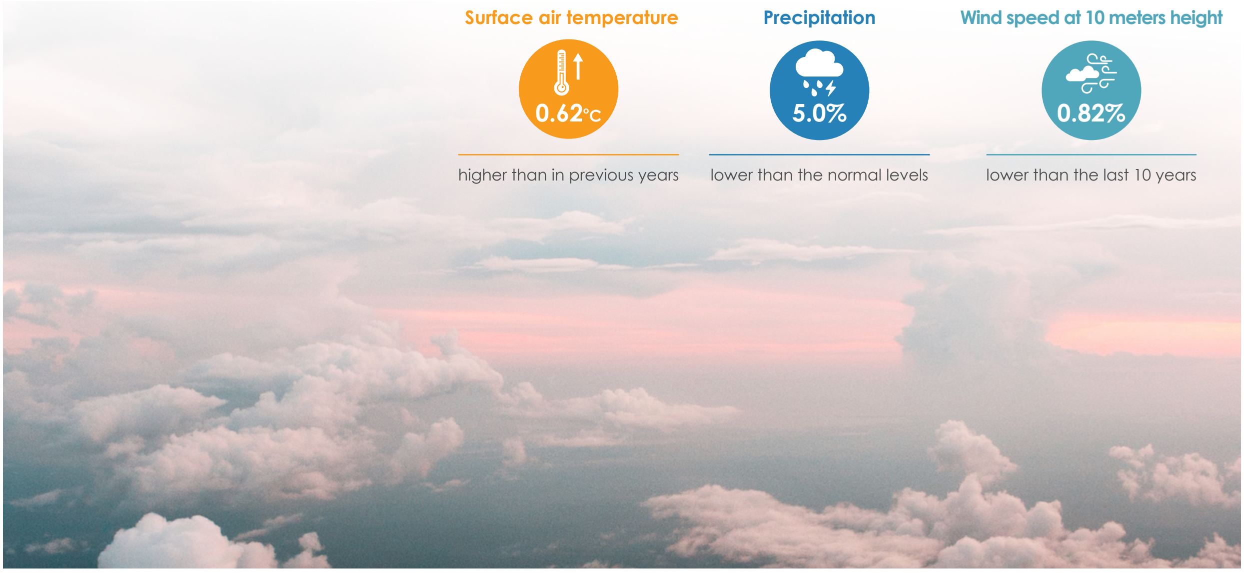
the number of cities with an annual average $PM_{2.5}$ concentration lower than the National Ambient Air Quality Standard Grade II (35 μg/m^3) increased to 253, reflecting a significant rise of 139% compared to the figures reported in 2015. Over the period from 2015 to 2022, the 3-year moving average of $PM_{2.5}$ concentrations both nationally and in the key regions consistently showed a downward trend. In 2022, the 90th percentile of the maximum daily 8-hour average O_3 concentrations (MDA8 O_3) in 339 cities at or above the prefecture level was 145 μg/m^3, showing a 5.8% increase compared to 2021. The number of cities meeting the National Standard Grade II for O_3 concentration annual evaluation in 2022 was 247, accounting for 72.9% of the total, with 6.5% of days exceeding the standard. Over the 3-year moving average, the O_3 concentrations increased from 2015 to 2019 but remained steady or slightly decreased from 2020 to 2022. The percentage of days with severe $PM_{2.5}$ pollution across the country was 0.7% in 2022, marking a 75% decrease compared to 2015. Simultaneously, the peak $PM_{2.5}$ concentration during heavy pollution also notably declined. After nearly a decade of air pollution control, significant changes were seen in spatial pattern. Cities in Hebei Province were no longer among the top 10 most polluted cities in terms of $PM_{2.5}$ concentration in 2022, with pollution centers shifting to Shaanxi and Henan provinces.

INDICATOR: The Impact of Meteorological Conditions on Air Quality Index (AQI)

On average, the national $PM_{2.5}$ pollution in 2022 demonstrated slightly unfavorable variations in meteorological conditions compared to those in 2021. However, these variations were generally conductive to the control of $PM_{2.5}$ pollution in the Yangtze River Delta and the Pearl River Delta regions. The meteorological condition index for $PM_{2.5}$ pollution decreased by 6.1% and 1.7%, respectively, compared to 2021, and by 5.4% and 6.9%, respectively, compared with the average of the last five years. While the atmospheric dispersion conditions in Beijing-Tianjin-Hebei, Chengdu-Chongqing region and the Fen-Wei Plain were worse than the average of the last 5 years and 2021, generally conductive to the increase of $PM_{2.5}$ concentration (China Meteorological Administration, 2023a). The analysis of the O_3 meteorological conditions evaluation index indicated that the national average O_3 meteorological conditions from May to September 2022 were more unfavorable, leading to an increase in O_3 concentration. The deteriorating meteorological conditions resulted in year-on-year increases in O_3 concentrations in Beijing-Tianjin-Hebei region, the Yangtze River Delta, the Fen-wei Plain, and Chengdu-Chongqing region to increase by 8.5%, 8.1%, 3.0%, and 11.0%, respectively, during May-September 2022. Additionally, these concentrations increased by 2.7%, 6.4%, 2.1%, and 10.7%, respectively, compared with the average of the last 5 years (China Meteorological Administration, 2023a). Sand and dust weather occurred for 10 days in 2022, which was 3 days less than that in 2021 and 2.2 days less than the average of the last 5 years. This reduction was attributed to overall favorable meteorological conditions in the spring of 2022, leading to a decrease in both the frequency and intensity of sand and dust weather (China Meteorological Administration, 2023b).

INDICATOR: Climate Change and Its Impact

The concentrations of the three primary global greenhouse gases (CO_2, CH_4, N_2O) reached record highs in observed values in 2022, aggravating climate change. The average surface air temperature in China is 0.62°C higher than in previous years (1991-2020), while the average precipitation is 5.0%



lower than the normal levels (China Meteorological Administration, 2023b). The middle and lower reaches of the Yangtze River, Sichuan and Chongqing experienced widespread record-breaking high temperature and heat waves. Southern areas faced severe summer and fall droughts, while South and Northeast China encountered frequent torrential rainfall characterized by prolonged duration, high intensity, and elevated extremes (Yin et al., 2023; China Meteorological Administration, 2023b). **As global warming intensifies, extreme climate events become more pronounced compared to average climate change.** Regional extreme warm events are anticipated to significantly increase, while cold events are expected to decrease markedly (Li et al., 2022a). There is an overall increasing and intensifying trend in extreme precipitation events in China (Dong et al., 2020; Xu et al., 2021). In 2022, China's wind energy resources experienced a slightly below-average year, with the annual average wind speed at 10 meters height being 0.82% lower than the average value of the last 10 years. Total solar energy resources increased in 2022, with the annual average total irradiation on the horizontal surface reaching the highest in the last 30 years. Both wind and solar energy demonstrated significant regional variations. In the scenario of pushing carbon reduction for "carbon neutrality", wind and solar resources are projected to increase, and their temporal variability is expected to decrease in the eastern part of China from 2040 to 2049, indicating an enhanced stability in solar and wind power generation (Lei et al., 2023). Simulation results for predicting future changes in wind and solar resources showed significant differences and uncertainties among various regions and emission scenarios (Gernaat et al., 2021).

02 SYNERGETIC GOVERNANCE SYSTEM AND PRACTICES

► **INDICATOR: Construction of a Synergetic Governance System**

In 2022, China witnessed further improvement in the synergy between air pollution control and carbon emission reduction. The report to the 20th National Congress of the Communist Party of China (CPC) placed increased emphasis on "cutting carbon emissions, reducing pollution, expanding green development while pursuing economic growth". Notably, a suite of recently issued policies and action plans, including those *addressing the synergizing reduction of pollution and carbon emissions, reduction of heavy-polluted weather, and control of ozone pollution and pollution caused by diesel trucks,* prominently underscores the significance of launching actions that synergize air pollution control and carbon emission reduction, thereby achieving co-benefits. As the consensus on the necessity of promoting synergetic governance has been reached in China, researchers have gradually figured out four pivotal research directions in the theory and practice of the synergetic governance system. These primarily include coordinating development with emission reduction by integrating governance objectives and implementation paths; balancing national and local actions by optimizing joint prevention and control as well as synergizing the regional actions; balancing short term with long term goals by exploring innovative modes of policy tools and governance mechanisms; integrating government and market forces to establish an open, transparent and widely engaging governance system.

► **INDICATOR: Synergetic Governance Policies**

The implementation of synergetic governance polices has continued to evolve in practice, guided by the overarching principles of coordinated planning, deployment, advancement, and evaluation for pollution and carbon emissions reduction. The effectiveness of administrative measures, focusing on access and assessment, has gradually come to the fore. Steady progress has been made in the pilot projects related to the environmental impact assessment of carbon emissions from construction projects in key industries and industrial park planning as well as assessments for carbon monitoring. Relevant aspects of greenhouse gas emission control have been incorporated into the assessment of the achievements of the 14th FYP[1] for

1 The five-year plan is China's policy blueprint for medium-term social and economic development.

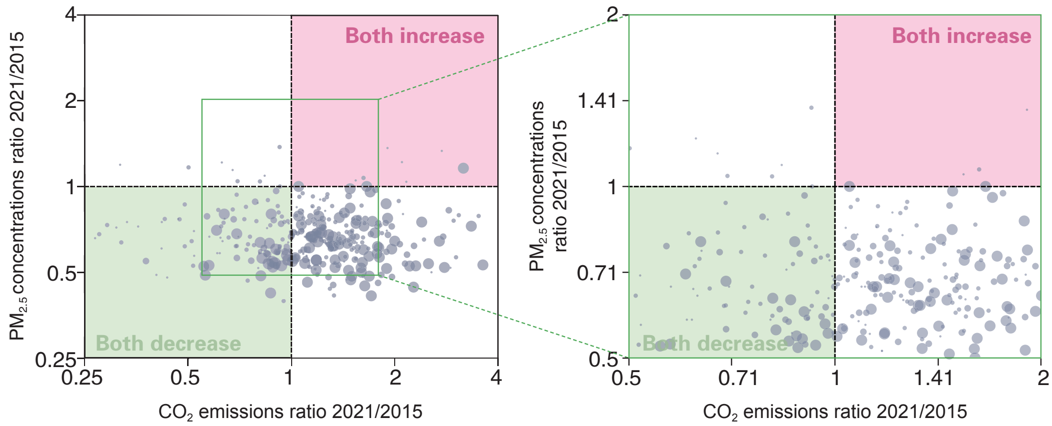
pollution prevention and control, with further optimization of requirements for total energy consumption control. The market-based economic incentive policies, with the carbon market as the mainstay, continued to evolve and innovate in application. A carbon market with the largest emissions coverage in the world was established with about CNY 2 trillion yuan being invested in pilot projects on climate investment and financing. The societal governance policy system for pollutant and carbon emission reduction with broad engagement of all sectors is further improved. New progress has been achieved in the low-carbon technologies catalog, carbon emission reduction incentives, and corporate carbon emission disclosure.

▶ **INDICATOR: Local Practices**

Local governments have been actively implementing the measures to reduce pollutants and carbon emissions. By the end of 2022, provinces and autonomous regions such as Jilin, Heilongjiang, Zhejiang, Anhui, Fujian, Jiangxi, Shaanxi, and Ningxia had officially issued documents to accelerate local practices in promoting synergetic progress in pollutant and carbon emission reduction. However, the progress of carbon emission peaking in different cities did not show an obvious correlation with economic development levels, total carbon emissions, and $PM_{2.5}$ concentration attainment, among other factors (Zhang et al., 2022; Jiang et al., 2021; Zhang et al., 2021). From 2015 to 2021, among 335 cities at or above the prefecture level, only 105 cities achieved the synergetic reduction of the annual average $PM_{2.5}$ concentration and CO_2 emissions, a figure that remained unchanged from 2015 to 2020 (Fig.2). 9 cities showed an increase in both annual average $PM_{2.5}$ concentration and CO_2 emissions, which is eight fewer than the period of 2015-2020. Most cities failed to achieve the synergetic reduction of $PM_{2.5}$ concentration and CO_2 emissions, demonstrating the urgent need to further promote the synergetic governance of pollutants and carbon emissions reduction at the city level.

Fig. 2

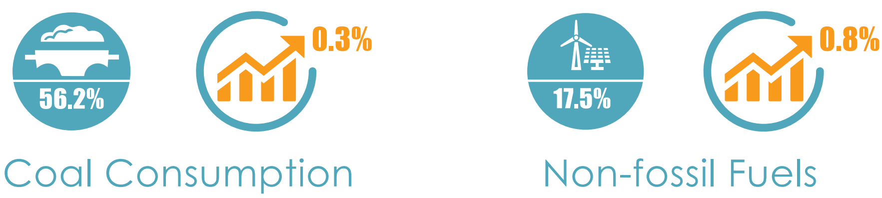
Progress in city-level CO_2 emission and $PM_{2.5}$ concentrations from 2015 to 2021. (The size of the dots depicts CO_2 emissions in 2021)



03 PROGRESS IN STRUCTURAL TRANSITION AND GOVERNANCE TECHNOLOGIES

▶ **INDICATOR:** **Transition of the Energy Structure**

A new trend has emerged in the energy structure transition. Driven by the ‘dual’ stimulus of energy security demands and the structure transition, growth has been seen in both coal and new energy consumption (Fig. 3). In 2022, coal consumption accounted for 56.2% of primary energy consumption, reflecting a year-on-year increase of 0.3 percentage points. The share of non-fossil energy consumption reached 17.5%, marking an increase of 0.8 percentage points from 2021. Renewable energy power generation reached a record high, with overall grid-connected solar, wind, nuclear and hydropower power generation increasing by 31.2%, 16.2%, 2.5% and 1.0% respectively. Solar and wind power generation exceeded 1 trillion kilowatt-hours (1.19 trillion kilowatt-hours) for the first time, and the installed capacity of renewable energy surpassed 1.2 billion kilowatts, exceeding that of coal power installed capacity for the first time. Serving as a cornerstone in energy structure transition process, there has been a new surge in the construction of coal power plants. Adhering to the principle of ensuring domestic energy security before undergoing a complete transformation of energy structure and actively and prudently advancing toward the goals of carbon dioxide emission peaking and carbon neutrality, China has put forward a new strategy for energy development. This strategy provides guidance for the ongoing progress in the green and low-carbon transition of the energy industry.



▶ **INDICATOR:** **Transition of the Industrial Structure**

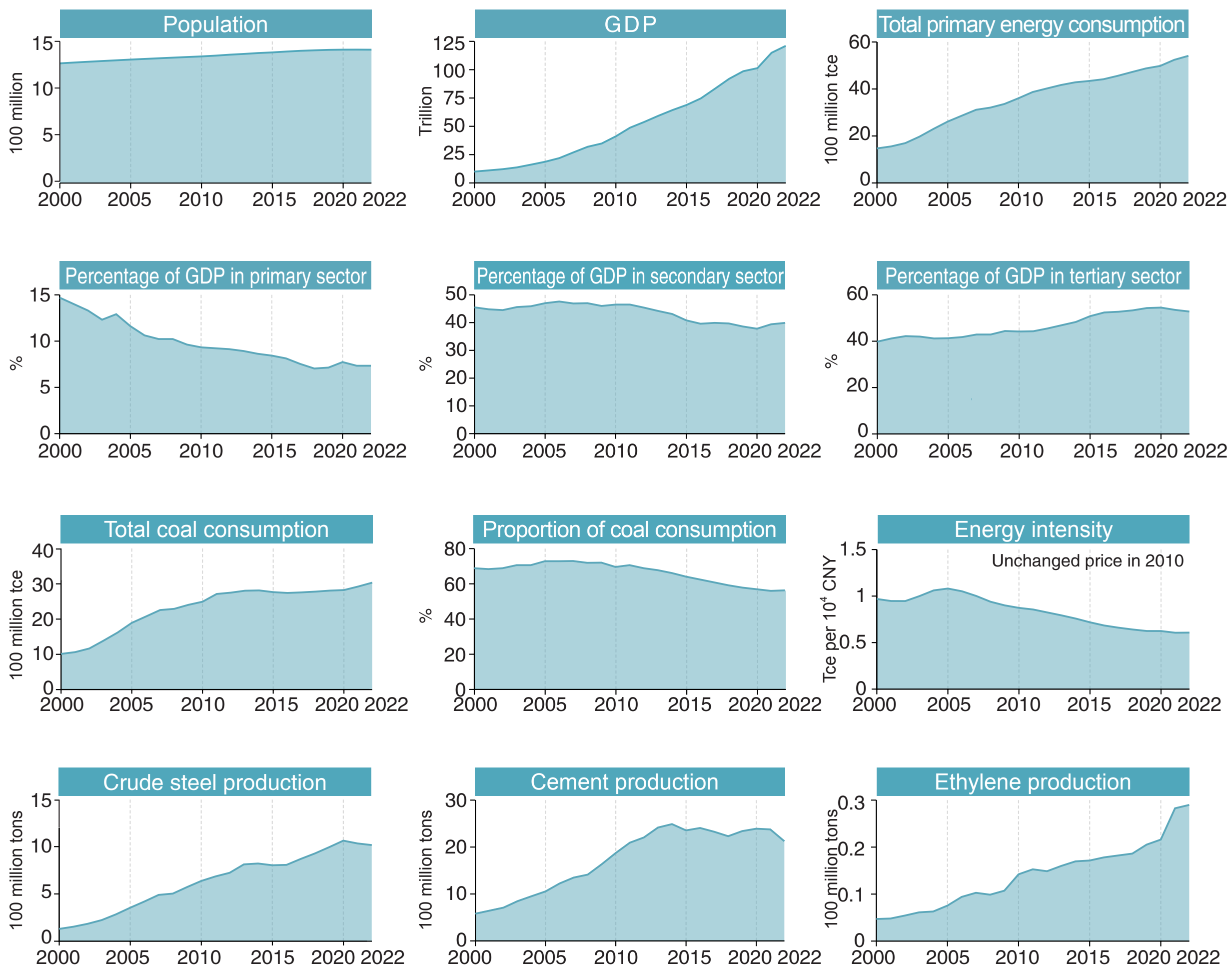
In terms of industrial structure transition, emerging industries and new business models have grown rapidly. In 2022, the value-added of the secondary industry increased from 39.4% to 39.5%, with the value-added of high-tech manufacturing growing by 7.4% compared to the previous year, accounting for 15.5% of the total value of industrial enterprises above a designated size, up from 15.1% (National Bureau of Statistics, 2023, 2022). The production of new energy vehicles reached 7.03 million units, marking an increase of 90.5% compared to the previous year. China has issued key policy including the *14th Five-Year Plan for Energy Saving and Emission Reduction* by the State Council, and *Implementation Guidelines for High Energy-Consuming Industries*, and a few more policy paper issued by the NDRC and other departments. Efforts were intensified to enhance energy efficiency in key sectors, with a focus on achieving carbon dioxide emission peaking and accelerating the green transformation and high-quality development of manufacturing. Local governments have actively responded to the national strategy of carbon dioxide emission peaking and carbon neutrality by formulating implementation plans at provincial level to further improve mechanisms for phasing out outdated production capacities, accelerating the green and low-carbon transformation of traditional industries as well as the strategic development of emerging and high-tech industries.

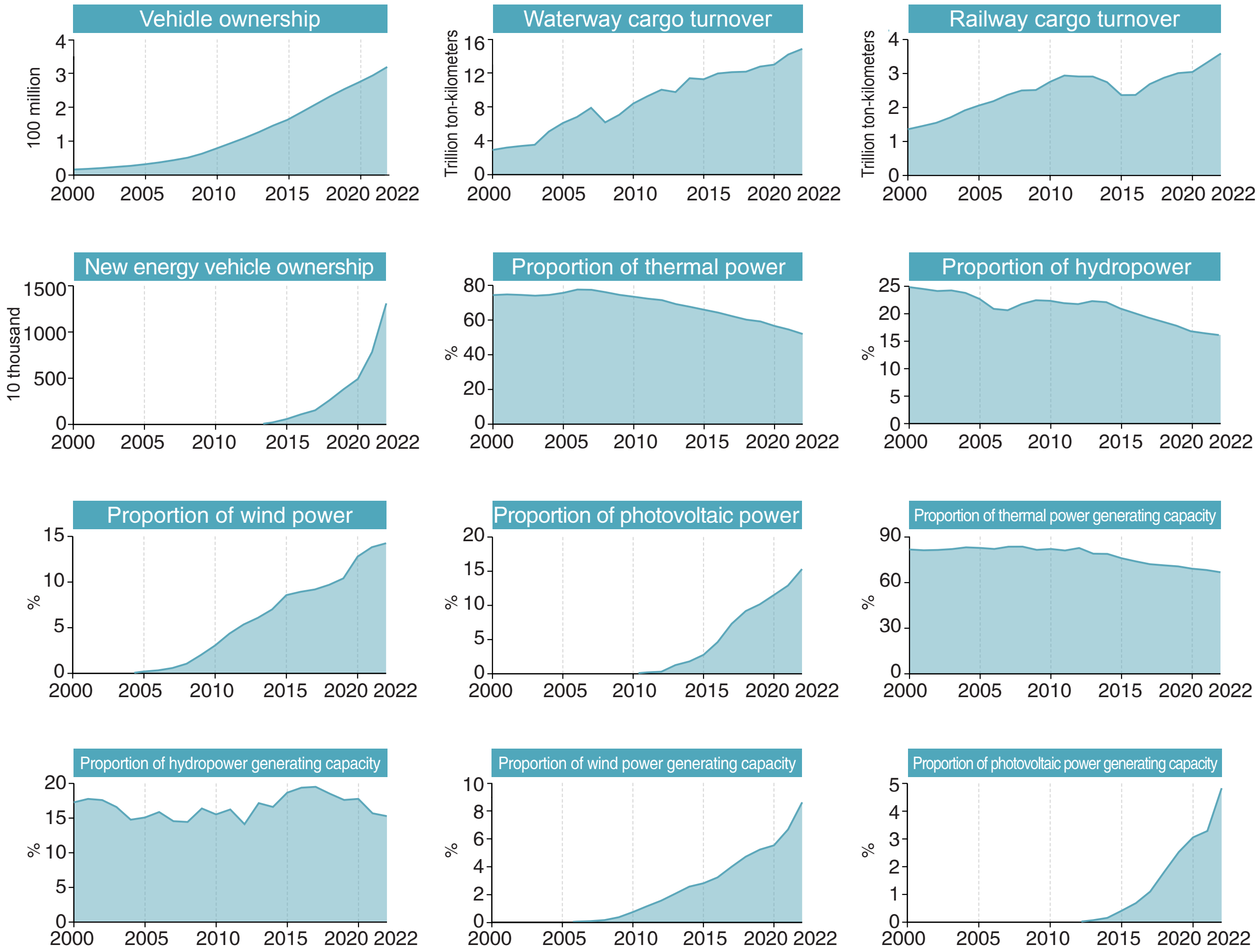
INDICATOR: Transition of the Transportation Structure

In terms of transportation structure transition, the transportation structure has been further optimized. In 2022, the total volume of freight transported by railway increased by 4.5% year-on-year, waterway freight transport volume increased by 3.8%, and road freight transport volume decreased by 5.5% (Ministry of Transport, 2023). The promotion of green travel for residents continued, with a cumulative total of 117 cities nationwide participating in the national program to improve public transport. Among them, 46 cities

Fig. 3

Progress in structural transformation from 2000 to 2022.





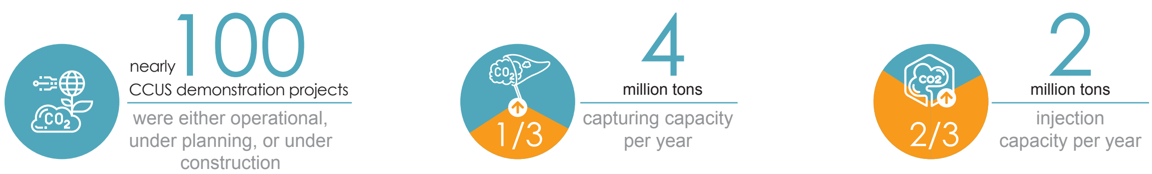
were awarded as Demonstration Cities for Public Transit and 97 cities met the standard in the assessment criteria for green travel advocacy, with a green travel rate exceeding 70% and a satisfaction rate of over 80%. Transportation energy efficiency and clean energy substitution have been steadily improved, with the average fuel consumption of the passenger vehicles industry reduced to 4.10 L/100 km, and the comprehensive energy consumption of the railroad unit transportation workload reduced to 3.91 tons of standard coal per million ton-kilometers (National Railway Administration, 2023). The production and sales of new energy vehicles (NEVs) have increased by 96.9% and 93.4%, respectively, and the nationwide charging infrastructure has reached 5.2 million units.

▶ **INDICATOR: Low-carbon Transition of Building Energy Use**

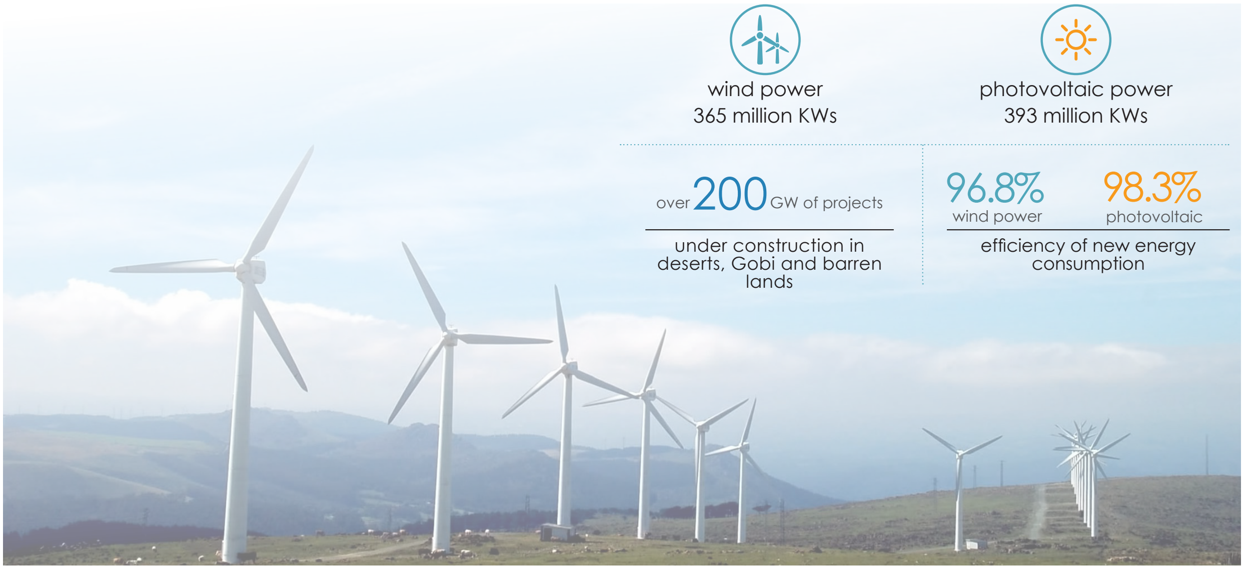
With regard to the low-carbon transition of building energy systems, the energy efficiency of building operations has been further improved. In 2021, the total carbon emissions from the operation of buildings in China were 2.2 billion tons of CO_2, accounting for 23% of the total emissions, with direct carbon emissions showing a downward trend (Tsinghua University Building Energy Efficiency Research Center, 2023). The electricity consumption for building operations significantly increased, exceeding 2.2 trillion kilowatt-hours, leading to an increase in indirect CO_2 emissions to 1.24 billion tons, accounting for 57% of the total emissions. The indirect carbon emissions from heating in northern urban areas have shown a year-on-year decline, accounting for 20% in 2021. The building sector has been undergoing a gradual shift from energy saving to carbon emission reduction, actively promoting the comprehensive reduction of pollutants and carbon emissions in buildings by addressing both direct and indirect emissions. Building on the management of total energy use amount and intensity in buildings, two new dimensions have been introduced: the optimization of building energy use structure and flexible management of energy use. With an emphasis on elevating building energy efficiency standards and fostering upgrades, China is committed to vigorously pushing forward the transition of energy use in buildings. This involves the development of renewable energy sources such as solar energy, and promoting the electrification of buildings.

INDICATOR: Promotion of CCUS Technology

Carbon Capture, Utilization, and Storage (CCUS) technology has demonstrated steady progress, marked by a rapid increase in the number of demonstration projects, a consistent decline in costs and energy consumption, and ongoing enhancements in related policies. As of the end of 2022, nearly one hundred CCUS demonstration projects were either operational, under planning, or under construction in China, representing almost double the number from 2021. These projects collectively provided a capturing capacity of 4 million tons per year and an injection capacity of 2 million tons per year, marking an increase of about 1/3 and 2/3 respectively, compared to the previous year (The Administrative Center for China's



Agenda 21, etc., 2023). China has gained a cost advantage in capture, with the integrated oil-displacing cost for the chemical industry potentially reduced to CNY 105 yuan/t CO_2, while the cost for the power and cement industries remained relatively high from 200 to 600 yuan per ton CO_2 and 305 to 730 yuan per ton CO_2, respectively (The Administrative Center for China's Agenda 21, etc., 2023). Continuous improvements have been made in CCUS technology standards, accompanied by the formulation and issuance of more relevant policies. Gradual identification of application targets for CCUS in hard-to-reduce industrial fields is also underway.



INDICATOR: Construction of New Power System

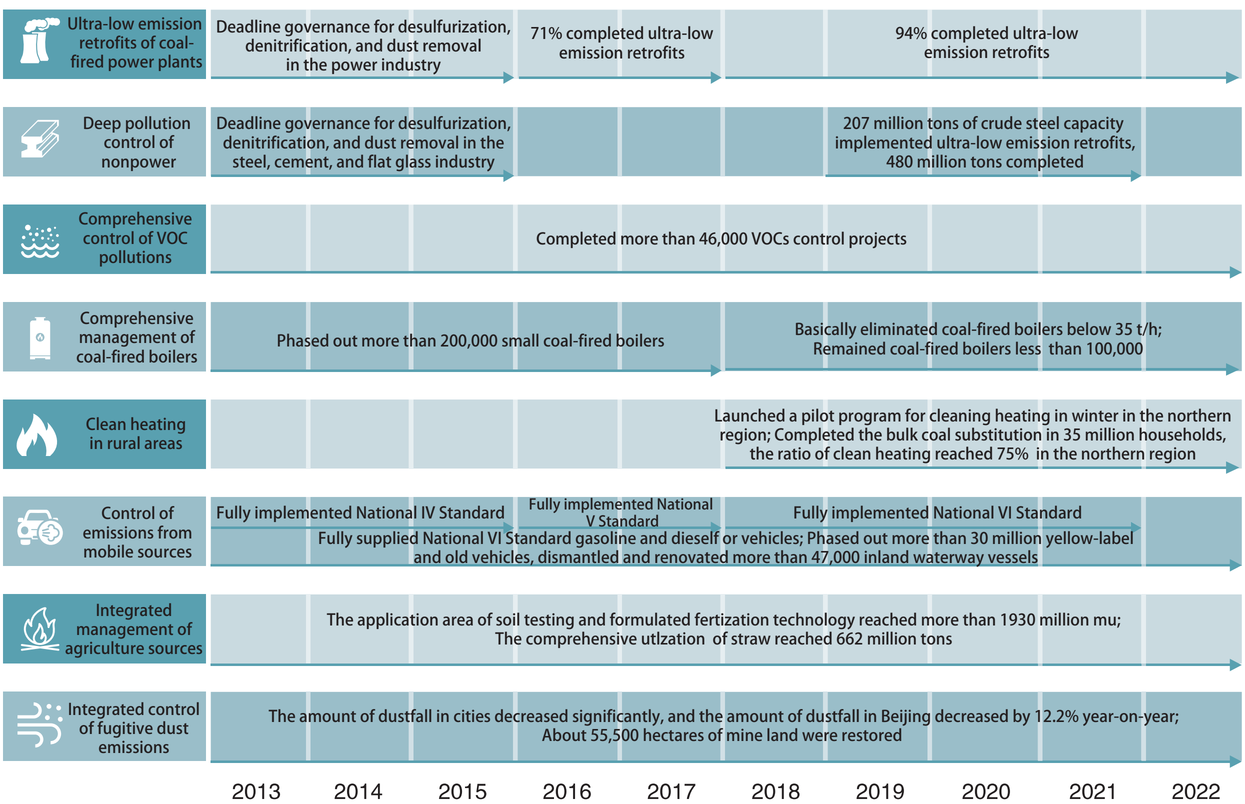
Regarding the development of a new power system, there has been a strong emphasis on promoting new energy sources as a secure and reliable alternative. As of the end of 2022, the installed capacity of wind power and photovoltaic power were 365 million kilowatts and 393 million kilowatts, respectively, making China the global leader in installed capacity for both. The construction of power stations in deserts, Gobi and barren lands has progressed steadily, with over 200 GW of projects under construction. The efficiency of new energy consumption has consistently improved, with the average utilization rate reaching 96.8% for wind power and 98.3% for photovoltaic in 2022. The structure of the power system has been gradually optimized with continuous enhancement of the west-east and north-south power transmission programs. A total of 35,100 km of transmission lines of 220 kV and above were set and put into operation, with 155.31 million kVA of substation equipment of 220 kV and above currently operational. Looking ahead to the future new power system, it is anticipated that the share of wind and solar power will reach 70%, while various types of thermal power will be utilized for adjusting electricity consumption peaks, regulating frequency, and providing inertia.

INDICATOR: Progress In Air Pollution Control

The progress in air pollution control has continued steadily (Fig. 4). By the end of 2022, 94% of coal-fired power units had completed the ultra-low emission retrofits. Approximately 1.05 billion kW of coal-fired power units in China now meet ultra-low emission standards (People's Daily Overseas Edition, 2023). Ultra-low emission retrofits for a total of 207 million tons of crude steel production capacity have completed, including key projects such as desulfurization and denitrification of sintered pellets and the closure of material yards for 480 million tons of crude steel production capacity, accounting for two-thirds of the country's total (China Metallurgical News, 2023). Rapid progress has been made in the prevention and control of VOCs pollution, with more than 46,000 related issues rectified nationwide (Ministry of Ecology and Environment of People's Republic of China, 2023a). The number of coal-fired boilers has been reduced to fewer than 100,000, and those with a capacity below 35 tons per hour have been mostly phased out (Ministry of Ecology and Environment of People's Republic of China, 2023b; China Environment News, 2022). Scattered coal substitution was completed in 35 million households, with full coverage of the clean heating pilot project in 88 cities. The clean heating area in the northern region has reached 17.9 billion square meters, achieving a clean heating rate of 75% (Clean Heating in Rural Areas, 2023). Over 30 million heavy-polluting vehicles and old vehicles were phased out and more than 47,000 inland waterway vessels were dismantled and renovated (Xinhua News Agency, 2023). Comprehensive supervision of environmental compliance of diesel vehicles was conducted, including supervision and random checks on motor vehicle inspection and testing institutions for five consecutive years based on "2 random inspection and one public disclosure" policy. 6 automotive enterprises were required to carry out environmental recalls (Ministry of Ecology and Environment of People's Republic of China, 2023c). Soil testing and formula fertilization were carried out on a total area of 1.93 billion mu each and the comprehensive utilization of straw has reached about 662 million tons (Hemiao, 2023; Zhiyan Intelligent Research Group, 2023). The control of various types of dust, including construction sites, roads, stockyards, bare lands, mines, continued to deepen, leading to a significant reduction in urban dustfall nationwide. The area of restored and treated mines has increased by approximately 55,500 hectares.

Fig. 4

Progress in China's air pollution controls from 2013 to 2022.



04 SOURCE DISTRIBUTION RESEARCH OF ATMOSPHERIC COMPONENTS AND EMISSION REDUCTION PATHWAYS

INDICATOR: Anthropogenic CO_2 Emissions

From 2005 to 2020, CO_2 emissions in most provinces of the country showed a fluctuating upward trend, with energy-intensive and industrial provinces playing a dominant role in the national CO_2 emission patterns. Among them, changes in the power sector were the primary drivers of the emission changes in most provinces, especially in major energy generation regions such as Xinjiang, Inner Mongolia, Ningxia and Shanxi. Meanwhile, the industrial sector emerged as the main contributor to the emission changes in provinces such as Hebei, Henan and Sichuan. In the developed regions in the east, such as Beijing city, Shanghai city and Guangdong province, emissions from residential use and transportation made a relatively prominent contribution. Throughout this period, most provinces (except Ningxia and Xinjiang) consistently witnessed a decline in carbon emissions intensity. Of these, 25 provinces met the regional carbon intensity targets set in the 13th FYP. From 2005 to 2015, 31 cities in China realized a strong decoupling economic growth and carbon emissions, while 185 cities achieved a weak decoupling (Shan et al., 2020).

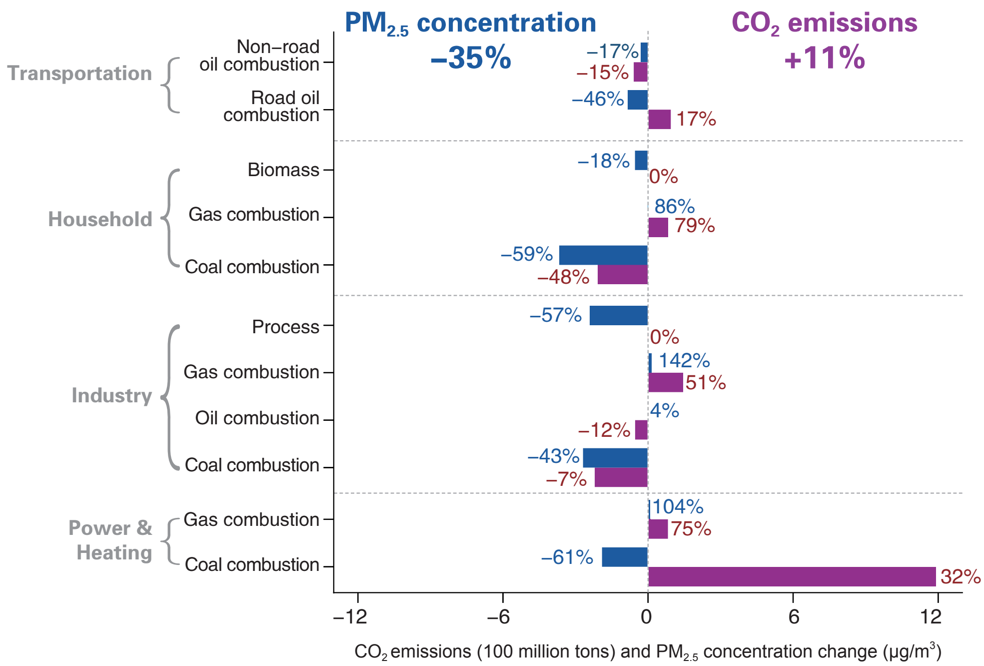
INDICATOR: Land Use Change and Terrestrial Carbon Sinks

A series of ecological protection and restoration projects implemented in China since the 1980s (e.g., reversing deforestation) has contributed to a significant increase in forest area. Land use changes, particularly the expansion of forest area, contributed to about 44% of the carbon sinks in terrestrial ecosystems

(Yu et al., 2022). The carbon storage in China's terrestrial ecosystem from 1980 to 2019 amounted to approximately 8.9 ± 0.8 PgC cumulatively, showing a consistent increasing trend. Currently, existing forests are dominated by middle-aged and young forests, which generally present a stronger carbon sequestration potential capacity (Zhang et al., 2017). Projections for the period 2000-2040 indicate that, with the growth of forest age, carbon storage in China's forest is projected to increase by 6.69 PgC (Yao et al., 2018). To maintain terrestrial carbon sinks at a high level for an extended period, it is essential to optimize the forest age structure through scientific forest management measures, so as to buy more time for industrial emission reduction under the strategic goal of "carbon neutrality," taking into account the ecosystems' response to external disturbances.

Fig. 5

Progress in the synergetic control of CO_2 emissions and $PM_{2.5}$ pollution in China from 2015 to 2021.

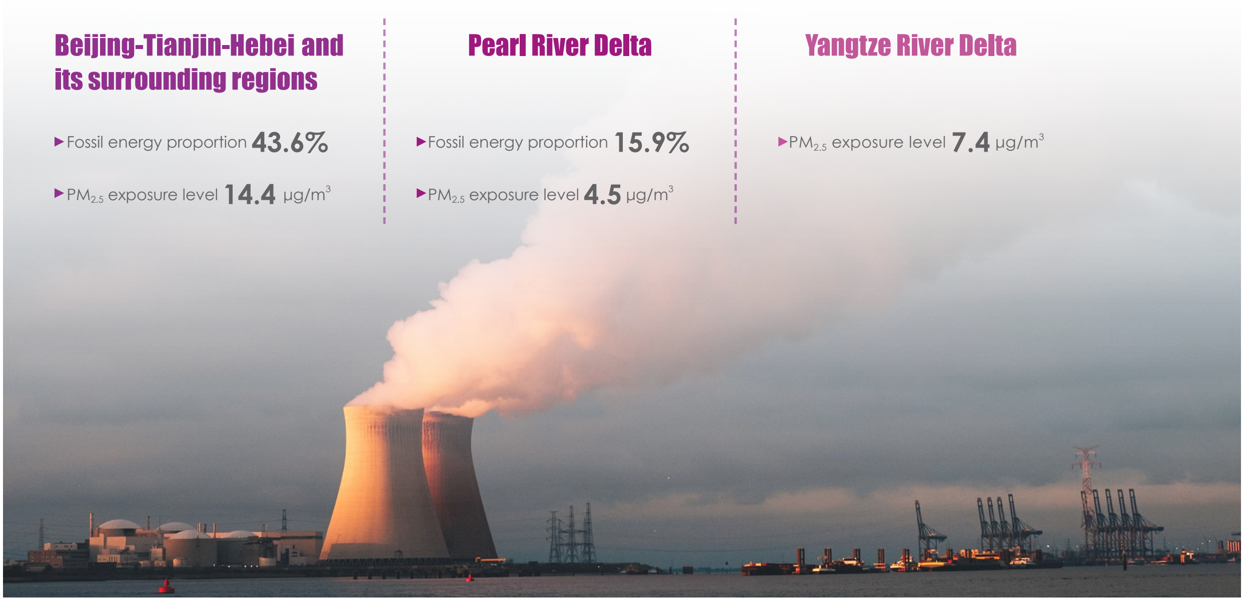


▶ **INDICATOR**: **Emissions of Air Pollutants and Progress of Coordinated Control**

Between 2015 and 2021, positive synergetic effects were gained by CO_2 emission reduction and $PM_{2.5}$ pollution control in China's industrial and civil sectors (Fig. 5). The coal consumption in particular, demonstrated positive outcomes of structural transition and scattered coal remediation measures during the 13th FYP. $PM_{2.5}$ concentration attributed to road traffic emissions further decreased by 46%, despite a significant growth in carbon emissions (up by 17%). In the power and heating sector, there was a significant negative correlation between CO_2 emission reductions and $PM_{2.5}$ pollution control. This was due to the sustained growth in the scale of coal-fired power generation in recent years and the development of gas-fired power generation, resulting in increased carbon emissions. However, the ultra-low emission retrofits of power sector contributed to a decline in $PM_{2.5}$ concentration. In terms of coal consumption, over one-third of provinces in the country achieved positive synergetic benefits between CO_2 emissions and $PM_{2.5}$ pollution control. The burning of fuel oil led to a general reduction of $PM_{2.5}$ in all provinces while CO_2 emissions showed an upward trend in the vast majority of provinces. Although gas consumption resulted in a widespread increase in CO_2 emissions, but its contribution to $PM_{2.5}$ pollution did not significantly rise, given its status as a clean energy source.

INDICATOR: Future Mitigation Potentials and Synergetic Pathway

Implementing a tailored synergetic pathway for pollutant and carbon emission reduction, with a focus on local conditions and key industries, can play a pivotal role in significantly improving air quality in China. Research indicates that in the Beijing-Tianjin-Hebei and its surrounding regions, where the iron, steel and cement industries make substantial contributions and face challenges in decarbonisation, the fossil energy proportion is projected to remain high at 43.6%. This comes with a $PM_{2.5}$ exposure level of 14.4 μg/m^3 under the 2060 carbon neutrality target (Cheng et al., 2021). In the Pearl River Delta, power and transportation sectors presented the greatest potential for carbon emission reduction, with the share of fossil energy projected to decrease to 15.9%, resulting in a $PM_{2.5}$ exposure level of 4.5 μg/m^3 (Liu et al., 2022). Similarly, the Yangtze River Delta, with its power and industrial sectors presented significant potential for carbon emission reduction, the $PM_{2.5}$ exposure level could be reduced to 7.4 μg/m^3 (Zheng et al., 2016). Key initiatives for synergetic emission reduction include the energy structure transition in the power sector and targeted governance. These measures can significantly increase the share of renewable energy power generation (exceeding 70%) and notably enhance air quality in densely populated areas. Targeted governance, involving the advanced phasing out of high-pollution units, maximizes the positive synergetic benefits. Electrification of end-use energy served as a crucial pathway to achieve synergetic carbon and pollutant emissions reduction in industries beyond electricity. Taking the iron and steel industry as an example, large-scale deployment of the Electric Arc Furnace (EAF) process in a green power system is projected to reduce the emissions of major air pollutants by more than 80% by 2060 (Li et al., 2022b).



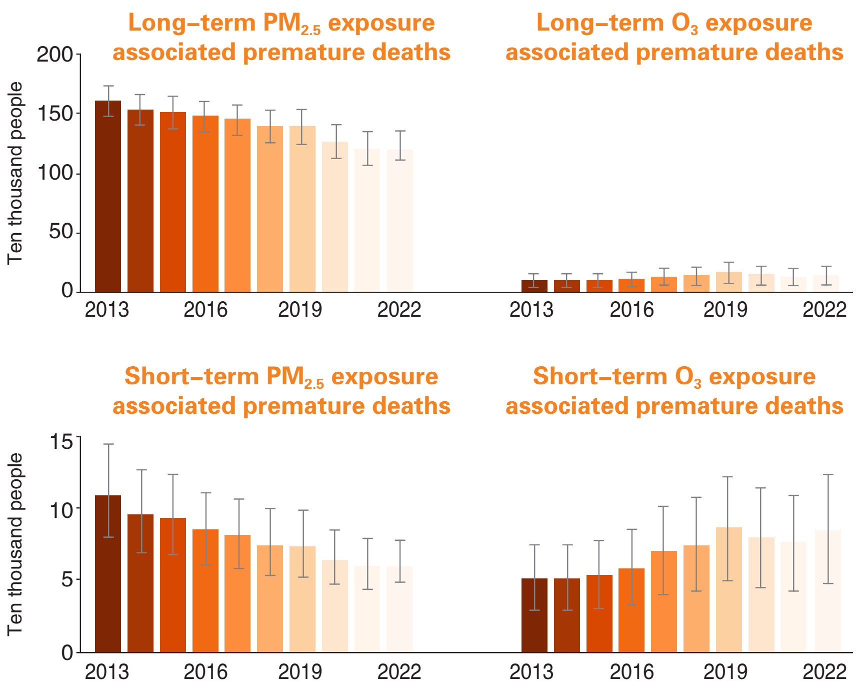
05 HEALTH IMPACTS AND BENEFITS OF COORDINATED CONTROL

▶ **INDICATOR: Health Impacts of Air Pollution**

In 2022, the annual population-weighted average (PWA) of $PM_{2.5}$ exposure remained the same as in 2021 but made a substantial 40.8% decrease from the levels observed in 2015. The most significant improvements were seen in the Beijing-Tianjin-Hebei and Pearl River Delta regions. In 2022, 38% of the country's population lived in areas exceeding China's $PM_{2.5}$ standards, marking a significant 37.5 percentage point decrease from 2015. However, O_3 exposure levels exhibited an increase in some regions in 2022, with a 6% rise in long-term O_3 exposure compared to 2021. Premature deaths associated with long-term and short-term O_3 exposure were 11.1% and 9.7%, respectively, indicating a growing threat to public health (Fig.6). NO_2 exposure levels decreased, with the national annual average NO_2 concentration in 2022 declining by 43.4% from that of 2013. To achieve the goals of carbon dioxide emission peaking and carbon neutrality and safeguard public health, China should enhance the synergetic governance of $PM_{2.5}$, O_3 and NO_2 while implementing more stringent air quality standards and strategies.

Fig. 6

Premature deaths associated with long-term and short-term exposure to $PM_{2.5}$ and O_3 in China from 2013 to 2022.



▶ **INDICATOR:** **Health Impacts of Climate Change**

Extreme high temperature or heatwave, resulting from climate change, have had a profound impact on public health. A report reveals that in 2021, with record-high temperatures in China, approximately 20,000 premature deaths attributable to heatwave were reported, causing economic losses amounting to 1.68% of gross domestic product (GDP) (Cai et al., 2022). The study highlighted that the impact of prolonged exposure to extreme high temperature on mortality risk was more pronounced in low-income, undereducated regions. Additionally, cold waves and typhoons also elevated the risk of death, while dust storms may increase the risk of cardiovascular-related fatalities (Sun et al., 2022; Li et al., 2020). Although incidents of wildfire increased due to high temperatures or heatwave, research on the related health risk remained insufficient. In the face of the threats caused by extreme weather events, both mitigation and adaptation measures are required. These include the establishment of a climate-health early-warning system for extreme weather events, the enhancement of personal protection measures, and the improvement of public infrastructures (Ebi, 2022). Studies indicate that adaptation measures like green roofs and high-albedo materials can help offset economic losses caused by high temperatures. China has been actively establishing risk-based early warning systems, effectively applied in the early floods warnings. (Zhang et al., 2023; Ministry of Ecology and Environment of People's Republic of China, 2022). Many countries worldwide have implemented heat wave health early warning systems, resulting in positive health outcomes. China is also piloting an early warning system for heat-wave health risks and has gained positive results in practice (Zhang et al., 2023).

▶ **INDICATOR:** **Health Co-benefits of Carbon Reduction**

Climate change-induced extreme high temperature and heatwave have led to an increase in ozone concentrations, posing public health risks. Research conducted in 13 cities showed that summer heat pushed up the risk of death for individuals with hypertension (Pan et al., 2022). Studies in the East China found that high temperatures and ozone jointly increased mortality for chronic obstructive pulmonary disease (COPD) (Fu et al., 2022). While climate mitigation policies contribute to improved air quality, the aging population may undermine the health benefits. To address these issues, the Chinese government has implemented green transportation policies aimed at reducing carbon and pollutant emissions, thereby enhancing public health. The widespread adoption of electric vehicles and cleaner power sources has the potential to further improve air quality and increase health benefits (Hsieh et al., 2022). Adaptive strategies are crucial in mitigating labor losses and economic costs as global warming exacerbates health and economic pressure (He et al., 2022).

Challenges & Solutions

In summary, taking carbon dioxide emission peaking and carbon neutrality goals as the driving force, China has established an initial top-level management system and policy framework for the synergetic governance of air pollution and climate change. To strengthen its scientific and technological foundation, China has accelerated the application of green and low-carbon technologies across energy, industry, transportation and other sectors. The dual objectives of achieving carbon dioxide emission peaking and carbon neutrality while consistently improving air quality are central to maximizing benefits for green development and public health. However, challenges persist as $PM_{2.5}$ pollution levels still exceed the new WHO air quality guidelines by more than six times, and carbon emissions continue to show a mild growth trend. The synergetic reduction of pollutant and carbon emissions is yet to be fully realized. Air pollution poses a severe threat to public health, compounded by the increasing frequency of extreme weather and climate events due to climate change. China faces significant hurdles in promoting the synergetic reduction of greenhouse gases and air pollutants, given the absence of a technical system to support the synergetic reduction of carbon emissions and pollutants. Strengthening the role of source management technologies in air quality improvement remains a crucial aspect to address these challenges.

It is true that China is still in the early stage of developing a comprehensive and synergetic governance system for carbon emissions reduction and pollution control. The guiding principle remains centered on cutting carbon emissions, reducing pollution, expanding green development, and pursuing economic growth.

- To accelerate the establishment of a synergetic system for pollution control and carbon emissions reduction, China aims to employ innovative policy mechanisms, set coordinated target paths, foster synergy among different regions and enhance cross-sector coordination.

- The core strategy of source management, together with administrative, economic and voluntary measures, will be crucial in actively leveraging and strengthening the role of structural transition in synergetic governance of carbon emission and pollution.

- China is committed to accelerating the low-carbon and green transition of the energy industry structure and exploring a tailored, region-specific path for pollutant and carbon emissions reduction, focusing on key industries, regions and cities. Industry-specific and region-based measures for carbon emissions reduction and pollution control will be systematically implemented.

- With a priority on public health protection, China plans to consistently tight air quality standards, aligning them progressively with international benchmarks such as the WHO Air Quality Guidelines (AQG). This approach is anticipated to drive fundamental improvements in air quality across the nation.

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