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Synergetic Roadmap

The 2022 report of synergetic roadmap on carbon neutrality and clean air for China: Accelerating transition in key sectors☆

Yu Lei [a, b, *, 1], Zhicong Yin [c, 1], Xi Lu [d, e, 1], Qiang Zhang [f, **], Jicheng Gong [g, ***], Bofeng Cai [b], Cilan Cai [f], Qimin Chai [h], Huopo Chen [i], Renjie Chen [j], Shi Chen [d], Wenhui Chen [k], Jing Cheng [l], Xiyuan Chi [m], Hancheng Dai [n], Xiangzhao Feng [o], Guannan Geng [d], Jianlin Hu [p], Shan Hu [q], Cunrui Huang [r], Tiantian Li [s], Wei Li [f], Xiaomei Li [h], Jun Liu [t], Xin Liu [u], Zhu Liu [f], Jinghui Ma [v], Yue Qin [n], Dan Tong [f], Xuhui Wang [w], Xuying Wang [a], Rui Wu [x], Qingyang Xiao [f], Yang Xie [y], Xiaolong Xu [z], Tao Xue [aa], Haipeng Yu [ab], Da Zhang [ac], Ning Zhang [ad], Shaohui Zhang [y], Shaojun Zhang [d], Xian Zhang [ae], Xin Zhang [h], Zengkai Zhang [af], Bo Zheng [ag], Yixuan Zheng [a], Jian Zhou [ac], Tong Zhu [g], Jinnan Wang [a, b], Kebin He [d, e]

[a] *Center of Air Quality Simulation and System Analysis, Chinese Academy of Environmental Planning, Beijing, 100041, China*
[b] *Center for Carbon Neutrality, Chinese Academy of Environmental Planning, Beijing, 100041, China*
[c] *Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/ Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing, 210044, China*
[d] *State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China*
[e] *Institute for Carbon Neutrality, Tsinghua University, Beijing, 100084, China*
[f] *Ministry of Education Key Laboratory for Earth System Modelling, Department of Earth System Science, Tsinghua University, Beijing, 100084, China*
[g] *State Key Joint Laboratory for Environment Simulation and Pollution Control, College of Environmental Sciences and Engineering and Center for Environment and Health, Peking University, Beijing, 100871, China*
[h] *National Center for Climate Change, Strategy and International Cooperation, Beijing, 100035, China*
[i] *Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China*
[j] *School of Public Health, Key Lab of Public Health Safety of the Ministry of Education and Key Lab of Health Technology Assessment of the Ministry of Health, Fudan University, Shanghai, 200032, China*
[k] *School of Economics and Management, Beijing University of Chemical Technology, Beijing, 100029, China*
[l] *Department of Earth System Science, University of California, Irvine, CA, 92697, USA*
[m] *National Meteorological Center, China Meteorological Administration, Beijing, 100081, China*
[n] *College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China*
[o] *Policy Research Center for Environment and Economy, Ministry of Ecology and Environment of the People's Republic of China, Beijing, 100029, China*
[p] *Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, School of Environmental Science and Engineering, Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, Nanjing University of Information Science and Technology, Nanjing, 210044, China*
[q] *Building Energy Research Center, School of Architecture, Tsinghua University, Beijing, 100084, China*
[r] *Vanke School of Public Health, Tsinghua University, Beijing, 100084, China*
[s] *China CDC Key Laboratory of Environment and Population Health, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, 100021, China*
[t] *Department of Environmental Engineering, School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing, 100083, China*
[u] *Energy Foundation China, Beijing, 100004, China*
[v] *Shanghai Typhoon Institute, Shanghai Meteorological Service, Shanghai, 200030, China*
[w] *College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China*
[x] *Transport Planning and Research Institute (TPRI) of the Ministry of Transport, Beijing, 100028, China*
[y] *School of Economics and Management, Beihang University, Beijing, 100191, China*
[z] *China Association of Building Energy Efficiency, Beijing, 100029, China*

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* Corresponding author. Chinese Academy of Environmental Planning, Beijing, 100041, China.
** Corresponding author. Department of Earth System Science, Tsinghua University, Beijing, 100084, China.
*** Corresponding author. College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China.
E-mail addresses: leiyu@caep.org.cn (Y. Lei), qiangzhang@tsinghua.edu.cn (Q. Zhang), jchgong@pku.edu.cn (J. Gong).

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[aa] Institute of Reproductive and Child Health/Ministry of Health Key Laboratory of Reproductive Health and Department of Epidemiology and Biostatistics, School of Public Health, Peking University, Beijing, 100080, China
[ab] Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, 730000, China
[ac] Institute of Energy, Environment, and Economy, Tsinghua University, Beijing, 100084, China
[ad] Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China
[ae] The Administrative Centre for China's Agenda 21 (ACCA21), Ministry of Science and Technology (MOST), Beijing, 100038, China
[af] State Key Laboratory of Marine Environmental Science, College of the Environment and Ecology, Xiamen University, Xiamen, 361102, China
[ag] Institute of Environment and Ecology, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, 518055, China

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A B S T R A C T

China is now confronting the intertwined challenges of air pollution and climate change. Given the high synergies between air pollution abatement and climate change mitigation, the Chinese government is actively promoting synergetic control of these two issues. The Synergetic Roadmap project was launched in 2021 to track and analyze the progress of synergetic control in China by developing and monitoring key indicators. The Synergetic Roadmap 2022 report is the first annual update, featuring 20 indicators across five aspects: synergetic governance system and practices, progress in structural transition, air pollution and associated weather-climate interactions, sources, sinks, and mitigation pathway of atmospheric composition, and health impacts and benefits of coordinated control. Compared to the comprehensive review presented in the 2021 report, the Synergetic Roadmap 2022 report places particular emphasis on progress in 2021 with highlights on actions in key sectors and the relevant milestones. These milestones include the proportion of non-fossil power generation capacity surpassing coal-fired capacity for the first time, a decline in the production of crude steel and cement after years of growth, and the surging penetration of electric vehicles. Additionally, in 2022, China issued the first national policy that synergizes abatements of pollution and carbon emissions, marking a new era for China's pollution-carbon co-control. These changes highlight China's efforts to reshape its energy, economic, and transportation structures to meet the demand for synergetic control and sustainable development. Consequently, the country has witnessed a slowdown in carbon emission growth, improved air quality, and increased health benefits in recent years.

1. Introduction

The world currently faces the dual challenges of air pollution and climate change [1,2]. These two issues are interconnected regarding their sources, impacts, and mitigation strategies [3,4]. Anthropogenic activities, such as fossil fuel combustion and utilization, industrial manufacturing, and livestock cultivation, are the shared sources of air pollutants and greenhouse gases (GHGs) [5]. Once released into the atmosphere, these species together affect climate systems and environmental quality [1,6].

Broadly, climate change and air pollution are intricately linked regarding physical mechanisms. On the one hand, climate change influences meteorological conditions and hence affects the emission, formation, accumulation, and dispersion of air pollutants [7,8]; on the other hand, air pollutants, especially aerosols that are suspended in the atmosphere, absorb and scatter solar radiation and interact with clouds, thereby affecting the climate system [9,10]. Moreover, both climate change and air pollution are involved in inducing public health burdens. For example, climate change is likely to increase the risk of mortality and morbidity through increased frequency of extreme heat/cold events and compound extremes [11–13]. Exposure to air pollutants, such as fine particulate matter ($PM_{2.5}$) or ozone (O_3), would also pose public health risks [14–16].

Given the shared origin of air pollutants and GHGs, it is reasonable to conduct co-control. Low carbon measures that cut fossil fuel usage would simultaneously reduce emissions of air pollutants, offering synergetic air quality improvements [17–19]. Similarly, clean air actions that promote energy, industrial, and transportation structure optimization, such as coal substitution, industrial facility upgrade, and old vehicle phase-out, would also yield GHG abatement benefits [20,21].

China, the world's largest energy consumer, faces an especially urgent demand for the synergetic control of air pollution and GHG emissions. Despite the successive implementation of clean air actions in the past decade, which has led to substantial declines in China's $PM_{2.5}$ concentrations [20,22,23], the country's air pollution issue persists [24,25]. Furthermore, with the widespread deployment of advanced emission control devices, the potential for further reductions via end-of-pipe measures is diminishing [4,26], necessitating a shift toward addressing emissions at their source, such as reforming the energy system. This demand aligns with the actions needed for achieving China's carbon neutrality pledge [27,28]. To facilitate synergetic control, the Chinese government promulgated the *Implementation Plan for Synergizing Reduction of Pollution and Carbon Emission* in June 2022. As the first initiative of its kind in a major economy that tightly integrates the goals of air pollution control and carbon dioxide (CO_2) emission reduction, it signifies a new era for China's approach to co-controlling air pollution and GHGs.

To track the synergetic progress of carbon neutrality and clean air in China, we designed an analysis framework that consists of indicators from various relevant aspects, including what is being done (such as the synergetic governance system and structural transition) and what are the consequences (such as emissions from shared sources, air quality, meteorological conditions, and health effects). Our goal is to regularly assess progress in each indicator to

[1] These authors contributed equally to this work.

establish a theoretical model for the synergistic management of carbon neutrality and clean air. Through this, we seek to identify challenges in formulating a synergetic roadmap for achieving both objectives in China and offer relevant policy recommendations. Our initial analysis, which reviews the progress of 18 indicators up to 2020, has been published as a *Perspective* in *Environmental Science and Ecotechnology* [29].

This 2022 roadmap serves as the first annual update, building upon the initial review. It offers the latest insights into progress, focusing on developments in 2021. The year 2021 holds significant importance for China's co-control of air pollution and GHG emissions, as it marked several milestones in key sectors. For example, in 2021, the total installed capacity of non-fossil fuel power generation exceeded that of coal-fired power plants for the first time [30]. The year 2021 also saw reductions in crude steel and cement production, breaking the growth trend in these sectors over the past decades [30]. In addition, China's carbon trading system completed its first year of operation. These advancements in governance systems and structural adjustments guide our analysis this year, particularly focusing on key sectors.

The 2022 roadmap consists of 20 indicators that cover the following five aspects: (1) synergetic governance system and practices, (2) progress in structural transition, (3) air pollution and associated weather-climate interactions, (4) sources, sinks, and mitigation pathway of atmospheric composition, and (5) health impacts and benefits of coordinated control. Compared to the previous review, this update introduces two new indicators, specifically, the construction of new power system (indicator 2.2) and the transition of the building energy use (indicator 2.5), and the order of the indicators has been adjusted. Additionally, there have been updates to the analytical methods for indicators 3.2, 4.1, 4.3, and 5.1, as listed in Panel 1. For example, in the indicator health impacts of air pollution (indicator 5.1), we incorporate the estimates of the public health burden induced by NO_2 exposure based on the most recent updates of epidemiological evidence of the health impacts of NO_2 pollution. See Panel 1 for the list of the 20 indicators.

The 2022 roadmap is organized as follows. Section 2 tracks the progress in synergetic policies and practices, with advances in three aspects summarized, including the construction of a synergetic governance system, economic policies for synergetic governance, and local practices. Section 3 tracks progress in structural adjustment and mitigation technology. It summarizes changes in energy, industrial, transportation, and building energy structures. It tracks advancements in the construction of new power systems, the promotion of Carbon Capture, Utilization, and Storage (CCUS) technology, and air pollution control. Section 4 focuses on air pollution and associated weather-climate interactions, with three indicators considered: changes in air quality, variations in adverse weather conditions, and climate change and its impact on air pollution. Section 5 evaluates changes and drivers of the atmospheric composition budget and explores future mitigation potentials. Section 6 focuses on the health impacts and benefits of coordinated control. It evaluates the health impacts of air pollution and climate change, with the health co-benefits of carbon reduction summarized and supplemented. The conclusion and policy implications are summarized in Section 7.

2. Synergetic governance system and practices

With China's political will in carbon mitigation and environmental protection strengthening, the idea of "co-control" or "synergetic control" of environmental pollution and CO_2 emissions has been emerging in recent policies released by the Chinese government. These top-tier policies, as well as the supporting strategic planning, laws and regulations, and standards, serve as the basis for a co-control that would yield higher benefits at a lower cost. This section aims to track the progress in recent years in constructing the synergetic governance system, key top-level designs, as well as supporting sectoral policies and local practices.

Panel 1
List of 20 indicators

1. Synergetic governance system and practices
- 1.1 Construction of a synergetic governance system
- 1.2 Economic policies for synergetic governance
- 1.3 Local practices

2. Progress in structural transition
- 2.1 Transition of the energy structure
- 2.2 Construction of new power system*
- 2.3 Transition of the industrial structure
- 2.4 Transition of the transportation structure
- 2.5 Transition of the building energy use*
- 2.6 Promotion of CCUS technology**
- 2.7 Progress in air pollution control

3. Air pollution and associated weather-climate conditions
- 3.1 Changes in air quality
- 3.2 Variations in adverse meteorological conditions
- 3.3 Climate change and its impact on air pollution

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 Emissions of air pollutants and progress of coordinated control
- 4.4 Future mitigation potentials and synergetic pathway

5. Health impacts and benefits of coordinated control
- 5.1 Health impacts of air pollution
- 5.2 Health impacts of climate change
- 5.3 Health co-benefits of carbon reduction

Note: This panel is adapted from Table 1 in Zhang et al., 2023 [29], with the number of indicators expanded from 18 to 20. The order of indicators has been updated compared to Table 1 in Zhang et al., 2023 [29]. The description of each indicator is documented in SI Table S1.

*Two new indicators are introduced, namely, (2.2) the construction of new power system and (2.5) the transition of the building energy use.

**The indicator "zero-carbon and carbon-negative technologies" in Zhang et al., 2023 [29] is replaced by (2.6) promotion of CCUS technology, which places a specific focus on the CCUS technology. CCUS is the abbreviation for Carbon Capture, Utilization, and Storage.

2.1. Construction of a synergetic governance system

In China, environmental protection and climate change mitigation are crucial to the government's duty to "continuously improve eco-environmental quality". Since 2021, the strategic planning issued by China's central government, for example, *China's* 14th *Five-Year Plan (2021–2025) for National Economic and Social Development and the Outline of 2035 Vision*, have clearly emphasized the emerging imperative for systematic emission abatements and synergetic control of environmental pollution and carbon emissions. To facilitate the fulfillment of carbon peaking and carbon neutrality targets on the foundation of existing environmental policies, the central government promulgated the *Implementation Plan for Synergizing Reduction of Pollution and Carbon Emission* in June 2022. As the world's first policy initiative tightly coordinating air pollution control and carbon emission mitigation, this implementation plan presents a comprehensive and multi-faceted roadmap for pollution-carbon co-control during the 14th Five-Year Plan (FYP) period (i.e., 2021–2025) and up to 2030. It marks a pivotal milestone in constructing the synergetic governance system in China. Also, it serves as an overarching tool for driving the national economic and social development towards a comprehensive green transformation.

In addition to strengthening synergetic control in the national strategic plan, existing policy management systems are being further enhanced, including environmental and carbon impact assessment, monitoring, regulation, and statistical verification. The efforts are expected to facilitate the integration of carbon emission control requirements into the well-established environmental governance system.

2.2. Economic policies for synergetic governance

A milestone has been achieved in the realm of market mechanisms with a breakthrough in the carbon emissions trading market. In late 2020, the Ministry of Ecology and Environment of China initiated the first compliance period of China's national carbon market, encompassing 2162 key emitting entities from the power generation sector. The annual coverage of CO_2 emissions amounts to approximately 4.5 billion tons, making it the world's largest carbon trading market regarding GHG emissions. From the commencement of trading on July 16, 2021, to the conclusion of the first compliance period on December 31, 2021, the cumulative trading volume of carbon emission quotas reached 179 million tons, with a total transaction value of CNY7.7 billion and an average transaction price of CNY42.9 per ton. The compliance rate was 99.5% (based on the compliance volume). 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.

Furthermore, efforts such as voluntary GHG reduction trading, carbon finance, and climate-related investment and financing have been further advanced. By the end of 2021, the Chinese certified emission reduction (CCER) trading system had amassed transactions totaling approximately 440 million tons of GHG reductions, with a cumulative transaction value of 5.84 billion yuan and an average price of CNY13 per ton of CO_2eq.

2.3. Local practices

Cities serve as the key units of the synergetic control of environmental pollution and GHG emissions, representing the crucial intersection of high-level strategic planning and practical implementation. In line with national objectives and local capacities, cities exemplified by Qingdao and Chengdu have undertaken innovative endeavors to foster synergetic control. Specifically, these cities have enacted and implemented synergetic action plans for air pollution and GHG co-control while promoting the integration of comprehensive emission inventories encompassing both air pollutants and GHGs. These proactive measures have significantly contributed to advancing the simultaneous air quality and carbon emissions management, yielding remarkable and satisfactory outcomes.

In 2021, about 36% of prefecture (or higher) level cities in China still failed to meet the National Ambient Air Quality Standard. Additionally, all cities' annual assessment indicators for $PM_{2.5}$ and O_3 failed to meet the updated World Health Organization Air Quality Guideline levels (WHO AQG) [31]. Regarding CO_2 emissions, only 12% of the cities have peaked their CO_2 emissions, cumulatively contributing to 10% of the national CO_2 emissions that year, according to the China City CO_2 Emissions Dataset [32,33]. Furthermore, substantial potential remains for enhancing synergy between air quality improvement and CO_2 abatements at a city level. As shown in Fig. 1, between 2015 and 2020, only one-third of the cities (115 cities) managed to achieve a co-reduction in CO_2 emissions and $PM_{2.5}$ concentrations (dots in the third quadrant in Fig. 1), while conversely, in 17 cities, both CO_2 emissions and $PM_{2.5}$ concentrations increased at the same time.

3. Progress in structural transition

The transition toward low-carbon production structures and applying advanced energy and emission reduction technologies are fundamental for reducing CO_2 and air pollutant emissions, yielding multi-faceted benefits of air quality improvement and climate mitigation. The indicators in this section cover progress in seven aspects: the transition of the energy structure, the construction of new power system, the transition of the industrial structure, the transition of the transportation structure, the transition of the building energy use, the promotion of CCUS technology, and the progress in air pollution control.

3.1. Transition of the energy structure

China has made remarkable progress in optimizing its energy structure. By 2021, the nationwide installed capacity of non-fossil fuel power generation surged to 1.12 billion kilowatts, marking a year-on-year increase of 13.4% [37]. This installed non-fossil capacity accounts for 47.0% of the national total, surpassing coal power (i.e., 46.7%) for the first time (Fig. 2u–x). Meanwhile, China's installed capacity of hydropower, wind power, solar power, and biomass power all ranked first in the world. Furthermore, energy efficiency has also been continuously improved. Despite a 5.2% increase in total energy consumption from 2020 to 2021, China achieved a 2.7% reduction in energy consumption and a 3.8% decline in CO_2 emissions per unit of Gross Domestic Product (GDP; Fig. 2i) [37].

3.2. Construction of new power system

As a major component of China's policy portfolio towards carbon neutrality, the country is transforming its power system by building a new power system dominated by renewables (Fig. 2r–t) [38–41]. With the installation of renewables expanding, the level of new energy accommodation capacity level continues to improve. In 2021, China's average consumption rates of wind power and photovoltaic (PV) power were 96.9% and 98.2%, respectively [42]. Meanwhile, the nationwide wind and PV power curtailment were 20.6 and 6.8 billion kWh, respectively, 8.9% and 4.2% lower than the 2017 levels, indicating the enhanced new energy accommodation capacity.

3.3. Transition of the industrial structure

China has gained remarkable achievements in transforming and restructuring industries, with the tangible benefits of these efforts becoming evident. In 2021, the value added in high-tech manufacturing increased by 18.2% over the previous year, and its share in the value added of large-scale industries increased from

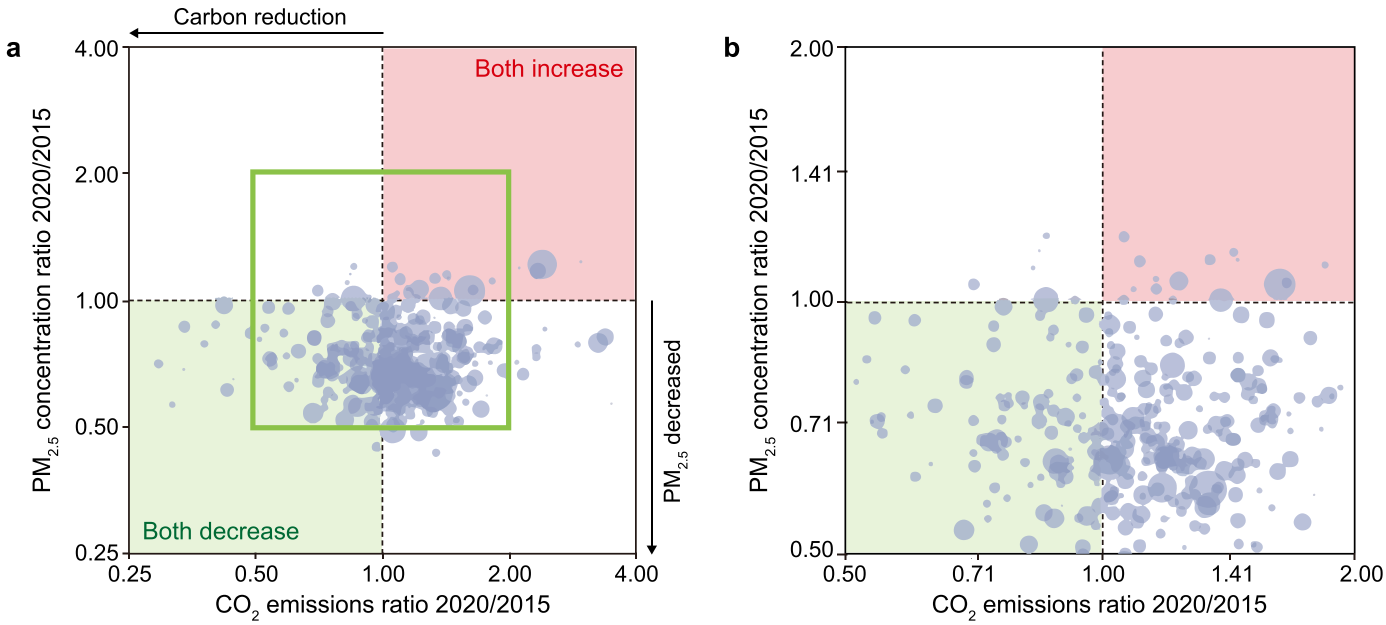

Fig. 1. Progress in city-level CO_2 emission and $PM_{2.5}$ pollution co-control. a, Changes in annual $PM_{2.5}$ concentrations and CO_2 emissions in Chinese cities from 2015 to 2020. **b**, Details of the area bounded by solid green lines in panel **a**. The size of the dots depicts CO_2 emissions in 2020. Data sources: China City Greenhouse Gas Working Group, 2020 [32]; Cai et al., 2018, 2019a, and 2019b [34–36]; China National Environmental Monitoring Centre, http://www.cnemc.cn/. This figure is adapted from Fig. 10 in Zhang et al., 2023 [29], with data updated to 2015–2020.

13.1% to 15.1% [30]. Specifically, the annual production of new energy vehicles surged to 3.7 million, reflecting a 152.5% annual increase. Meanwhile, notable progress has been observed in key heavy industrial sectors. For example, in 2021, crude steel and cement production dropped after several years of growth, which are 3.0% and 1.2% lower than the previous year, respectively (Fig. 2j and k). It is projected that, with effective structural adjustment measures implemented, the industrial sector is expected to achieve overall carbon emission peaking during the 14th FYP period, and the sectoral carbon emissions will decline steadily after the emission peak [43–48].

3.4. Transition of the transportation structure

China has made substantial strides in establishing a low-carbon transportation system. The promotion of electric vehicles has seen notable acceleration, fueled by several incentive policies, such as strategic plans for new energy vehicle (NEV) sales. In 2021, a total of 3.5 million NEVs were sold, representing a market share of 13.4%. This surge brought the total population of NEVs in China to reach 7.8 million (of which 81.6% are battery electric vehicles; Fig. 2p), marking a 1.6-fold surge compared to 2020 [49]. The transportation structure has also been gradually optimized. In 2021, railway and waterway freight volumes increased by 4.9% and 8.2%, respectively, reaching 4.8 and 8.2 billion tons (Fig. 2n–o) [50]. These increases would help alleviate pressures on the on-road freight transportation sector. In addition, medium- and long-distance travel has experienced a gradual shift from road to high-speed railways, fostering a 16.8% average annual growth in railway passenger traffic between 2015 and 2021.

3.5. Transition of the building energy use

China is prioritizing a systematic approach to enhance energy efficiency and control emissions in the building sector. By 2020, the cumulative area covered by energy-efficient buildings in urban areas nationwide had exceeded 23.8 billion square meters, accounting for more than 63% of the total civilian building area [51]. Furthermore, concerted efforts are underway on both the heat source and demand sides to mitigate direct energy-related emissions from rural buildings comprehensively. By 2020, substantial progress has been made in transitioning the “heat source” towards cleaner alternatives such as natural gas and electricity. This transition has resulted in a remarkable increase in the clean heating rate in rural areas, reaching 28% nationwide [39,52]. In the future, measures to improve building energy efficiency and optimize building energy structure, such as building electrification and applying distributed renewables, could be promoted [53].

3.6. Promotion of CCUS technology

CCUS is currently the most promising carbon-negative technology to offset large-scale GHG emissions from fossil fuels, which is vital for achieving the carbon neutrality goal. By March 2022, 50 CCUS demonstration projects have been put in operation or under construction in China, with a total of over two million tons of CO_2 injected and stored [54]. These demonstration projects provide a total capturing capacity of 2–3 million tons per year and an injection capacity of 1–2 million tons per year [54]. Moving ahead, the combination of CCUS with cross-cutting technologies, such as energy efficiency, end-use energy conservation, energy storage, and hydrogen energy, will become an important solution to carbon neutrality [55].

3.7. Progress in air pollution control

Since 2013, air pollution control has been unfolding rapidly in China. As shown in Fig. 3, comprehensive measures targeting power plants, industrial facilitates, coal burning, and motor vehicles have been rigorously enforced, successfully fostering synergies between air pollution control and carbon emission reductions. Since 2015, coal-fired power plants have undergone ultralow

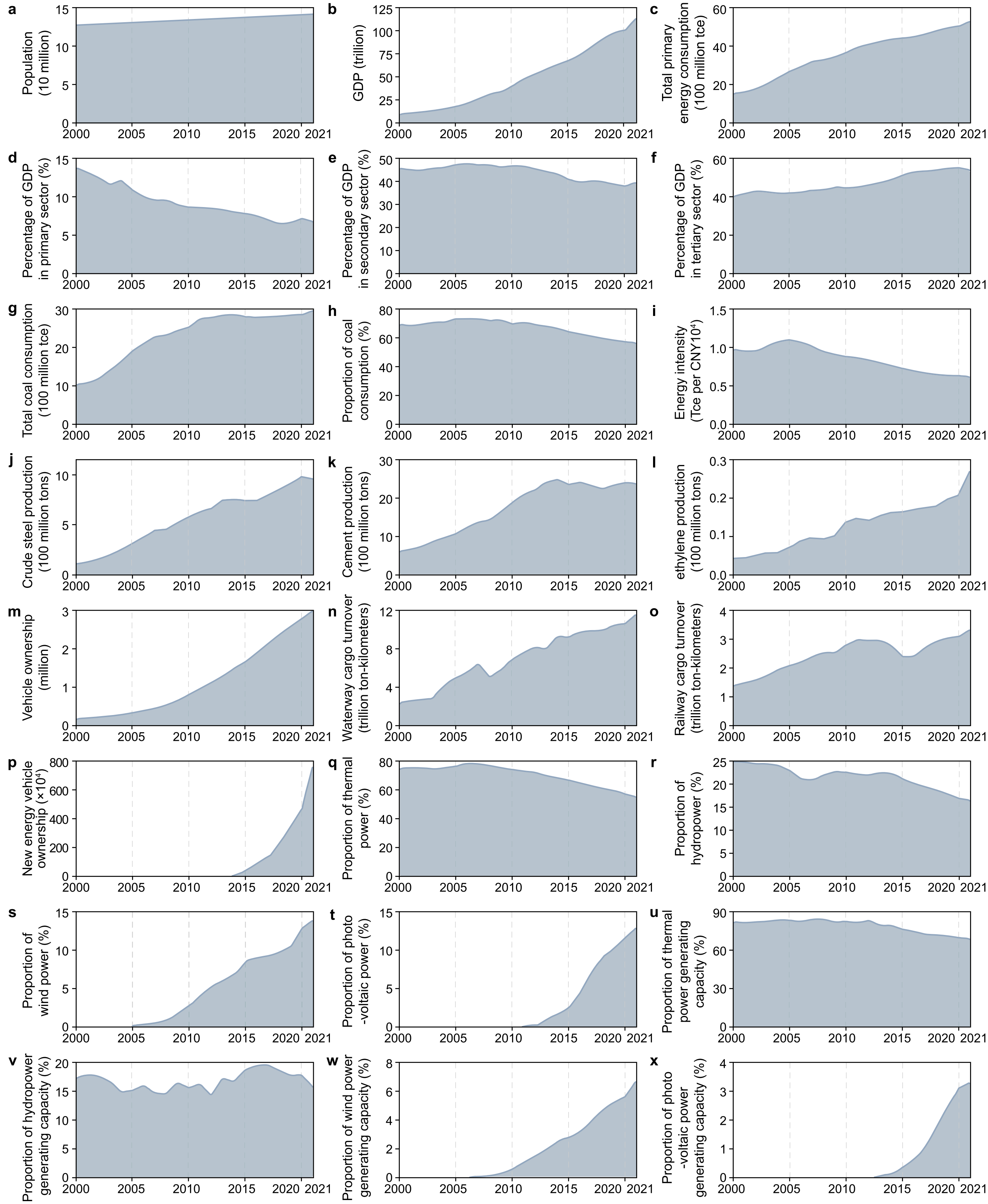

Fig. 2. Progress in structural transformation from 2000 to 2021, as depicted by various socio-economic factors. These socio-economic factors include population (**a**), GDP (**b**), total primary energy consumption (**c**), percentage of GDP in primary sector (**d**), percentage of GDP in secondary sector (**e**), percentage of GDP in tertiary sector (**f**), total coal consumption (**g**), proportion of coal consumption (**h**), energy intensity (**i**), crude steel production (**j**), cement production (**k**), ethylene production (**l**), vehicle ownership (**m**), waterway cargo turnover (**n**), railway cargo turnover (**o**), new energy vehicle ownership (**p**), proportion of thermal power (**q**), proportion of hydropower (**r**), proportion of wind

emission retrofitting to cut their pollutant emissions to levels similar to the gas-fired power plants. By the end of 2021, 1.03 billion kW of coal-fired power units had realized ultralow emission standards, establishing the largest clean coal-fired power generation system globally (see the first row in Fig. 3) [56]. Non-power industries have also undergone substantial pollution control efforts. Specifically, from 2019 to 2021, 145 million tons of steel production capacity were fully upgraded to meet the ultra-low emission standard, with an additional 536 million tons of capacity undergoing such upgrades (see the second row in Fig. 3) [57]. Additionally, by 2021, coal-fired boilers with a capacity of 35 tons of steam per hour or below had essentially been phased out, with the number of existing coal-fired boilers accounting for only 1/50 of the 2013 total (see the fourth row in Fig. 3) [58,59]. China has also enacted increasingly stringent emission standards for motor vehicles. The China VI standards for light-duty gasoline and heavy-duty diesel vehicles were implemented nationally on July 1, 2020, and July 1, 2021, respectively (see the sixth row in Fig. 3) [60,61]. In addition to the above measures, in-depth pollution control measures targeting volatile organic compound (VOC) emissions, fugitive dust emissions, and rural environmental issues have also been put into action (Fig. 3) [62–64].

4. Air pollution and associated weather-climate interactions

Changes in air quality and the magnitude of associated weather-climate interactions serve as indicators that directly illustrate the environmental impacts of air pollution and carbon co-control. With that, this section reviews the changes in air quality and variations in adverse meteorological conditions in recent years, as well as climate change and its impacts on air pollution.

4.1. Changes in air quality

Air quality has been continuously improving in China in the past decade. In 2021, the average $PM_{2.5}$ concentration in 339 cities at or above the prefecture level was 30 μg m^{-3}, 34.8% lower than the 2015 level (Fig. 4a). During 2020–2021, the $PM_{2.5}$ concentrations in the Beijing-Tianjin-Hebei and its surrounding regions (BTHSA), the Fen-Wei Plain (FWP), and the Yangtze River Delta region (YRD) declined much more than in other regions, while it rebounded slightly in Chengdu–Chongqing region (CC) and the Pearl River Delta region (PRD). Although $PM_{2.5}$ concentrations continued to decrease from 2015 to 2021 in China, there were still 100 cities exceeding the National Ambient Air Quality Standard Grade II for annual $PM_{2.5}$ concentration in 2021, implying that $PM_{2.5}$ pollution is still severe in China.

In 2021, the 90th percentile of the maximum daily 8-h average (MDA8) O_3 concentrations ranged from 94 μg m^{-3} to 197 μg m^{-3} across Chinese cities, with an average concentration of 137 μg m^{-3}, which was 0.7% lower than the 2020 average level (Fig. 4c). Compared to 2020, the O_3 concentrations in the CC, BTHSA, and YRD decreased by 8.5%, 5.3%, and 0.7%, respectively; while in the FWP and PRD increased by 2.5% and 3.4%, respectively. The O_3 concentrations in cities across the country increased from 2015 to 2019 and fluctuated after 2019. Measuring the three-year running average, the O_3 concentrations in China and key regions continued to increase from 2015 to 2020, while they remained flat or decreased slightly during 2020–2021.

The ratio of severely polluted days across the country was 1.3% in 2021, which was 58.0% lower than that in 2015 (3.1%), indicating the remarkable effects of the control of heavy pollution in air pollution control. Among the key regions, the ratio of severely polluted days in BTHSA and FWP was both 3.1% in 2021, which decreased by 70.0% and 38.0%, respectively, compared with the 2015 levels. By 2021, the PRD region has been free of severe pollution for two consecutive years.

4.2. Variations in adverse meteorological conditions

The formation, accumulation, and diffusion of aerosol pollutants are closely related to various meteorological conditions [7]. In 2021, meteorological conditions generally favored good air quality. The evaluation of the meteorological condition index of $PM_{2.5}$ pollution (EMI) indicated that the national average $PM_{2.5}$ meteorological conditions in 2021 were comparable to that in 2020 (Fig. 4b). Notably, atmospheric diffusion conditions in the BTHSA, YRD, and FWP regions in 2021 showed improvement, leading to reductions in $PM_{2.5}$ concentrations by about 7.8%, 1.9%, and 0.1% compared with 2020 levels, and 6.8%, 7.2%, and 7.0% compared with the average of the previous five years. Severe $PM_{2.5}$ pollution generally occurs in winter with stagnant meteorological conditions [65]. The probability of stagnant meteorological conditions in the three key regions in the winter of 2021 was decreased. Correspondingly, the proportion of severely polluted days in the BTHSA and FWP decreased from 9.7% to 8.3% in 2016 to 3.1% in 2021 and from 1.3% to 0.4% in YRD.

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 [66]. The evaluation of the meteorological condition index of O_3 pollution showed that meteorological conditions nationwide from May to September 2021 were more favorable than the previous year, which led to the reductions in O_3 concentration in BTHSA, YRD, FWP and CC by 5.9%, 1.1%, 1.5%, and 5.2%, respectively, compared with the same period in 2020, and by 5.6%, 1.6%, 2.7% and 3.3%, respectively, compared with the average of the previous five years (Fig. 4d).

The fluctuations in meteorological conditions significantly contribute to the increase or decrease of $PM_{2.5}$ and O_3 concentrations, particularly influencing the occurrence of 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 decreasing trend of $PM_{2.5}$ and O_3 concentrations.

4.3. Climate change and its impact on air pollution

The weather-climate extreme occurred frequently in 2021 due to the warming climate [67], which might affect the impacts of the weather variation on air pollution [68]. In 2021, the national average temperature was 1.0 °C higher than the long-term average (1981–2010), marking the highest since 1951. Additionally, the average precipitation was 6.7% above the long-term average, with northern regions experiencing the second-highest historical precipitation levels. China saw a range of extreme weather and climate events throughout the year, including rapid shifts between extreme cold and warm conditions in January and February [69], the strongest sandstorm in nearly a decade in March [70], and

power (**s**), proportion of photovoltaic power (**t**), proportion of thermal power generating capacity (**u**), proportion of hydropower generating capacity (**v**), proportion of wind power generating capacity (**w**), proportion of photovoltaic power generating capacity (**x**). Data sources: National Bureau of Statistics, http://www.stats.gov.cn; Ministry of Public Security, http://www.mps.gov.cn/. This figure is adapted from Fig. 4 in Zhang et al., 2023 [29], with data for years 2020 and 2021 added, and trends for ethylene production, the proportion of thermal power generating capacity, the proportion of hydropower generating capacity, the proportion of wind power generating capacity, and proportion of photovoltaic power generating capacity supplemented.

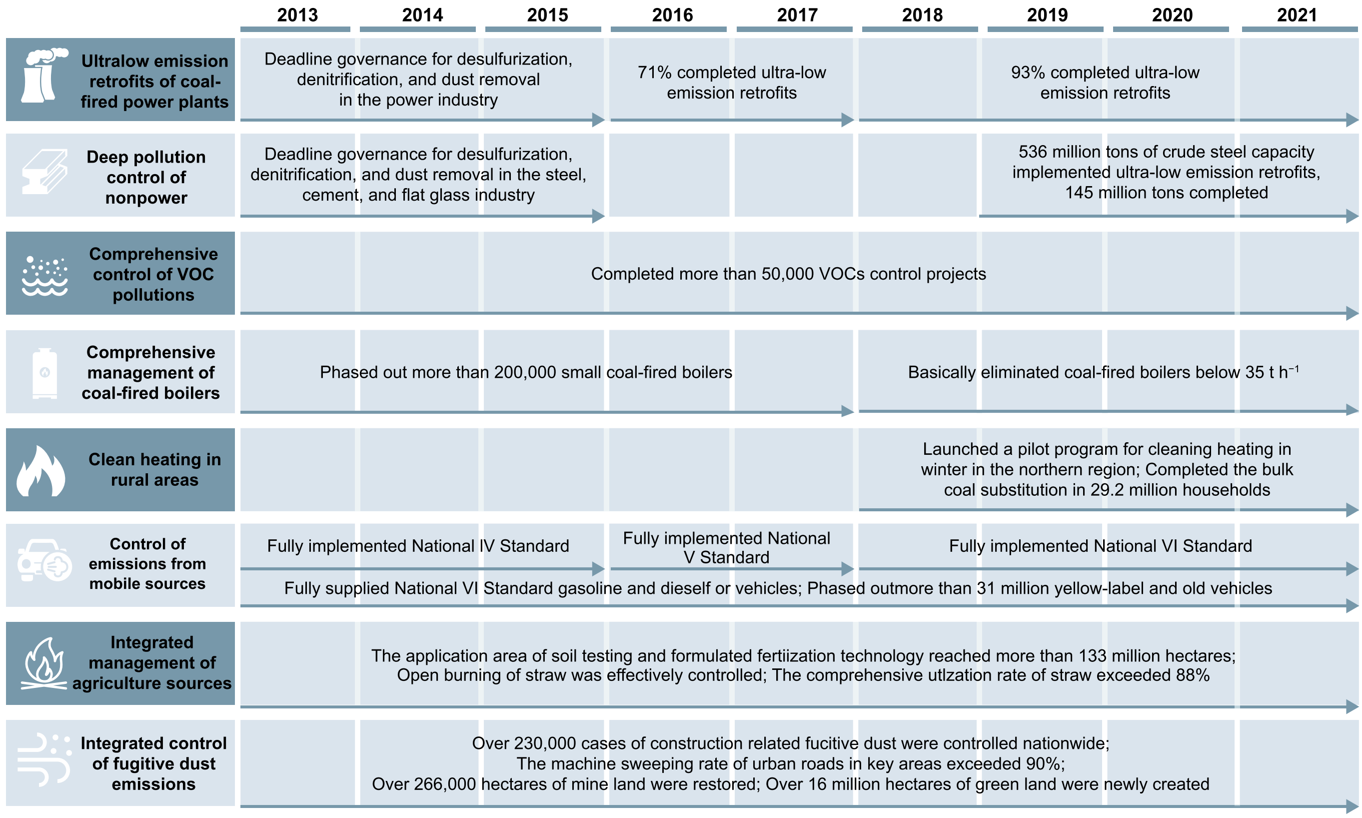

Fig. 3. Progress in China's air pollution control from 2013 to 2021. Data sources: Ministry of Ecology and Environment, unpublished data. This figure is adapted from Fig. 5 in Zhang et al., 2023 [29], with data for the year 2021 added.

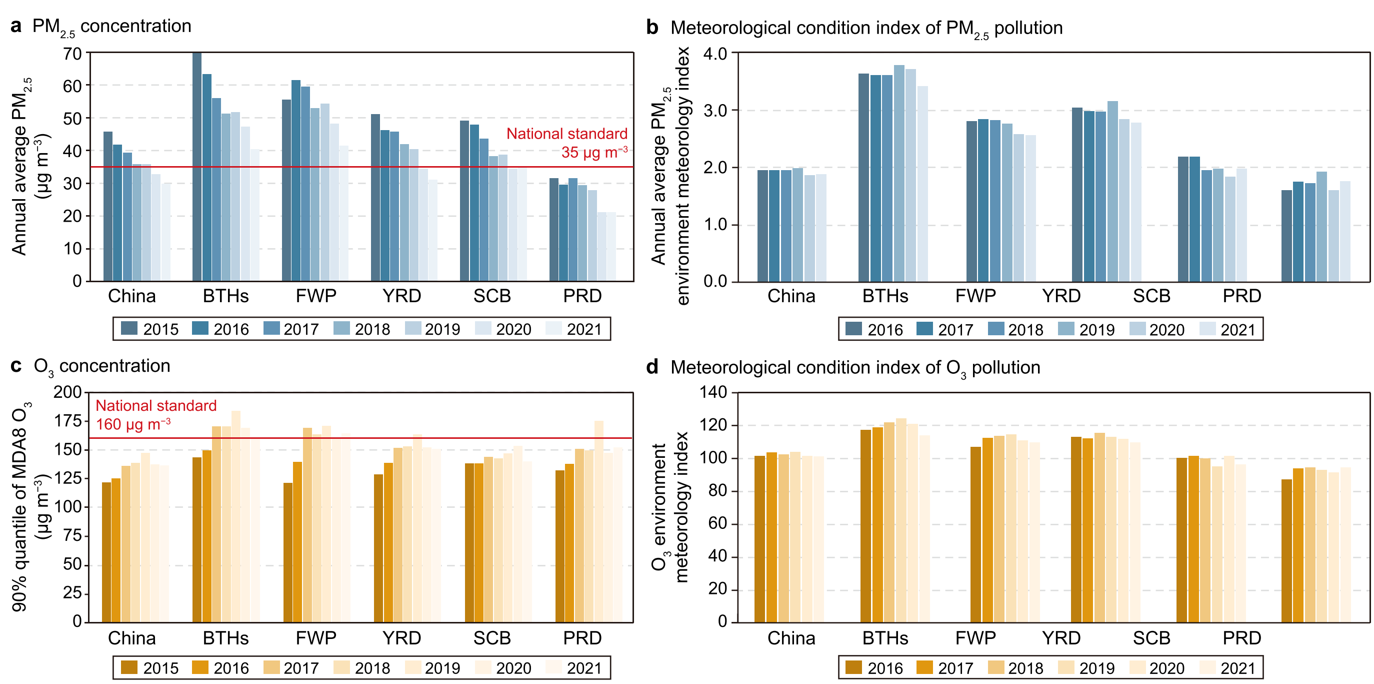

Fig. 4. Variations in air quality and the associated meteorological condition index over China and key regions from 2015 to 2021. a, Annual average $PM_{2.5}$ concentration. **b**, Meteorological condition index of $PM_{2.5}$ pollution. **c**, Annual 90th percentile of MDA8 O_3. **d**, Meteorological condition index of O_3 pollution. Data source: China National Environmental Monitoring Centre, http://www.cnemc.cn/. This figure is adapted from Fig. 1 in Zhang et al., 2023 [29], with data for the year 2021 added and trends for the meteorological condition index of $PM_{2.5}$ and O_3 supplemented.

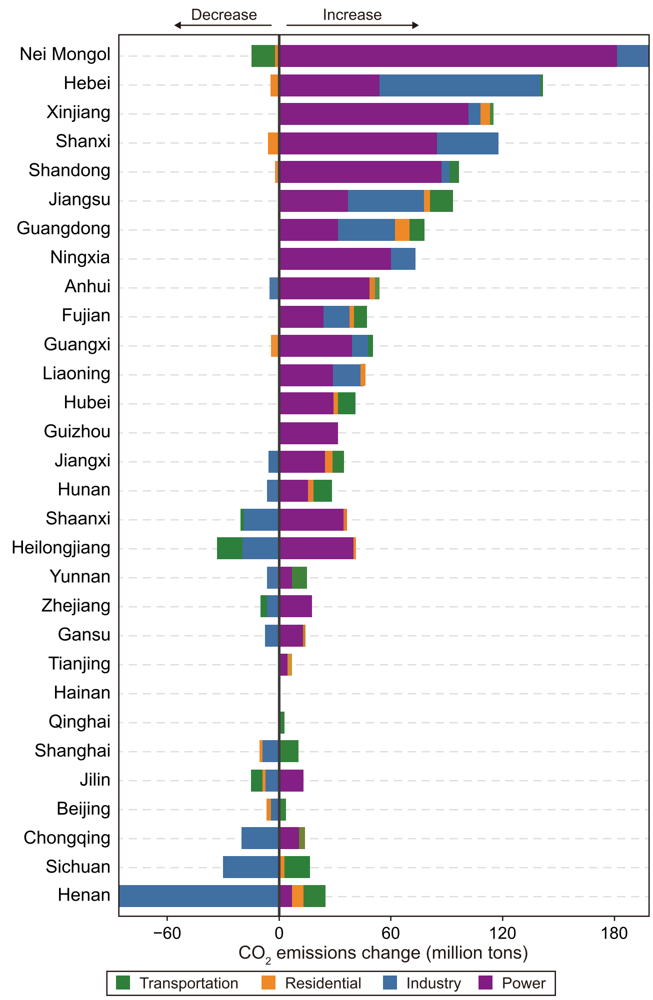

Fig. 5. Changes in provincial CO_2 emissions in China between 2015 and 2020. Data source: Shan et al., 2018 [81]; Shan et al., 2020 [82]; CEADs, 2021 [83].

extremely heavy rainfall in Henan province in July [71]. These events underscore the increasing risk of extreme weather and disasters in China within the context of global climate change [72].

In the future, China is anticipated to face more severe heatwaves due to rising global GHG emissions. Under the high emission scenario (SSP5-8.5), China's annual maximum temperature is projected to increase by approximately 5.1 °C by the end of the 21st century [73]. However, strict emission reductions following the SSP1-2.6 scenario could limit this increase to 2.0 °C [74]. Nevertheless, extreme minimum temperatures will rise more than extreme maximum temperatures, reducing the likelihood of extreme cold events. Meanwhile, extreme precipitation events in China are expected to increase significantly [75]. Even under the SSP1-2.6 scenario, the probability of extreme precipitation is projected to rise by about 20% by the end of the 21st century and over 60% under the SSP5-8.5 scenario [76]. Moreover, global warming from increased GHG emissions will also elevate the risk of compound extreme disasters such as heatwaves, droughts, heavy rains, floods, landslides, and debris flows in China [77].

As global warming continues, the Arctic Oscillation will strengthen, weakening the East Asian winter monsoon. This, in turn, is likely to elevate the risk of haze and ozone pollution in eastern China, primarily due to more stable weather conditions and rising temperatures [78,79]. When GHG emissions follow the RCP8.5 scenario, even if aerosol emissions remain at current levels, $PM_{2.5}$ concentrations and pollution days in China are expected to increase significantly by the end of the 21st century [80]. These meteorological variations would also pose challenges to achieving the goal to eliminate severely polluted days during the 14th FYP period.

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

Revealing the sources of air pollutants and GHG emissions is the basis for formulating effective control measures. Additionally, estimating the synergetic levels of implemented actions in various sectors could also provide insights into future policymaking. This section aims to track the progress of synergetic control of CO_2 and air pollutant emissions at sectoral and regional levels, summarize the understanding of the magnitude of carbon sinks in terrestrial ecosystems, and analyze future mitigation potentials and synergetic pathways.

5.1. Anthropogenic CO_2 emissions

Achieving the goals of carbon emission peaking and carbon neutrality calls for concerted efforts from both carbon emission reduction and carbon sink expansion. During 2015-2020, most Chinese provinces experienced pronounced increases in carbon emissions (Fig. 5). Four-fifths of provinces (i.e., 25) show an upward trend in CO_2 emissions, among which Nei Mongol experienced a growth of more than 180 million tons. Such a growing trend in CO_2 emissions was mainly contributed by the power sector. In total, the estimated CO_2 emissions from the power sector in 27 out of 30 investigated provinces show an increasing trend from 2015 to 2020, except for Beijing, Shanghai, and Qinghai. However, there were encouraging signs in other sectors, as the industrial, transportation, and residential sectors all demonstrated notable reductions in carbon emissions. For example, the descending trends in CO_2 emissions from the industrial and residential sectors were witnessed in approximately 50% and 30% of provinces, respectively. This underscores the critical role of deep decarbonization in the power sector for realizing China's future climate targets.

5.2. Land use change and land carbon sinks

Despite an ascending trend in carbon emissions in China, carbon sinks in terrestrial ecosystems have exhibited great potential to offset part of anthropogenic carbon emissions over the past decades. A recent observation demonstrated that carbon sinks in China's terrestrial ecosystems had grown by up to 10–20% during the period of 2010s, in comparison to the period through the 2000s [84]. The observed upward trend in carbon sinks is largely attributable to ever-growing forests during the past two decades, over which the percentage of forest coverage increased from only 4.83% during the 2000s to 23.04% during the 2010s [85]. However, the proportion of anthropogenic carbon emissions offset by terrestrial carbon sinks has declined. It is shown that the proportion of offset carbon emissions by carbon sinks has dropped from 21 to 24% throughout the 2000s to merely 7–15% throughout the 2010s [84]. More importantly, the ability of carbon sinks to offset fossil fuel carbon emissions is expected to show a downtrend in the coming future, partly attributable to the increasing age of forests, which generally have a lower capacity for carbon sequestration [84]. Therefore, strong efforts in ecosystem management are urgently needed to sustain terrestrial carbon sequestrations.

5.3. *Emissions of air pollutants and progress of coordinated control*

The synergy of controlling CO_2 emissions and $PM_{2.5}$ air pollution exhibits substantial sectoral heterogeneity. From 2015 to 2020 (the 13th FYP period), the industrial sector showed positive synergetic effects between CO_2 emission reduction and air quality improvement due to the optimized sectoral energy structure and manufacturing structure. Conversely, the power and heating sector showed negative synergetic effects, with increases in CO_2 emissions driven by increasing coal-fired power generation during the 13th FYP period and decreased $PM_{2.5}$ pollution due to the tightening emission standards. Similarly, $PM_{2.5}$ pollution from the transportation and residential sectors decreased by 22–23%, while CO_2 emissions increased by 8%, despite efforts being made to optimize transportation structure and substitute raw coal with cleaner energy sources.

The synergies between carbon control and $PM_{2.5}$ abatements also exhibited substantial spatial heterogeneity during 2015–2020. Our estimates reveal that only five provinces (i.e., Beijing, Chongqing, Henan, Sichuan, and Jilin) achieved overall positive synergies (dots in the third quadrant in Fig. 6a). Other provinces all showed improved air quality but increased CO_2 emissions (dots in the second quadrant in Fig. 6a). Specifically, provinces dominated by heavy industries (e.g., Hebei, Shanxi, Nei Mongol, and Shandong) showed significant negative synergetic effects, indicating that the decarbonization of the heavy industry sector remains in an early stage. The effectiveness of synergetic control at the provincial level also varied by sector (Fig. 6b–g). The power and heating sector showed negative synergetic effects in most provinces (Fig. 6b). Conversely, the industrial sectors in more than half of Chinese provinces (e.g., Beijing, Shanghai, Chongqing, and Sichuan) achieved synergies during the 13th FYP period (Fig. 6c). However, in heavily industrialized provinces, such as Hebei, Shanxi, and Nei Mongol, industrial CO_2 emissions were estimated to increase by around 15% on average, regardless of declined sectoral $PM_{2.5}$ pollution. Regarding the transport and residential sectors, they exhibited negative synergetic effects in nearly two-thirds of Chinese provinces (Fig. 6d–e), suggesting that energy conservation consumption reduction and structural transformation measures in these sectors should be further strengthened.

5.4. *Future mitigation potentials and synergetic pathway*

The goals of carbon peak and carbon neutrality will promote the synergetic reduction of air pollution emissions and consequently lead to tremendous improvements in air quality. Scenario-based analysis indicates that achieving carbon neutrality goals would reduce the national annual average $PM_{2.5}$ concentration to around 10 $\mu g\ m^{-3}$ and drive the 90th percentile of MDA8 O_3 concentrations down to around 100 $\mu g\ m^{-3}$ by 2060 [24,25]. The synergetic benefits of carbon neutrality goals are not static, and they depend on the strategic design of different technology pathways. For example, the technology pathway led by renewable energy would yield an additional 35% co-benefit of air quality improvement compared to the pathway led by Carbon Capture and Storage technology [86]. Therefore, incorporating the consideration of air quality co-benefits into the decision-making of carbon-neutral pathway selection will be of critical significance to a fundamental improvement in environmental quality and the practical protection of public health in the future.

Technology pathway for synergetic emission reductions of carbon and air pollution varies across different sectors. Taking the power sector as an example, the structural transition to renewable energy and the strategic retirement in the power sector would be key measures to maximize the potential climate and air quality benefits. Previous research revealed that the increasing penetration of renewable energy would reduce SO_2 and NO_x emissions by over 50% in thermal power plants located in the eastern region when achieving the goal of carbon emission peaking [87]. It is demonstrated that early retirement and targeted pollution controls could

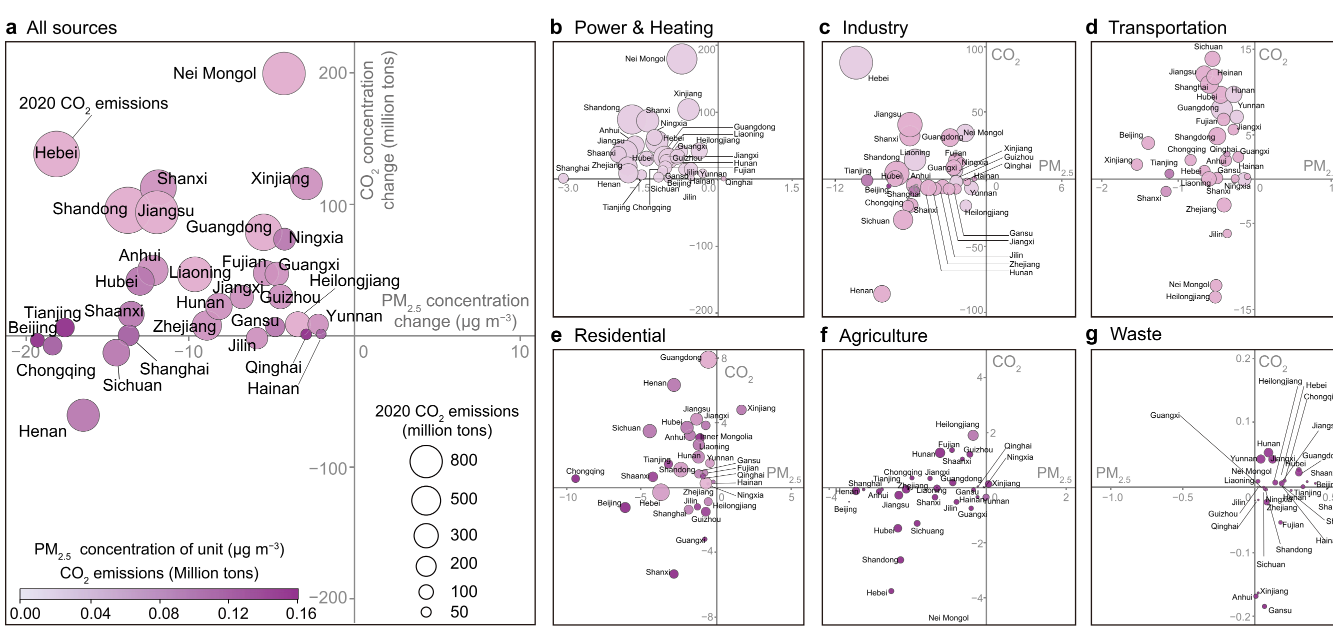

Fig. 6. Progress in the synergetic control of CO_2 emissions and $PM_{2.5}$ pollution in each Chinese province from 2015 to 2020. Results for all sources combined (**a**), the power and heating sector (**b**), the industrial sector (**c**), the transportation sector (**d**), the residential sector (**e**), the agricultural sector (**f**), and the waste management sector (**g**). The size and color of the circle markers represent the sectoral CO_2 emissions and the ratio of $PM_{2.5}$ concentration to CO_2 emissions, respectively. Data source: estimated in this study based on the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC (https://meicmodel.org.cn/); and the Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS; https://iiasa.ac.at/models-tools-data/gains).

avoid more than 0.2 million premature deaths in China in 2030 under a 1.5 °C climate target [88]. The transition in the power system would also contribute to synergetic emission control of carbon and air pollutants in other sectors by increasing the terminal electrification level. For example, the iron and steel sector could substantially reduce emissions of air pollutants by over 80% in 2060 through the widespread adoption of electric arc furnaces fueled by a power system driven by renewable energies [89]. Those results highlight the importance of constructing a low-carbon and environmentally friendly power generation system.

6. Health impacts and benefits of coordinated control

Exposure to air pollutants, extreme weather events, or natural hazards has been known to adversely affect human health by increasing the mortality or morbidity risk due to non-communicable chronic diseases or infectious diseases. And the synergetic control will bring health benefits from air pollution and climate change mitigation. The indicators in this section cover progress in three aspects: health impacts from exposures to air pollution, health effects of climate change, and health co-benefits of synergetic control. Tracking the progress in each indicator provides a guide for optimizing policies to protect public health better.

6.1. Health impacts of air pollution

Based on a well-developed method with inputs from multiple state-of-the-art products [22], air pollution exposure levels keep declining in China. In 2021, the annual population-weighted average (PWA) of $PM_{2.5}$ exposure was 31.2 μg m^{-3}, which decreased by 6.8% and 30.3%, respectively, compared to 2020 and 2017. The short-term $PM_{2.5}$ exposure level has also been reduced significantly. In 2021, the PWA of the $PM_{2.5}$-polluted days (i.e., the average daily $PM_{2.5}$ concentration >75 μg m^{-3}) was 23 days, which is 25 days fewer than that in 2017.

In addition, the decreasing trends in both long- and short-term O_3 exposures continued. Specifically, the PWA of MDA8 O_3 exposure during the peak season (i.e., the maximum of six months moving average within a calendar year) decreased by 3.4 μg m^{-3} (3%) from 2020 to 2021. However, the long-term level of O_3 exposure for most Chinese citizens still exceeded 60 μg m^{-3}, which is the recommendation level from the newly updated WHO AQG [31], suggesting that O_3 remains an important health-damaging ambient air pollutant in China.

Moreover, the concentration of NO_2 has been steadily declining. According to the satellite-enhanced estimates, the 2021 annual PWA of NO_2 exposure was 20.6 μg m^{-3}, which decreased by 6.0% and 20.3%, respectively, compared to 2020 and 2017. Even so, the value was still above the WHO AQG, 10 μg m^{-3}. Accordingly, NO_2 is also an unneglectable air pollutant in China.

Generally, trends in air pollution-related health burden follow the trends in pollution exposure levels. As shown in Fig. 7, our assessment suggests there were 1.21 million (95% CI: 1.07–1.35 million) and 60,000 (95% CI: 40,000–80,000) premature deaths attributable to long- and short-term $PM_{2.5}$ exposures, respectively, in 2021. Some studies suggest that the health hazards of O_3 exposure are independent of those of $PM_{2.5}$. The premature deaths associated with long- and short-term O_3 exposure were estimated at 130,000 (95% CI: 60,000–210,000) and 80,000 (95% CI: 40,000–110,000), respectively (Fig. 7) in 2021. The number of non-accidental premature deaths attributable to short-term NO_2 exposure was estimated as 47,800 (95% CI: 37,200–58,500), based on the exposure-response function from the study of 272 China cities [90]. However, it is worth mentioning that the deaths associated with NO_2 exposure might partially overlap with those of $PM_{2.5}$ or O_3. In a word, long-term $PM_{2.5}$ exposure remains the major contributor to the disease burden of air pollution in China.

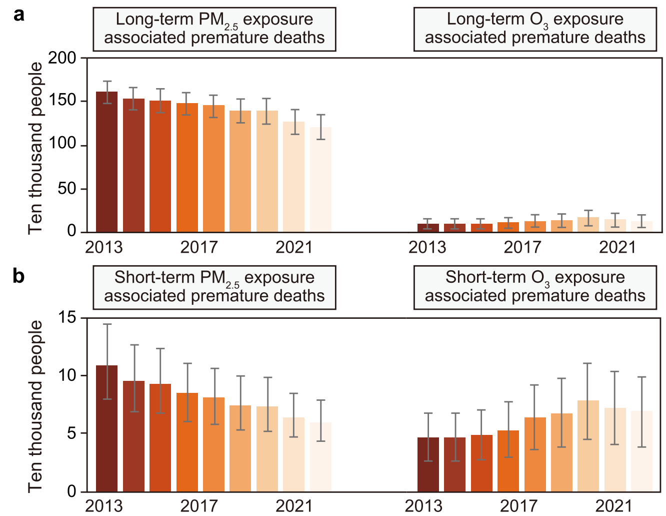

Fig. 7. Premature deaths associated with long-term and short-term exposure to $PM_{2.5}$ and O_3 in China from 2013 to 2021. a, Trends in premature deaths associated with long-term air pollution exposure. **b**, Trends in premature deaths associated with short-term air pollution exposure. Data source: estimated in this study based on method in Xiao et al., 2022 [22].

6.2. Health impacts of climate change

In 2021, extreme weather events intensely occurred in China. These extreme weather events have seriously threatened human health and caused colossal medical burdens and economic losses to the hit areas.

Extreme high temperature or heatwave affects human body temperature regulation, adversely affecting the physiological and circulatory systems and introducing cardiovascular, cerebrovascular, or respiratory diseases. In China, during the past four decades, premature deaths attributable to heatwaves have increased by 2.8 times, from 3679 in 1980 to 15,500 in 2010 [91]. The burden of heatwave was spatially clustered in East and Central China, especially in Shandong, Henan, and Hebei Provinces.

Extreme rainfall and rain-induced flood or waterlogging cause accidental injuries, including drowning, electric shock, fire, and physical trauma. Around 4000 deaths (including those permanently missing) could be directly attributed to floods per year in China [92]. On July 20, 2021, 14.8 million people living in Zhengzhou, Henan Province, were exposed to extremely heavy rainfalls. During the disaster, ~400 people were dead, and many public facilities were damaged. Particularly, patients or vulnerable people were indirectly affected by the lowered accessibility to medical services (including ambulance and medical treatment). In addition, once exposed to extreme rainfall or flood, the adverse effects may further increase the risk of non-infectious diseases, such as ischemic stroke [93,94], and mental illnesses, such as schizophrenia [95]. Extreme weather can also increase the risk of infectious diseases, such as hemorrhagic conjunctivitis, influenza, tuberculosis, epidemic meningitis [96], hand-foot-and-mouth disease [97], hemorrhagic fever [98] and dengue fever [99] by affecting the reproduction, transmission, and distribution of pathogens.

In the face of the threats caused by extreme weather, both mitigations and adaptations are required. Mitigations, such as reducing emissions of greenhouse gases, are fundamental ways to promote human sustainability. Regarding adaptations, quick action could focus on establishing a climate-health early-warning system for extreme events, boosting emergency responses to protect health.

6.3. Health co-benefits of carbon reduction

Realizing the carbon neutrality goal will bring profound changes in the energy mixes and technologies, significantly alleviating air pollution and improving human health. Considering multiple energy and technology pathways for achieving carbon neutrality, $PM_{2.5}$ concentrations could decline to 18.7–23 μg m^{-3} and 6.1–11 μg m^{-3} in 2035 and 2060, respectively [25,86]. When health co-benefits are incorporated into the climate policymaking process, a carbon-neutral pathway that relies more on renewable energy development and avoids over-reliance on negative-emission technologies should be encouraged. In 2060, $PM_{2.5}$ concentration following the renewable-dominated pathway would decrease to 6.1 μg m^{-3}, and the accumulated avoided premature deaths would be 29–50 million [86].

The optimized selection of low-carbon goods or services in energy, production, and consumption will significantly reduce carbon and air pollutant emissions, thus greatly improving human health. If coal is entirely replaced by renewable energy or natural gas in China's power sector by 2030, up to 17.1–24.2 thousand premature deaths could be avoided [100]. Further, considering the early retirement of existing power plants, 77.2 thousand premature deaths could be avoided in 2030 [88]. Meanwhile, it's worth noting that the contribution of pollutants stemming from agricultural trade cannot be underestimated. Approximately 1–2 μg m^{-3} of $PM_{2.5}$ in eastern China can be attributed to NH_3 emissions associated with producing food for export, leading to 26.3 thousand premature deaths annually [101]. In addition to these measures, individuals' choices also play a significant role. When people opt for sustainable practices, such as adopting vegetarian diets, practicing food conservation, and increasing walking and cycling, up to 2.81 million and 809 thousand premature deaths could be avoided annually by 2040 due to diet and exercise, respectively [102].

7. Conclusion and implication

China has identified “carbon peak and carbon neutrality” and “building a Beautiful China” as two strategic goals of Ecological Civilization Construction. Coordinated efforts to reduce air pollution and carbon emissions have become the inevitable choice for effectively realizing China's long-term climate and environmental goals and hence serve as the steering wheel leading the green transition of China's economy.

Climate change mitigation and air pollution control demonstrate high levels of synergy in physical mechanisms, objectives, governance systems, mitigation strategies, and overall benefits. Building on the scientific rationale for co-control, since 2015, China has made notable progress in building a pollution-carbon synergetic governance system accompanied by gradually optimized energy, industrial, and transportation structures. Specifically, the release of the *Implementation Plan for Synergizing Reduction of Pollution and Carbon Emission* in June 2022 marked a milestone in China's efforts to build a synergetic governance system. Notably, in 2021, the proportion of coal in China's total energy consumption decreased to 56.0%, reflecting a year-on-year reduction of 0.8%. Moreover, the proportion of non-fossil power generation capacity reached 47.0%, surpassing coal-fired capacity (46.7%) for the first time. Additionally, crude steel and cement production declined in 2021 after several years of growth, indicating the effectiveness of China's industrial restructuring efforts. A positive synergetic effect between CO_2 abatement and air quality improvement in the industrial sector has emerged. The past years have also witnessed the surging penetration of electric vehicles, with the sales of electric vehicles in China in 2022 more than doubled compared with 2021, while electric vehicle sales in 2021 tripled relative to 2020. Consequently, the synergetic level between pollution control and carbon abatement has gradually improved.

With these efforts, increasing trends in anthropogenic CO_2 emissions have substantially slowed; emissions of major air pollutants, such as SO_2, NO_x, and primary $PM_{2.5}$, have been markedly reduced. Consequently, air quality has steadily improved in recent years, both nationally and in key regions, with a substantial decrease in the number of severely polluted days. In 2021, the national average $PM_{2.5}$ concentration was 30 μg m^{-3}, marking a 34.8% decrease from the 2015 level, and the proportion of severely polluted days was 1.3%, 58.0% lower than that in 2015. The improved air quality has brought substantial health benefits: over the five years from 2017 to 2021, premature deaths associated with long-term and short-term exposure to $PM_{2.5}$ decreased by 23.9% and 26.2%, respectively.

Future actions should be based upon a governance system that adopts a synergetic control strategy as the overarching framework and expedites establishing an integrated action portfolio that advances abatements in both environmental pollution and CO_2 emissions. This entails strengthening emission control from the very beginning of the sources (e.g., improving the efficiency of resources and energy uses and decarbonizing the energy system), emphasizing coordination across space (e.g., optimizing industrial layout), enhancing technological optimization (e.g., breakthrough energy generation and manufacturing technologies), and focusing on policy innovation (e.g., optimizing the carbon market mechanism). In response to the need for “pollution control in a lawful, targeted, and science-based way,” the science and technology innovative mechanisms would be prompted, facilitating the development of a new generation of synergetic pollution-carbon control technology system that supports multi-objective environmental protection. Furthermore, it is recommended to prioritize public health protection in the synergetic governance system. This could include timely tightening of air quality standards and gradually aligning them with the WHO AQG, thereby driving fundamental improvements in air quality. Finally, those successful stories of synergetic control in key sectors could be promoted and adopted to a wider spectrum of sectors to enhance synergies throughout the entire economy.

To better support policymaking and the implementation of co-control strategies, several future research directions are recommended. First, an integrated emission inventory that simultaneously estimates emissions of air pollutants and GHGs at a high sectoral and spatial resolution is urgently needed. Such an emission inventory would facilitate the identification of key sectors and key regions for co-control and serve as the basis for optimizing the mitigation pathways. Second, a methodology framework that could subjectively evaluate the effectiveness of implemented and proposed policies is yet well developed. For example, how to systematically evaluate the degree of synergy for policies and measures remains unclear. Third, it is recommended to develop integrated approaches for optimizing synergetic mitigation pathways across multiple spatial and temporal scales.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2023.100335.

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