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Emission trends of air pollutants and CO_2 in China from 2005 to 2021

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Abstract. China is facing the challenge of synergistic reduction of air pollutants and CO_2 emissions. However, the studies on its historical progress and future priorities are insufficient. This study compiled China's emission inventory of air pollutants and CO_2 from 2005 to 2021 (ABaCAS-EI v2.0 dataset) based on a unified emission-source framework by considering the influences of activity level, technology evolution, and emission control policies. The characteristics of air pollutants and CO_2 emissions were comprehensively analyzed from multiple dimensions such as time, space, sector, and synergies between air pollutants and CO_2 emissions. Mitigation policies have decoupled the emissions of air pollutants and CO_2 with economic development in China since 2013. In the context of growing activity levels, energy structure adjustment and energy and material saving reduced the average annual increase rate of CO_2 emissions by 7 % after 2011. Based on this, end-of-pipe control contributed 51 %–98 % of air pollutant emission reductions after 2013. Industrial boilers and residential fossil fuel combustion sectors in seven provinces (Beijing, Tianjin, Shanghai, Jilin, Henan, Sichuan, and Qinghai) achieved emission reductions in both air pollutants and CO_2 during 2013–2021. The declining trends in both the sectoral and regional emission ratios of air pollutants to CO_2 indicated that the potential for synergistic emission reduction in China declined from 2013 to 2021. The emission ratios in 2021 showed that residential fossil fuel combustion, iron and steel industry, and transportation exhibited relatively higher co-benefits of SO_2, $PM_{2.5}$, NO_x, and VOC emission reductions when CO_2 emissions were reduced. Most cities with a higher potential to synergistically reduce NO_x, VOC, and CO_2 emissions were within the Yangtze River Economic Belt, while those with a higher potential to co-control SO_2 and CO_2, and $PM_{2.5}$ and CO_2 were in southern and northeast China, respectively. Further deconstruction of the sectoral emissions in 2021 suggested future reduction measures: for example, controlling coal consumption in the energy field; promoting innovative technologies with low air pollutant emission intensities and coal-saving measures in the iron and steel industry; combining coal and carbonate replacement technologies with separated particle control measures in the cement industry; and controlling light-duty passenger vehicles, heavy-duty trucks, agricultural machinery, and inland water transport in the transportation sector. Our dataset and findings provide insights into the co-control of air pollutants and CO_2 emissions in the future in China and other countries with the same demand. Our ABaCAS-EI v2.0 dataset can be accessed from https://doi.org/10.6084/m9.figshare.21777005.v1 (S. Li et al., 2022) by species, sector, and province.

1 Introduction

Presently, China faces two strategic tasks – improving air quality, and achieving carbon peak and carbon neutrality. In June 2022, the "Implementation Plan for Synergistic Effectiveness in Reducing Pollution and Carbon" was issued by the Ministry of Ecology and Environment (MEE) and six other departments, which proposed the synergistic reduction of pollution and carbon to promote the overall green transformation of economic and social development (MEE et al., 2022). Promoting the co-control of air pollutants and CO_2 has become inevitable for China's comprehensive green transformation in the new development stage. Therefore, to support the co-control of air pollutants and CO_2 emissions, establishing an updated emission inventory of air pollutants and CO_2 is vital.

Since the past decade, China has implemented several emission control policies to mitigate air pollutants and CO_2 emissions. To control CO_2 emissions, China issued its first comprehensive policy document on climate change in 2007, the National Climate Change Program (CPGPRC, 2007), which clarified key fields and corresponding reduction measures to address climate change by 2010. Since 2011, reducing CO_2 emission intensity has been included as a blinding target in the Five-Year Plan (CPGPRC, 2008). During these years, CO_2 emission reduction measures have been increasingly emphasized and widely implemented, and by the end of 2020, China's CO_2 emissions per unit of gross domestic product (GDP) reduced by 48.4 % compared to that in 2005 (CPGPRC, 2021). Among air pollutants, SO_2 and particle emissions have been preferentially controlled since the 1990s, followed by NO_x emissions based on the 12th Five-Year Plan (2011–2015) (CPGPRC, 2011). In 2013, the Action Plan for the Prevention and Control of Air Pollutants was issued (CPGPRC, 2013), in which key control sectors and air pollution mitigation measures were comprehensively refined. Since then, emissions of multiple air pollutants have rapidly decreased (Zheng et al., 2018; Wang et al., 2022; Lu et al., 2020), and the annual average $PM_{2.5}$ concentration in China has declined by 58.3 % from 72 $\mu g\,m^{-3}$ in 2013 to 30 $\mu g\,m^{-3}$ in 2021 (MEE, 2021).

Previous studies have separately analysed the emission changes and their drivers of air pollutants and CO_2 (Zheng et al., 2020; Geng et al., 2021; C. Li et al., 2022). With the increasing demand for the synergistic reduction of air pollutants and CO_2 emissions, researchers have focused on the emission characteristics of air pollutants and CO_2 in key sectors (e.g., residential combustion, cement industry, and airport) (You et al., 2022; Liu et al., 2021; Tao et al., 2021; Tang et al., 2022) and key regions (e.g., Yangtze River Delta and Pearl River Delta) (Huang et al., 2021; J. Zheng et al., 2021). For example, Huang et al. (2021), B. Zheng et al. (2021), and Gao et al. (2022) analyzed the spatial and sectoral distribution of air pollutants and CO_2 emission characteristics for a given year. Zheng et al. (2018) analyzed the interannual national emission changing trends from 2010 to 2017 and preliminarily explored the contributions of pollution control and activity changes to six macro-emission-source categories; namely, power, industry, residential, transportation, solvent use, and agriculture. However, the changes in air pollutants and CO_2 emissions during 2005–2021 and their drivers still need to be explored. More importantly, few studies have examined the sector or region that has achieved emission reductions for both air pollutants and CO_2 or the sector or region that has a larger synergetic reduction potential.

Accordingly, to bridge this gap, we compiled a coupled emission dataset of air pollutants and CO_2 in mainland China from 2005 to 2021; that is, the Air Benefit and Cost and Attainment Assessment System-Emission Inventory version 2.0 (ABaCAS-EI v2.0), which is an updated version of the ABaCAS-EI (ABaCAS-EI, 2022). The dataset covers CO_2 and nine types of air pollutants, including 11 major source categories and more than 280 subsectors. Historical changes in air pollutants and CO_2 emissions and their relationships were also explored from the perspectives of control policies, source contributions, and spatial–temporal characteristics. Additionally, the emission status and potential reduction directions have also been discussed for key fields that are expected to reduce air pollutants and CO_2 emissions synergistically during the 14th 5-year period in China. The emission dataset and analysis results of this study can provide a foundation for the future synergistic reduction of air pollutants and CO_2.

2 Methods and data

2.1 Emission-source categories

A unified emission-source framework was established for the coupled emission inventory based on the emission-source framework of air pollutants in ABaCAS-EI and the guidelines for the emission inventory of greenhouse gases (NDRC, 2011; Goodwin et al., 2019). The 11 major source categories were power plant, industrial boiler, residential combustion, transportation, open burning, industrial process, solvent usage, oil storage and transportation, waste treatment, agriculture, and other residential sources. Each source had four levels of information: source name (e.g., power plant), subsector name (e.g., coal-fired power), fuels/products/materials (e.g., coal), and technology (e.g., pulverized coal boiler). The air pollutants covered in this emission inventory were SO_2, NO_x, PM_{10}, $PM_{2.5}$, BC, OC, VOCs, NH_3, and CO. The emission-source framework is presented in Table S1.

For each subsector and species, emissions related to both energy consumption (energy-related emissions) and non-energy consumption processes (process-related emissions) were considered. For example, air pollutants and CO_2 emissions from coal combustion and raw material decomposition during the cement clinker production process were all considered in our emission inventory. The energy consumption process generally refers to the fuel combustion and flaring processes, where fuel types, including coal, oil, gas, biomass (or biofuel), and waste, are consumed. Additionally, processes that use energy, such as coking, were also identified as energy-related processes. Other activity processes, such as material treatment and product usage, were identified as non-energy processes.

2.2 Coupled emission inventory

A coupled emission inventory of air pollutants and CO_2 was established based on the emission factor method, as shown in Eq. (1):

$$E_{i,j,p} = A_{i,j} \times \mathrm{EF}_{i,j,p} \times \left(1 - \eta_{i,j,p,k} \times R_{i,j,p,k}\right). \quad (1)$$

Here, i represents the province, including 31 provinces in China (excluding Hongkong, Macao, and Taiwan); j represents the emission source, including 285 emission accounting units; p represents emission species, including nine types of air pollutants and CO_2; k represents end-of-pipe control measures, such as electrostatic precipitator and fabric filter to control particle emissions; E stands for emission; A is the activity data, such as fuel consumption, product, and material consumption; EF is the emission factor without end-of-pipe pollution control; η is the measure-specific pollution removal efficiency; and R is the measure-specific application ratio.

To simultaneously calculate air pollutants and CO_2 emissions, the uniform activity dataset was collected and organized considering the estimated demand for both air pollutants and CO_2 emissions under the unified emission-source framework. Most activity data were shared for CO_2 and air pollutants concerning fuel consumption and output of industrial products, while some data were separated for CO_2 or air pollutant emission estimations, such as calcium carbide production for CO_2 and solvent use for VOCs. The activity data were mostly collected from official sources with quality assurance. Details of each emission source are presented comprehensively in Table S2. The emission factors of air pollutants were obtained from localized experiments or integrated from related literature, and those of CO_2 were obtained by referring to the guidelines for the emission inventory of greenhouse gases in China (NDRC, 2011) and the guidelines issued by the Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al., 2006; Goodwin et al., 2019). The measure-specific removal efficiencies and their application ratios for air pollutants are collected from official reports, national environmental statistics, industrial investigations, and previous studies (Liu et al., 2018, 2019; Wang et al., 2019; Zheng et al., 2019; Liu et al., 2021; B. Zheng et al., 2021). Data on emission factor, measure removal efficiency, and application ratio have been introduced in detail in our previous peer-reviewed research (Table S3). Regarding CO_2 removal, current carbon capture, utilization, and storage (CCUS) technologies are still in the scientific research or demonstration stage, and the annual carbon capture capacity (3 Mt yr^{-1}) is only 0.02 % of the actual emissions in 2021 (Cai et al., 2021). Annual CO_2 removal of each province or point source was calculated based on the commissioning time and carbon removal capacity of each demonstration project.

2.3 Uncertainty analysis of the emission inventory

Uncertainties in emission inventories are mainly due to a lack of comprehensive or local information on activity data, emission factors, and pollutant removal conditions. In this study, a Monte Carlo simulation was performed to quantify the uncertainty in emission estimates. Parametric distributions linked to the reliability and accuracy of some data were introduced in our previous studies (Table S3) or collected from the literature (Lang et al., 2014, 2018; Li et al., 2020; Zhou et al., 2022), and CO_2-related data were collected from the IPCC guidelines (Goodwin et al., 2019; Eggleston et al., 2006) and literature (Choulga et al., 2021). The Monte Carlo simulation was then repeated 10 000 times to estimate the emissions with a 95 % confidence interval. The uncertainty of the total emissions per species was obtained by combining the values obtained by subsector by province.

3 Results and discussion

3.1 Trends of air pollutants and CO_2 emissions

According to the ABaCAS-EI v2.0 dataset, SO_2, $PM_{2.5}$, NO_x, VOC, NH_3, and CO_2 emissions in China were 5.5 (3.9–6.6) Mt, 6.6 (2.8–10.5) Mt, 15.8 (11.2–20.8) Mt, 23.1 (10.7–46.6) Mt, 9.7 (4.6–14.9) Mt, and 12.9 (12.4–13.8) Gt in 2021, respectively. We compared our results with other published datasets, such as the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC; Zheng et al., 2018), China High Resolution Emission Gridded Data (CHRED; Gao et al., 2022), Community Emissions Data System (CEDS; O'Rourke et al., 2021), Emissions Database for Global Atmospheric Research (EDGAR; Crippa et al., 2020), and International Energy Agency dataset (IEA, 2022) (Fig. S1). The emission trends of air pollutants and CO_2 were generally consistent across the different emission datasets. Owing to the differences in the emission-source frameworks (considering CO_2 emission sources, for example, in Table S4), some differences were observed among the absolute emissions of the various datasets.

Figure 1 shows the trends in air pollutants and CO_2 emissions in China from 2005 to 2021. All air pollutant emissions have declined since 2013. The CO_2 emissions showed an increasing trend but at a slower growth rate. During 2005–2011, CO_2 emissions had increased by 68 %, which is roughly comparable to the growth rate of the GDP (87 %).

However, from 2011 to 2021, China's CO_2 emissions only increased by 20 % when GDP growth was up to 91 %. It can be concluded that China's CO_2 emissions have relatively decoupled with GDP after 2011 as defined by Organisation for Economic Co-operation and Development (OECD, 2002). The different trends in the emissions of air pollutants and CO_2 in China were closely related to reduction policies. As discussed above, the annual growth rate of CO_2 emissions significantly reduced since 2011, when the carbon emission intensity was included in the national Five-Year Plan (CPGPRC, 2008). SO_2 and $PM_{2.5}$ emissions continuously decreased since 2005 owing to the requirements of total emission control of SO_2 and particles according to the 11th Five-Year Plan. After 2013, almost all air pollutant emissions started decreasing after the "Action Plan for the Prevention and Control of Air Pollutants" was issued (CPGPRC, 2013).

3.2 Sectoral contributions to the emissions of air pollutants and CO_2

3.2.1 Sectoral emission changes

To identify key emission reduction sectors in the past, we further comprehensively analyzed emission changes in a total of 15 subsectors (Fig. 2). Before 2013, SO_2 emissions were mainly reduced from power plants, whereas $PM_{2.5}$ and VOC emissions were mainly reduced from the cement industry and on-road vehicles, respectively, which is closely related to the sector-specific emission standards implemented around 2005 (MEE, 2003a, b, 2004). Additionally, with increasing socio-economic development, the spontaneous phase-out of residential biofuel also contributed to emission reductions of $PM_{2.5}$ and VOCs.

After 2013, air pollutant emissions of almost all sectors started declining with the implementation of the Action Plan for the Prevention and Control of Air Pollutants (CPGPRC, 2013) and the Three-Year Action Plan to Win the Battle against the Blue Sky (CPGPRC, 2018). For SO_2, power plants, industrial boilers, and residential fossil fuel combustion were the major reduction contributors, which accounted for more than 75 % of SO_2 emission reductions during 2013–2021 in China. End-of-pipe control played a significant role in the first two sectors. Further, the proportion of coal-fired generator units completing ultra-low emission retrofitting increased from 36 % in 2013 to 93 % in 2021. By the end of 2017, the end-of-pipe control level for coal-fired industrial boilers had approached that of coal-fired generator units. Contrastingly, considerable SO_2 emission decline in the residential sector was likely due to the energy structure adjustment measures, especially "coal to electricity" and "coal to gas" in northern China, which sharply cut sectoral coal consumption from 173 million tonnes of standard coal (Mtce) in 2013 to 98 Mtce in 2021. Power plants and industrial boilers also contributed the largest (almost 70 %) NO_x reductions during 2013–2021 in China because of their ultra-low emission retrofit. Moreover, the cement industry and on-road vehicles contributed an additional 17 % to NO_x emission reductions. In the cement industry, some provinces in China took the lead in implementing ultra-low emission standards without national mandatory requirements in recent years, and the proportion of production lines equipped with high-efficiency removal facilities (e.g., a combination of low NO_x combustion technology and selective non-catalytic reduction technology) has increased from less than 1 % in 2013 to approximately 25 % in 2021. Further, the proportion of on-road vehicles under China IV–VI standards increased by 50 % from 2013 (16 %) to 2021 (65 %), with NO_x emission factors after exhaust gas treatment being 82 %–96 % lower than China II vehicles and 44 %–87 % lower than China III vehicles (Wen et al., 2021). For $PM_{2.5}$, the iron and steel industry, open burning, and the cement industry were the major reduction contributors, accounting for 29 %, 20 %, and 12 % of $PM_{2.5}$ emission reductions, respectively, during 2013–2021 in China. These reductions were likely attributed to end-of-pipe control measures. After the related policy was issued (MEE et al., 2019), the proportion of steel production capacity having completed or conducting ultra-low emission retrofitting sharply increased to approximately 60 % nationally within 3 years. Owing to the "no open burning" policy, the average proportion of open burning of straw in China reduced from approximately 25 % in 2013 to 10 % in 2021. Moreover, the no open burning policy also contributed to 1.8 Mt VOC emission reductions during 2013–2021, although its contribution was offset by the increased use of solvents having high VOC content. Regarding NH_3, the fertilizer sector dominated the emission changes with 1.1 Mt NH_3 emission reductions during 2013–2021, likely due to the policy of total fertilizer application control in recent years. End-of-pipe control measures can be attributed to the air pollutant emission reductions during 2013–2021 in China. A preliminary assessment based on the control variate method (Zhang et al., 2019) showed that end-of-pipe control measures contributed approximately 74 % (51 %–98 %) of the total emission reductions.

Furthermore, power plants were the dominant contributor to the increase in CO_2 emissions, accounting for 47 %–77 % of the total CO_2 incremental emissions from 2005 to 2021. This was likely because of the continuous increase in fossil fuel consumption, with the share of coal consumption being above 90 % in the power plant sector. Notably, if the energy structure and efficiency were kept at the levels in the year 2005, the CO_2 emissions from power plants would increase by a factor of 2.4, the same increase fold as in total power generation (including fossil fuel and non-fossil energy generation) from 2005 to 2021. However, the actual sectoral CO_2 emissions showed only a 1.0-fold increase. By inference, the energy mix transformation and energy efficiency improvement offset half of the CO_2 emission increase. In terms of the energy structure, the proportion from non-fossil fuel generation increased by 16 % during 2005–2021 (NBS, 2021),

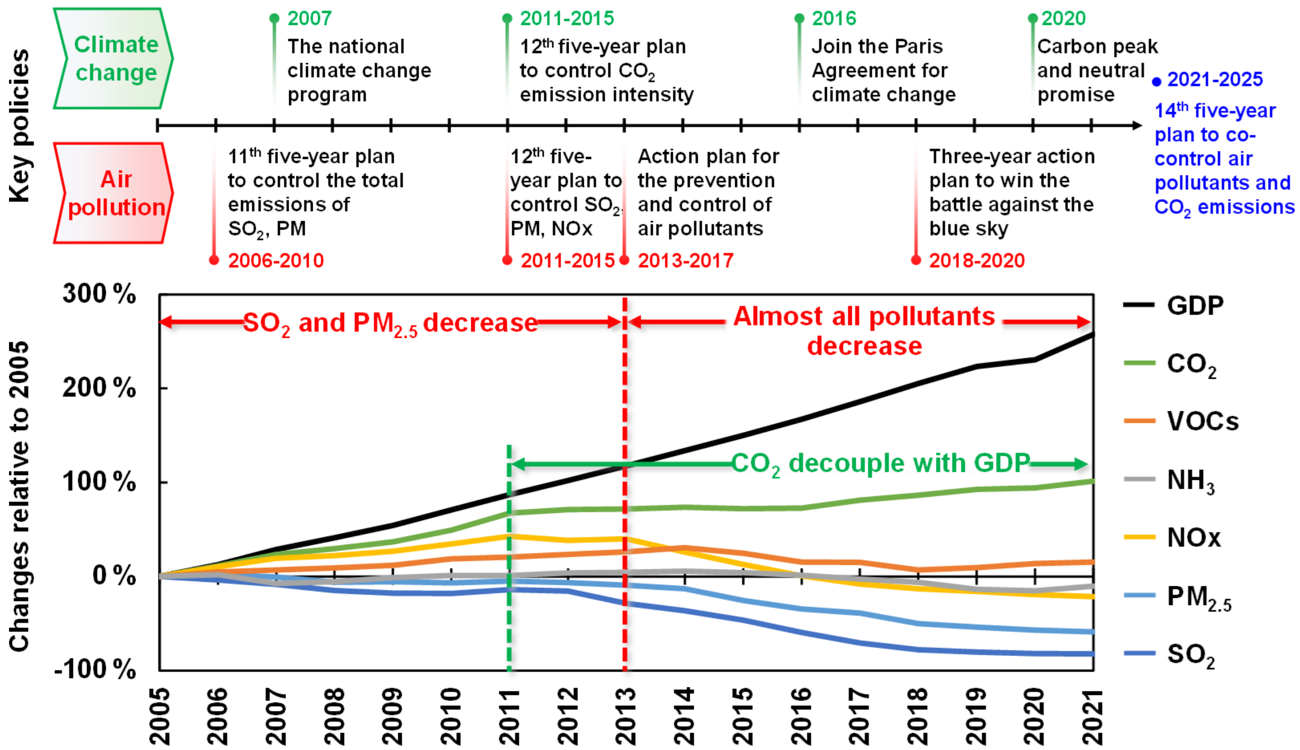

Figure 1. Interannual variations of GDP, and emissions of air pollutants and CO_2 relative to 2005 in China.

especially after 2013 (a 10 % increase from 2013 to 2021). In terms of energy efficiency, the energy consumption rate for electricity supply declined from 370 gce $kW h^{-1}$ (grams of coal equivalent per kilowatt hour) in 2005 to 303 gce $kW h^{-1}$ in 2021 (EBCEPY, 2021). Simultaneously, similar measures were also implemented in other sectors, which resulted in a shrink of CO_2 emissions growth after 2013 (Fig. 2). For example, energy structure adjustment measures, such as replacing coal and promoting clean energy, have been vigorously promoted in the industrial boiler and residential sectors, which decreased sectoral coal consumption by 23 % and 44 % from 2013 to 2021, respectively. Further, energy efficiency during 2013–2021 in the industrial boiler industry, the iron and steel industry, the cement industry, and on-road vehicle sectors increased by 12 %, 10 %, 10 %, and 22 %, respectively.

3.2.2 Sector-specific synergy of air pollutants and CO_2 emissions

The sector-specific changes in air pollutants (excluding NH_3) and CO_2 emissions are shown in Fig. 3. The seven sectors shown in the figure account for 89 % of CO_2 emissions and 22 %–84 % of air pollutant emissions in 2021 (Fig. S2). We found that industrial boilers and residential fossil fuel combustion first achieved simultaneous reductions of air pollutants and CO_2 emissions from 2013 to 2021, which was attributed to the energy structure adjustment in these two sectors, as discussed above. However, CO_2 emissions did not change significantly from the iron and steel industry and off-road machines during 2013–2021, whereas air pollutant emissions gradually decreased. This was primarily because of a combination of energy and material saving and end-of-pipe control measures. On the one hand, the decrease in energy and material consumption rates offset the effects of increased activity on the sectoral emissions of air pollutants and CO_2. For instance, the coal and coke consumption rates in blast furnaces decreased from 148 and 553 $kg\,t^{-1}$ in 2013 to 145 and 461 $kg\,t^{-1}$ in 2021, respectively, thereby largely curbing coal consumption in the iron and steel industry. The oil consumption rates for agriculture machinery, construction machinery, railway transport, and inland waterway transport declined by 2 %, 3 %, 17 %, and 19 %, respectively. On the other hand, end-of-pipe control measures, such as ultra-low emission retrofitting in the iron and steel industry and emission standard upgrades for off-road machines, resulted in additional air pollutant emission reductions in these two sectors. However, CO_2 emissions from the power plant industry, cement industry, and on-road vehicle sectors are still increasing, indicating significant carbon reduction challenges in the coming decades.

Several studies have indicated that with the exhaustion of end-of-pipe control reduction effects in the future, more ambitious carbon reduction measures would be needed to collaboratively mitigate air pollutant emissions to achieve the

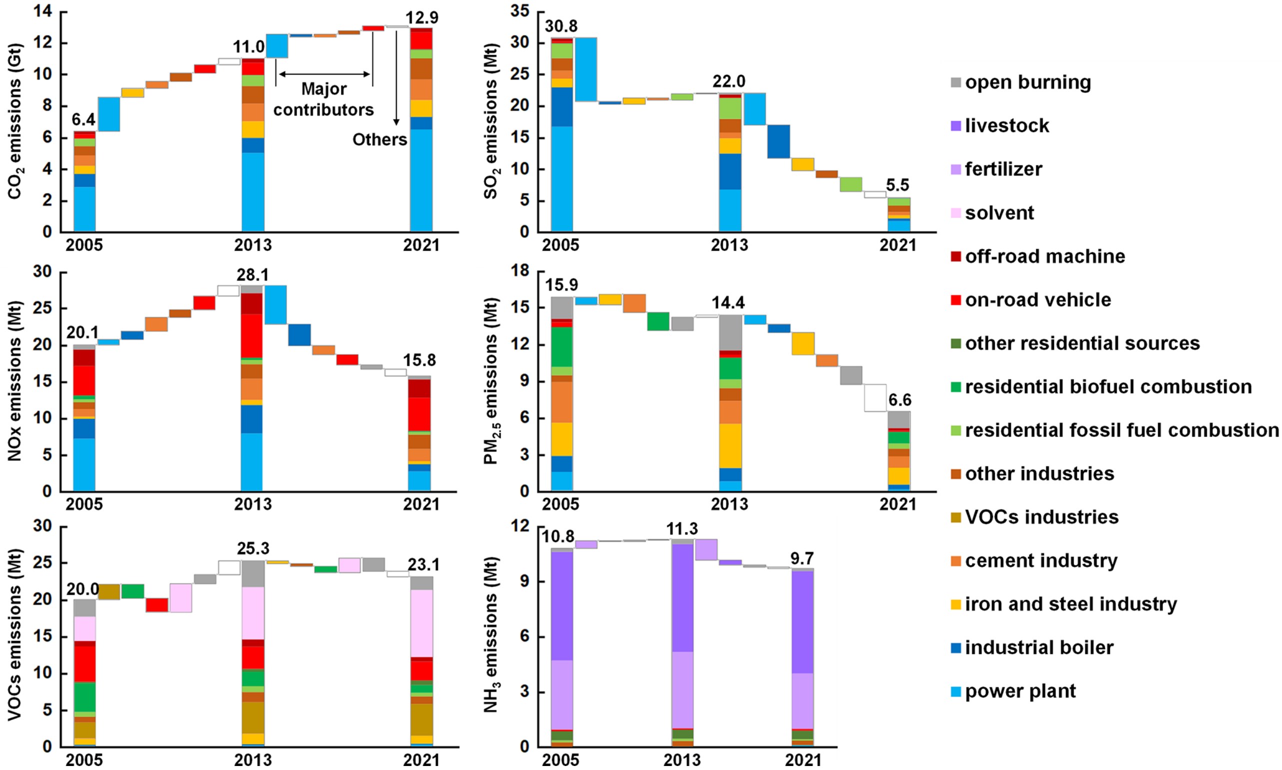

Figure 2. Sectoral contributions on the emission changes of air pollutants and CO_2 from 2005 to 2021 in China.

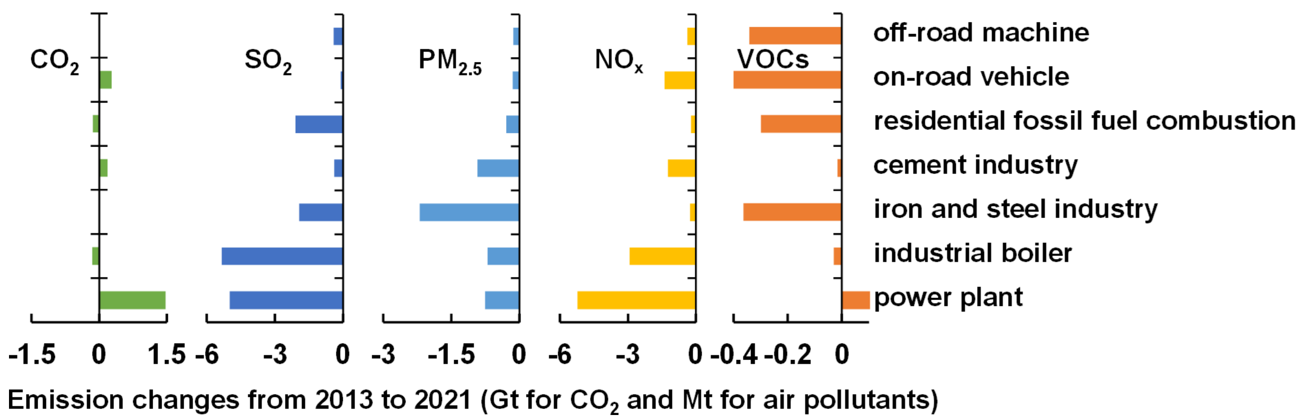

Figure 3. Sectoral contributions to the emission changes of air pollutants and CO_2 in China during 2013–2021.

World Health Organisation air quality guidelines (Cheng et al., 2021; Xing et al., 2020). In this study, to identify sectors with large air pollutant reduction potential per unit CO_2 emission reduction, ratios of air pollutant emissions to CO_2 emissions were calculated for each sector. The larger the ratio, the greater the potential for the synergistic reduction of air pollutant emissions under the same CO_2 reduction level.

In China during 2013–2021, all ratios of air pollutants to CO_2 for key sectors decreased to varying degrees (Fig. 4). Specifically, sectoral SO_2/CO_2, $PM_{2.5}$ / CO_2, NO_x/CO_2, and VOCs / CO_2 ratios declined 49.9 %–99.6 %, 25.0 %–89.2 %, 17.0 %–74.1 %, and 69.0 %–81.1 %, respectively. This probably resulted from the relatively faster emission reduction rates of air pollutants than those of CO_2, thus revealing the faster mitigation progress of air pollutants than that of carbon in China in recent years. The greater the proportion of air pollutants that are reduced, the lesser the air pollutant emissions remain to be synergistically reduced with CO_2 emissions; that is, the synergistic reduction potential of all sectors weakened. Therefore, identifying sectors with greater potential for synergistic emission reductions is even more important to support effective policymaking in the future.

In 2013, the value of SO_2/CO_2 ratio was the highest (6.0) in the industrial boiler sector, followed by the residential fossil fuel combustion sector (4.8). However, in 2021, the highest ratio sector was residential fossil fuel combustion (2.1), with its value being more than 4 times larger than those of other sectors, indicating the potential priority of this sector to synergistically reduce SO_2 and CO_2 emissions in the future. Energy consumption, particularly from coal combustion, is a major source of SO_2 and CO_2 emissions. As an energy consumption (especially coal) sector with almost no end-of-pipe control, it is reasonable and predictable that the residential sector had the greatest potential for synergistic SO_2 and CO_2 reduction in the future when the reduction potential for end-of-pipe control measures was gradually exhausted. For the NO_x/CO_2 and VOCs / CO_2 ratios, transportation sectors, including on-road vehicles and off-road machines, were primarily focused upon, with more than 2 times higher values than those of other sectors. Further, although the iron and steel industry sector had the highest $PM_{2.5}$ / CO_2 ratio in both 2013 (3.4) and 2021 (1.3), the ratio value gradually decreased. Particularly, the $PM_{2.5}$ / CO_2 ratio for the iron and steel industry sector was more than twice that for the other sectors in 2013, while this value reduced to 1.6 in 2021. Other sectors with comparable ratio levels in 2021, such as residential fossil fuel combustion (0.8), off-road machine (0.8), and the cement industry (0.7), are also suggested for consideration in future synergistic reductions of PM and CO_2.

Although the emission ratio results in this study indicated a general direction for synergistic reduction, the ratio only represented the potential of synergistic reduction rather than the real ability, and this gap requires additional attention and further research. This difference may be due to different mechanisms of air pollutants and CO_2 production in different sectors. For example, emissions of both $PM_{2.5}$ and CO_2 from the off-road machine sector were directly related to the oil combustion process, which indicated a high potential and ability of this sector to achieve synergistic emission reduction. In the cement industry, $PM_{2.5}$ emissions mostly originated from material treatment processes (such as cement grinding), and CO_2 emissions mainly resulted from coal combustion and raw material calcination. The independent emission generation processes of $PM_{2.5}$ and CO_2 suggest that although the cement industry sector had a relatively high ratio of $PM_{2.5}$ / CO_2, its actual synergistic reduction ability was likely poor. Thus, based on the results of this study and the emission mechanisms, further in-depth analysis, such as that from the perspective of reduction measures, is still needed in the future.

3.3 Regional contributions to air pollutants and CO_2 emissions

3.3.1 Provincial emission changes

Figure 5 shows the provincial emission changes in air pollutants and CO_2 from 2005 to 2013 and 2013 to 2021. Before 2013, only Beijing achieved reductions in both air pollutants and CO_2 emissions. Nearly two-thirds of the provinces achieved reductions in SO_2 and $PM_{2.5}$ emissions, while CO_2, NO_x, and VOC emissions increased in over 90 % of the provinces. Guangdong, Zhejiang, Jiangsu, and Shandong, which were the major contributors in reducing national SO_2 and $PM_{2.5}$ emissions, were all located in regions with heavy air pollution (Jiang et al., 2022), such as the Pearl River Delta (PRD; including some cities located in Guangdong), the Yangtze River Delta (YRD; including Shanghai, Jiangsu, Zhejiang, and Anhui), and the Beijing–Tianjin–Hebei region and its surrounding provinces (BTHs; including Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan). Inner Mongolia had the largest CO_2 emission increase (450 Mt) in China during 2005–2013 due to its high coal consumption (top three in 2013) and the largest increase in coal consumption (210 Mt) during 2005–2013 among the Chinese provinces.

After 2013, seven provinces, namely Beijing, Tianjin, Shanghai, Jilin, Henan, Sichuan, and Qinghai, achieved co-control of the air pollutants and CO_2 emissions. However, most provinces are still experiencing a decline in air pollutant emissions and an increase in CO_2 emissions. Among the provinces, Hebei, Shandong, and Henan contributed the most to national air pollutant emission reductions, all of which were located in the BTHs region, which has comprehensive and stringent reduction measures (CPGPRC, 2013, 2018). Further, inner Mongolia, Xinjiang, and Shandong accounted for the largest increases in CO_2 emissions in recent years and were the top thermal power generators with a faster increase in thermal power generation and coal consumption in China during 2013–2021. Notably, one-third of the provinces, particularly Liaoning, Jiangsu, and Fujian, were still under pressure to reduce both CO_2 and VOC emissions.

3.3.2 Performance of cities on the co-control of air pollutants and CO_2

Air pollutants and CO_2 emissions were concentrated in the central and eastern parts of China owing to the dense populations and more developed economies in these regions (Fig. S3). To identify hotspots with a greater potential for the synergistic reduction of air pollutants and CO_2, cities with higher CO_2 emissions were selected to calculate the ratios of air pollutants to CO_2 emissions. Finally, 160 cities in 29 provinces (except for Hainan and Xizang provinces) were selected in this study, which accounted for 80 % of the national CO_2 emissions. Their air pollutant to CO_2 emission ratios in 2013 and 2021 were also calculated (Fig. 6). Gener-

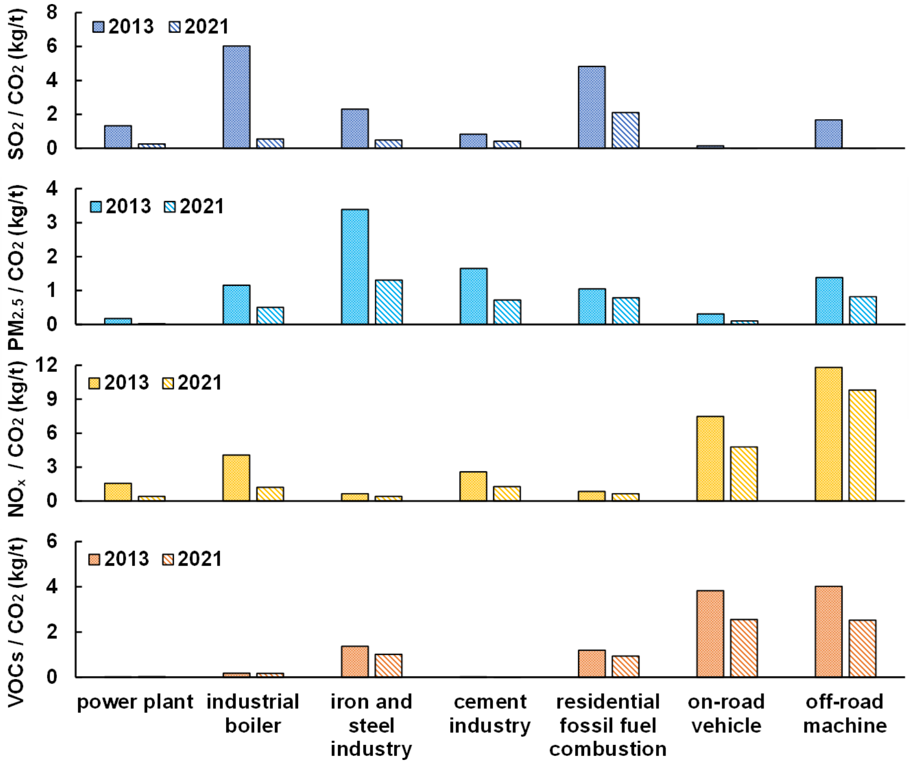

Figure 4. Emission ratios of air pollutants to CO_2 in 2013 and 2021 in China.

ally, a nationwide decline in this ratio was observed. Ratios of SO_2/CO_2 showed the largest decrease of 78 % on average, followed by $PM_{2.5}$ / CO_2 (61 %), and NO_x/CO_2 (51 %). This result was consistent with the analysis results from the perspective of emission sectors, implying that the potential for cities to reduce these three air pollutants and CO_2 synergistically may have reduced by more than half on average. However, the VOCs / CO_2 ratio decreased only by 21 % on average; moreover, the ratios increased by 1 %–24 % in 32 cities. Considering that the current level of VOCs control in China is still weak, a large potential exists for the co-control of VOC and CO_2 emissions in the future, especially in the transportation sector, as discussed in Sect. 3.2.2.

We further explored the relationship between the ratio decline and the city's gross regional product (GRP). For SO_2/CO_2 and $PM_{2.5}$ / CO_2, their decline proportions generally increased as the city GRP increased; in other words, the relatively developed cities, such as Beijing and Shanghai, had the fastest decline in the synergistic reduction potential for SO_2, $PM_{2.5}$, and CO_2 emissions. These cities were mostly located in the key regions of China's air pollution mitigation in the past decade (such as BTHs, YRD, PRD, and the Sichuan–Chongqing region), whose reduction intensity (i.e., the application ratio of emission reduction measures) was much greater than that in other cities. At the same time, emission reductions of SO_2 and $PM_{2.5}$ were mainly contributed by end-of-pipe control measures in power plants and industrial sectors (as discussed in Sect. 3.2.1) that do not have synergistic emission reduction effects. These factors ultimately led to a significant decrease in the potential for synergistic reductions in relatively developed cities. While for NO_x/CO_2 and VOCs / CO_2, their decline proportion decreased as the city GRP increased; the more developed cities maintained a higher emission ratio, especially when their GRP was larger than CNY 1000 billion. Unlike SO_2 and $PM_{2.5}$, the decline of synergistic reduction potential in NO_x and VOCs with CO_2 is much smaller in more developed cities. Considering the considerable contributions from the transportation sector to NO_x and VOC emissions (Fig. S2), the promotion of new energy vehicles in recent years was probably the main reason, which was recognized as a measure with a high synergistic reduction ability. By the end of 2021, the new energy vehicle population in Shanghai, Beijing, and Shenzhen increased to 635 000, 507 000, and 544 000, respectively, where the proportions of new energy buses were up to more than 50 %. Although industrial end-of-pipe control measures also contributed to NO_x and VOC emission reductions nationwide, new energy vehicles were more widely promoted in relatively developed cities, which had more vehicles and stronger financial strength than less developed cities. This measure finally avoided a greater decrease in the synergistic reduction potential of NO_x and VOCs with CO_2 in more developed cities as in the case of SO_2 and $PM_{2.5}$.

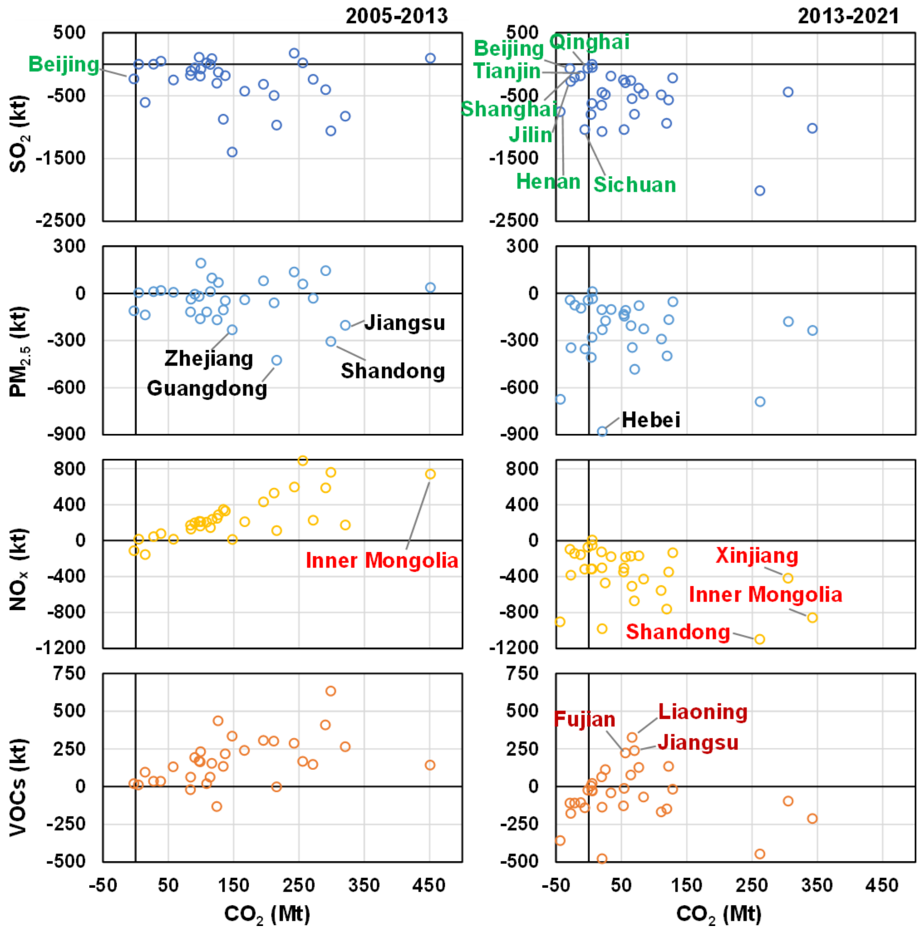

Figure 5. Provincial emission changes of air pollutants and CO_2 during 2005–2013 and 2013–2021.

The average ratio of SO_2/CO_2 in cities was 2.0 in 2013, while cities with a ratio > 2.0 were rarely observed by 2021; further, high values in 2021 were found in five cities (Guiyang City, Liupanshui City, Zunyi City, Bijie City, and Qiannan Zhou) in northwest Guizhou Province and three cities (Kunming City, Qujing City, and Honghe Zhou) in northern Yunnan Province. In 2013, the average ratio of $PM_{2.5}$ / CO_2 in cities was 1.3, with 70 cities above the average; however, the number of cities decreased to just four in 2021, which were Harbin City and Qiqihar City in Heilongjiang Province, Songyuan City in Jilin Province, and Guilin City in Guangxi Province. More than 95 % of the cities had a NO_x/CO_2 ratio of > 2.0 in 2013, while in 2021, only six cities were observed. These cities were all within the Yangtze River Economic Belt, including Chongqing City, Chengdu City, and Deyang City in Sichuan Province; Wuhan City and Huangang City in Hubei Province; and Anqing City in Anhui Province. Regarding the VOCs / CO_2 ratio, some separate hotspots located in Yunnan, Xinjiang, and the BTHs region gradually disappeared from 2013 to 2021, while the ratios of some cities in Liaoning Province and eastern coastal areas increased slightly. In 2021, only 12 cities within the Yangtze River Economic Belt showed a VOCs / CO_2 ratio of > 3.0, including two cities (Chengdu City and Deyang City) in Sichuan Province, four cities (Huanggang City, Jingzhou City, Xiangyang City, and Yichang City) in Hubei Province, and six cities (Taizhou City, Zhoushan City, Jinhua City, Shaoxing City, Ningbo City, and Hangzhou City) in Zhejiang Province.

Summing up the target cities with a higher emission ratio of air pollutants to CO_2, it can be inferred that city clusters within the Yangtze River Economic Belt have a relatively high potential to conduct synergistic reductions of NO_x, VOC, and CO_2 emissions, especially in Chengdu, Chongqing, and Huanggang cities. Moreover, cities with a higher potential to co-control SO_2 and CO_2, and $PM_{2.5}$ and CO_2 were separately located in southern and northeastern China.

3.4 Implication for air pollutants and CO_2 emission reduction in the future

According to policies for future emission mitigation (MEE et al., 2022), the structural adjustments of energy, industry, and

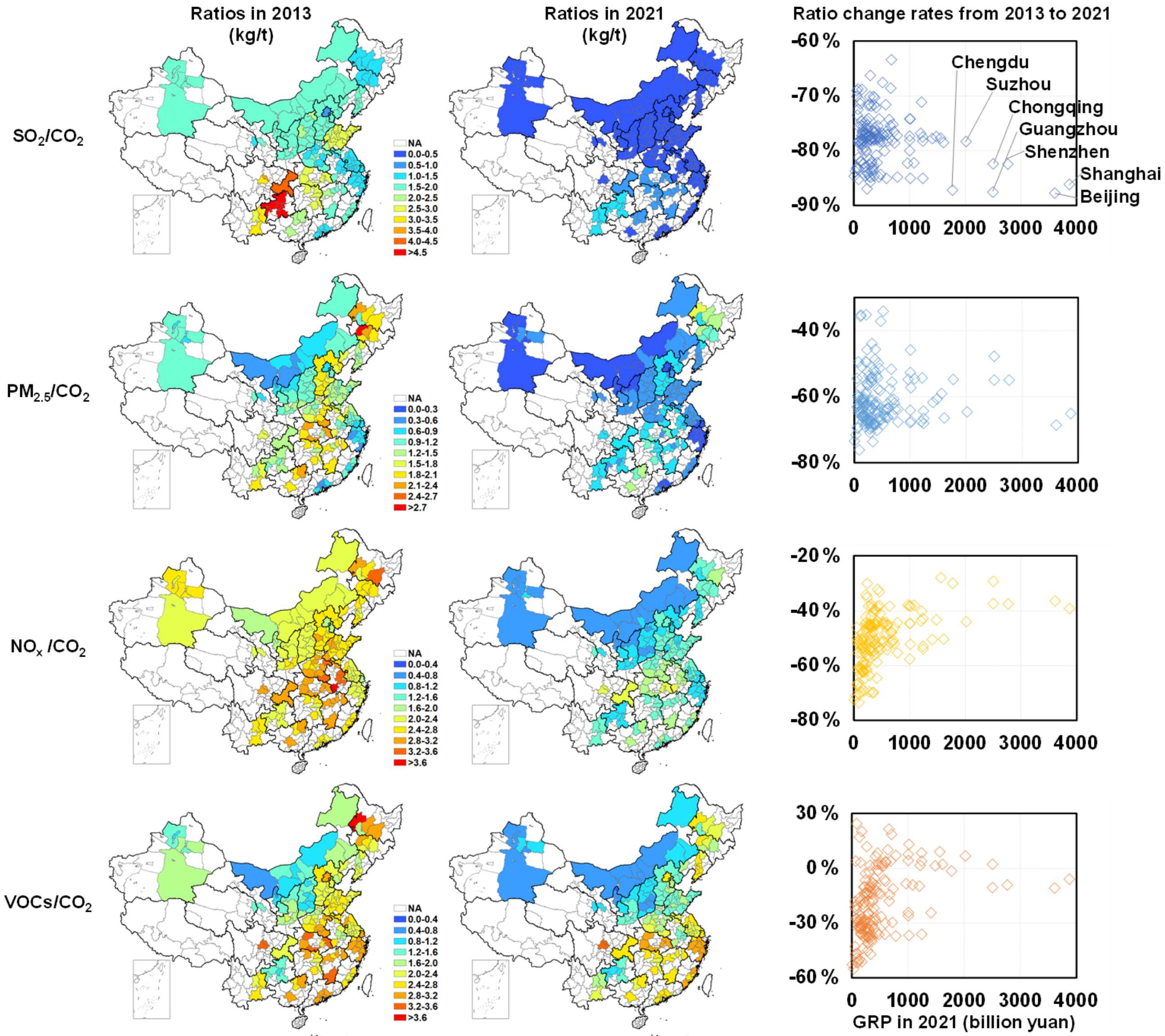

Figure 6. The city's ratios and their change rates of air pollutant emission to CO_2 emission during 2013—-2021 in China (NA: data not analyzed, GRP: gross regional product).

transportation are key measures to promote the synergistic reduction of air pollutants and CO_2. Therefore, we comprehensively analyzed these sectors to explore future synergistic emission reduction measures.

Power plants, residential combustion, and industrial boilers were the major energy combustion sectors, which consumed 64 % of total fuel consumption in 2021. Figure 7 shows that coal was still the dominant fuel in 2021 in China, which accounted for 78 % of the total fuel consumption of energy sectors and contributed 91 %, 88 %, 33 %, and 83 % of CO_2, SO_2, $PM_{2.5}$, and NO_x emissions from energy sectors, respectively. Moreover, power plants were still the major coal-fired sector with 86 % of energy consumption. Thus, limiting total coal consumption in the future remains a key control policy for the energy sectors. Notably, although biomass only accounted for 7 % of the total fuel consumption of the energy sectors, it contributed 66 % of $PM_{2.5}$ emissions, because almost no particularly efficient control measures (especially end-of-pipe measures) were employed for residential combustion. Given the difficulty of using de-dusting equipment for residential biomass combustion, biomass fuels are suggested to be concentrated in power plants or industrial sectors as a "zero-carbon" energy that can install end-of-pipe measures.

The iron and steel and cement industries were the major industrial sectors contributing 51 %–79 % of industrial CO_2 and most air pollutant emissions in 2021 in China. To achieve a synergistic reduction in these two sectors, clean energy pro-

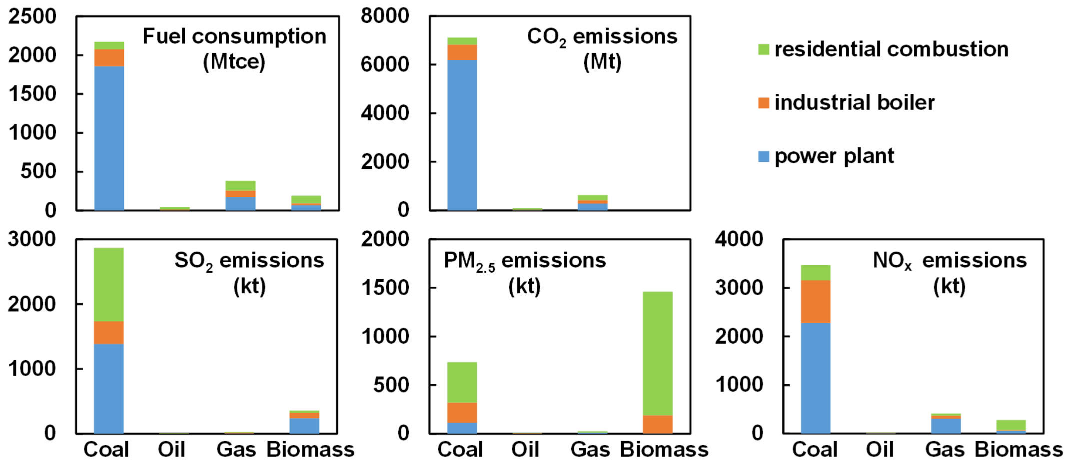

Figure 7. Fuel consumption and related emissions from energy sectors in 2021 in China.

motion and technological reform are ideal control measures for implementation in the future (Wei et al., 2022). Therefore, this study further analyzed the sectoral emissions of energy- and process-related components for control measure implementation (Fig. 8).

In the iron and steel industry, coal is the dominant fuel used in the processes, such as coking, sintering, and blast furnace iron-making. Emissions related to coal consumption are recognized as energy-related emissions; moreover, emissions produced from other processes, such as iron ore treatment, steel-making, casting, and steel-rolling, are process-related emissions. The emission proportions of each process were either calculated based on our emission inventory or were collected from the literature (Ning and Qin, 2006; Zhang et al., 2012; Wang et al., 2014). Interestingly, in 2021, more than 90 % of CO_2 was related to energy consumption, but more than 60 % of air pollutant emissions were related to production technology and process. This contradiction poses a significant challenge for the iron and steel industry conducting synergistic emission reductions of air pollutants and CO_2. This indicated that replacing coal with clean energy (e.g., natural gas and biofuel) is not sufficient to effectively mitigate sectoral air pollutant emissions; instead, promoting innovative technologies (e.g., H_2-based direct reduced iron technology), which have low air pollutant emission intensity and the co-benefit to reduce or avoid coal consumption, is recommended.

Coal is also the major fuel used in cement clinker calcination in the cement industry. Process-related emissions are released during processes, such as raw material processing, material grinding, and cement grinding. The emission proportions of each process were either calculated based on our emission inventory or were collected from the literature (Bai et al., 2019). Coal consumption contributes 34 %, 22 %, and 65 % of CO_2, SO_2, and NO_x emissions, respectively, in 2021, indicating that promoting clean energy has considerable potential and value to achieve synergistic reduction. Regarding process-related emissions, CO_2 was mainly released from the use of limestone, SO_2 was mainly released from the use of raw materials containing sulfate, and $PM_{2.5}$ was closely related to the grinding process. This indicated that improving the material structure or quality has the potential to co-control CO_2 and SO_2 emissions, whereas specific control measures are needed to reduce sectoral $PM_{2.5}$ emissions with limited synergistic reduction potential.

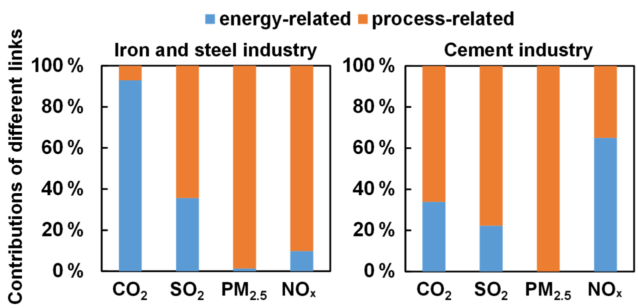

Figure 8. Deconstruction of emissions from major industrial sectors in 2021 in China.

The transportation sector includes nine types of on-road vehicles and four types of off-road machines (Fig. 9). Considering that oil combustion is the main source of sectoral emissions, promoting new energy and improving fuel efficiency are two possible measures to synergistically reduce air pollutants and CO_2 emissions (Wu et al., 2017). In the on-road vehicle subsector in 2021, light-duty passenger vehicles contributed 43 % of CO_2 and 49 % of VOC emissions, while heavy-duty trucks contributed 33 % of CO_2 and 65 % of NO_x emissions. This suggested that emission reduction measures should be prioritized for light-duty passenger vehicles and heavy-duty trucks. For the off-road machine subsector, agricultural machinery and inland water transport contributed 32 %–58 % and 31 %–58 % of air pollutants and CO_2 emissions, respectively, indicating their considerable potential for synergistic reduction.

3.5 Emission uncertainty analysis

Based on the Monte Carlo simulation, the uncertainties in the emission estimation for SO_2, $PM_{2.5}$, NO_x, VOCs, NH_3, and CO_2 were within [−30 %, 19 %], [−58 %, 60 %], [−29 %, 32 %], [−54 %, 102 %], [−53 %, 53 %], and [−4 %, 6 %]. Uncertainties in emission inventories were mainly due to a lack of comprehensive or local information on activity data, emission factors, and pollutant removal conditions. The highest uncertainty was observed for VOC emissions. One important reason for this is that the complexity of VOC-related emission sources likely introduced great uncertainty in acquiring activity data and testing emission factors. For example, the solvent sector accounts for nearly half of VOC emissions in China. Although this study has considered nearly 30 types of solvents used in several fields (such as industry, transportation, agriculture, and residential) (Table S1), in real life, each type of solvent includes multiple products with different features (such as being solvent based, water based, and powder based) and compositions from various manufacturers. Further, owing to sectoral complexity, there are still no public or official statistics on the consumption of different types of solvents for different applications, and localized testing of emission factors for different types of solvents is also limited. In recent years, several teams have attempted to test solvent-related VOC emission factors (Sun et al., 2020; Gao et al., 2021). Future studies could combine these works to further reduce emission uncertainties. Additionally, $PM_{2.5}$ emissions also have a relatively high level of uncertainty, which is related to the difficulty in accessing pollutant removal conditions in industrial sectors. In recent years, as emission standards continue to be stringent, end-of-pipe equipment (such as desulfurisation, denitrification, and dust removal facilities) has been widely used and rapidly updated in various industrial sectors (Wang et al., 2020; Bo et al., 2021). However, as such data are still subject to a high level of confidentiality and a certain release lag, the emission inventory may not be able to accurately and promptly capture the application and efficiency of the equipment, thus, creating uncertainties in emission estimates. Future inventory updates will require the revision of such data based on new pollution censuses or environmental statistics.

4 Data availability

The ABaCAS-EI v2.0 dataset can be accessed from https://doi.org/10.6084/m9.figshare.21777005.v1 (S. Li et al., 2022).

5 Conclusions and implication

To support the co-control of air pollutants and CO_2 emissions in China in the future, we introduced the ABaCAS-EI v2.0 dataset, which is a coupled emission inventory of air pollutants and CO_2 based on a unified emission-source framework. An analysis of interannual emission trends from 2005 to 2021 revealed that China's air pollutants and CO_2 emissions decoupled from economic development. The implementation of reduction measures has been the major driver affecting emission changes in the past decade in China. Further, on exploring the changes in sectoral emissions, we found that air pollutant emissions were mitigated faster than CO_2 emissions in China. Generally, the implementation of structural adjustment measures and energy and material saving measures has significantly slowed the rate of increase in CO_2 emissions; moreover, end-of-pipe control measures have dominantly contributed to the emission reductions of air pollutants for most sectors. During 2013–2021, the power plant industry, the cement industry, and the on-road vehicle sectors were still in the phase of decreasing air pollutant emissions but showed an increase in CO_2 emissions. Analysis of regional emission changes revealed that the number of provinces achieving emission reduction in both air pollutants and CO_2 increased from one (Beijing) during 2005–2013 to seven (Beijing, Tianjin, Shanghai, Jilin, Henan, Sichuan, and Qinghai) during 2013–2021. However, more than three-quarters of the provinces are still experiencing reduced air pollutant emissions and increased CO_2 emissions. Based on the emission status and ratio method of air pollutants to CO_2, we preliminarily explored future emission reduction directions in China. The discussion is based on policy preference for reducing air pollutants per unit of CO_2 emission reduction. Among these sectors, residential fossil fuel combustion had the greatest potential for synergistic emission reduction of SO_2 and CO_2, corresponding to the effects of the iron and steel industry on $PM_{2.5}$ and CO_2 and those of the transportation sectors on NO_x, VOCs, and CO_2. Among cities, city clusters with relatively higher potential to synergistically reduce NO_x, VOC, and CO_2 emissions were mostly in the Yangtze River Economic Belt, while those with higher potential to co-control SO_2 and CO_2, and $PM_{2.5}$ and CO_2 were separately located in southern and northeastern China. Considering measure implementation, the mitigation potential of measures to optimize the field structure and save energy and materials should be further promoted to achieve synergistic emission reductions of air pollutants and CO_2. For example, controlling the total coal combustion and promoting new energy will remain the focus of future synergistic emission reductions in the energy sector, with attention paid to the need for biomass fuels accompanied by air pollutant control equipment. Innovative process technologies with coal substitution can bring more effective synergistic emission reduction profits to the iron and steel industry. Further, for the cement industry, new energy and pollutant-specific emission reduction

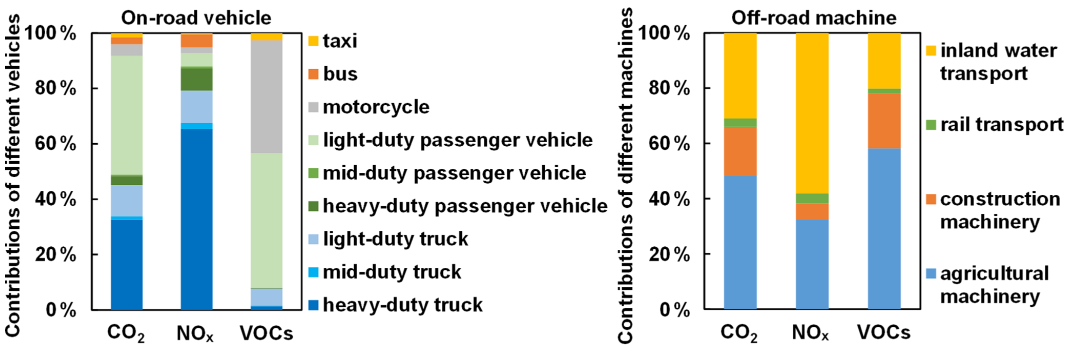

Figure 9. Emission contributions from different types of transport facilities in 2021 in China.

technologies should be promoted. Light-duty passenger vehicles, heavy-duty trucks, agricultural machinery, and inland waterways are the focus of synergistic emission reduction in the transportation sector.

However, this emission inventory dataset has certain shortcomings. In terms of species, only conventional pollutants and CO_2 were included in this dataset. However, as research on pollution causes, climate change, and health risks progresses (Cui et al., 2022; Liu et al., 2023; Zheng et al., 2023), the importance and emission estimation needs are gradually increasing for non-conventional pollutants (e.g., semi-volatile and intermediate volatile organic compounds and heavy metals) and non-CO_2 greenhouse gases (e.g., CH_4 and N_2O). An integrated and coupled dataset containing multiple pollutants and greenhouse gases has yet to be established. In terms of sources, the emission estimation method was relatively simplified and rough for non-industrial sectors such as cooking, livestock farming, and fertilizer application in our dataset. However, the impact of these sectors on air quality and climate change may gradually increase with the standardization and improvement of industrial sector controls (Xu et al., 2022). The methodology for accounting for non-industrial emissions requires further refinement and improvement.

The ABaCAS-EI v2.0 dataset in this study can provide data support for future synergistic emission control of air pollutants and CO_2 in China. Analysis of the historical emission reduction process and deconstruction of the current emission status can provide insights for future planning and formulation of synergistic emission reduction policies and paths. Simultaneous reduction of sectoral air pollutants and CO_2 emissions is possible from different measures, but this does not imply that the emission sector has truly achieved synergistic reduction. Moreover, reductions are not synergetic when one measure has an opposite effect on air pollutants and CO_2 emissions (Zhang et al., 2019; Shi et al., 2022). Thus, future studies on emission reduction measures and their synergistic reduction effects and potential should be further conducted.

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Author contributions. SL, SW, QW, and JH designed the study. SL developed the emission inventory. YZ, DO, HZ, LH, KL, XQ, YW, and ML helped to improve the emission inventory. YJ and DY did the spatial distribution of the emission inventory. SL wrote the original draft; all the co-authors revised the paper.

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