https://doi.org/10.5194/essd-2022-464
Preprint. Discussion started: 10 January 2023

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 reducing air pollutants and CO_2 emissions in the coming decades. The coupled emission inventory of air pollutants and CO_2 is a prerequisite to designing the synergetic emission reduction strategy. This study compiled China's emission inventory of air pollutants and CO_2 during 2005–2021 (ABaCAS-EI v2.0 dataset) based on a unified emission source framework and uniformed activity. The 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 & material saving brought a 7 % drop in the average annual growth rate of CO_2 emissions after 2011; on the basis, end-of-pipe control contributed 51 %–98 % of air pollutants emission reductions after 2013. Sectors of industrial boilers and residential fossil combustion, and seven provinces (including Beijing, Tianjin, Shanghai, Jilin, Henan, Sichuan, and Qinghai) have achieved emission reductions of both air pollutants and CO_2 during 2013–2021. The declining trends in both sectoral and regional emission ratios of air pollutants to CO_2 indicated that the potential for synergistic emission reduction in China has declined from 2013 to 2021. The emission ratios in 2021 show that the residential fossil fuel combustion, iron and steel industry, and transportation have relatively higher co-benefits of SO_2, $PM_{2.5}$, NOx, and VOCs emission reductions when reducing CO_2 emissions. Most of the cities with higher potential to synergistically reduce NOx, VOCs, and CO_2 emissions are located within the Yangtze River Economic Belt; those with higher potential to co-control SO_2 and CO_2, and $PM_{2.5}$ and CO_2 are in southern and northeast China, respectively. What's more, a further deconstruction of sectoral emissions in 2021 has 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 effects in the iron and steel industry; combining coal and carbonate replacing technologies with separated particle control measures in the cement industry; controlling light-duty passenger vehicle, heavy-duty truck, agricultural machinery, and inland water transport in the transport field. Our dataset and analysis can provide insights into future co-control of air pollutants and CO_2 emissions for China and other countries with the same demand worldwide. Our ABaCAS-EI v2.0 dataset can be accessed from https://doi.org/10.6084/m9.figshare.21777005.v1 (Li et al., 2022) by species, sector, and province.

1 Introduction

China faces with two strategic tasks: achieving a fundamental improvement in 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, proposing to take the synergistic reduction of pollution and carbon as the overall grasp 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 becomes an inevitable choice for China's comprehensive green transformation in the new development stage. Therefore, to support the co-control of air pollutants and CO_2 emissions, it is vital and urgent to establish an update-to-date emission inventory of air pollutants and CO_2.

In the past decade, China has implemented a series of emission control policies to mitigate air pollutants and CO_2 emissions. For CO_2, China issued its first comprehensive policy document on climate change in 2007— National Climate Change Program (CPGPRC, 2007), which clarified the key fields and corresponding reduction measures to address climate change by 2010. Since 2011, the reduction of 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; by the end of 2020, China's CO_2 emissions per unit of GDP (Gross Domestic Product) have fallen by 48.4 % compared to 2005 (CPGPRC, 2021). For air pollutants, SO_2 and particle emissions have been preferentially controlled since the 1990s, followed by NOx emissions from the 12th five-year plan period (2011–2015) (CPGPRC, 2011). In 2013, “Action plan for the prevention and control of air pollutants” has been issued (CPGPRC, 2013), in which key-controlled sectors and air pollution mitigation measures have been comprehensively refined. Emissions of multiple air pollutants have rapidly decreased since then (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 2020 (MEE, 2020).

Previous studies have separately analysed the emission changes and their drivers for air pollutants and CO_2 (Zheng et al., 2020; Geng et al., 2021; Li et al., 2022). With the increasing demand for synergistic reduction of air pollutants and CO_2 emissions, researchers have paid attention to 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) or key regions (e.g., Yangtze River Delta and Pearl River Delta) (Huang et al., 2021; Zheng et al., 2021b). Huang et al. (2021), Zheng et al. (2021a), and Gao et al. (2022) analysed the spatial and sectoral distribution of air pollutants and CO_2 emissions characteristics for a given year. Zheng et al. (2018) analysed the interannual national emission changing trends from 2010 to 2017, and preliminarily explored the contributions from pollution control and activity change on six macro emission source categories including power, industry, residential, transportation, solvent use, and agriculture. However, the emission changes of air pollutants and CO_2 during 2005–2021 and its drivers are still needed to be explored. More importantly, few studies have answered the question of which sector or which region has achieved the emission reductions for both air pollutants and CO_2 and which sector or region has larger synergetic reduction potential.

Here, we have compiled a coupled emission dataset of air pollutants and CO_2 in mainland China from 2005 to 2021, that is, ABaCAS-EI v2.0 (Air Benefit and Cost and Attainment Assessment System-Emission Inventory version 2.0), which is an updated version of ABaCAS-EI (http://www.abacas-dss.com/abacas/Software.aspx; last access: 14 December 2022). The dataset covers CO_2 and 9 types of air pollutants and includes 11 major source categories and more than 280 subsectors. The historical changes in air pollutants and CO_2 emissions and their relationships have been deeply explored from the aspects of control policies, source contributions, and spatial-temporal characteristics. What's more, 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 14th five-year period in China. The emission dataset and analysis in this study can supply data foundation and provide insight for 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 are 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 has four levels of information, including 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 include SO_2, NOx, PM_{10}, $PM_{2.5}$, BC, OC, VOCs, NH_3, and CO. The emission source framework is shown in Table S1.

It should be noticed that for each subsector and each species, emissions related to both energy consumption (energy-related emissions) and non-energy consumption processes (process-related emissions) are considered; for example, air pollutants and CO_2 emissions from coal combustion and raw material decomposition during cement clinker production process are all considered in our emission inventory. The energy consumption process generally refers to the fuel combustion and flaring process, where fuel types including coal, oil, gas, biomass (or biofuel), and waste consumed as fuel. Besides, a process where the energy is used as material, such as the coking process, is also identified as an energy-related process in this study. Other activity processes, such as material treatment and product usage, are identified as the non-energy process.

2.2 Coupled emission inventory

The coupled emission inventory of air pollutants and CO_2 is established based on the emission factor method following Eq. (1):

$$E_{i,j,p} = A_{i,j} \times EF_{i,j,p} \times \left(1 - \eta_{i,j,p,k} \times R_{i,j,p,k}\right) \tag{1}$$

where *i* represents province, including 31 provinces in China (excluding Hongkong, Macao, and Taiwan); *j* represents emission source, including 285 emission accounting units; *p* represents emission species, including 9 types of air pollutants and CO_2; *k* represents end-of-pipe control measure, such as electrostatic precipitator and fabric filter to control particle emissions; *E* is emission; *A* is activity data, such as fuel consumption, product, and material consumption; *EF* is emission factor without end-of-pipe pollution control; η is measure-specific pollution removal efficiency; *R* is measure-specific application ratio.

To calculate the emission of air pollutants and CO_2 simultaneously, the activity dataset is uniform for both, which is collected and organized considering the estimation demand of both air pollutants and CO_2 emissions under the unified emission source framework. Most of the activity data are shared for CO_2 and air pollutants, such as fuel consumption and output of industrial products; at the same time, some data are separately required for CO_2 or air pollutants emission estimation, such as calcium carbide production for CO_2 and solvent use for VOCs. The activity data information and sources for each emission source are listed in Table S2. The data sources of air pollutants emission factors have been introduced in our previous studies in detail (Table S3), and those of CO_2 are referred to the guidelines for 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 data sources of removal efficiency and application ratio for air pollutants are collected from official reports, national environmental statistics, and industrial investigation; while considering the CCUS (Carbon Capture, Utilization, and Storage) technologies are still in the stage of scientific research or demonstration without widely industrial promotion (Cai et al., 2021), the application ratio for CO_2 is set to zero in this study.

2.3 Uncertainty analysis of emission inventory

Uncertainties in emission inventories are mainly due to the lack of detailed or local information on activity data, emission factors, and pollutant removal conditions. In this study, a Monte Carlo simulation has been performed to quantify the uncertainty in emission estimates. Parametric distributions linked to the reliability and accuracy of some data have been introduced in our previous studies (Table S3) or collected from the literature (Lang et al., 2014; Lang et al., 2018; Li et al., 2020; Zhou et al., 2022); CO_2-related data are collected from IPCC guidelines (Goodwin et al., 2019; Eggleston et al., 2006) and literature (Choulga et al., 2021). The Monte Carlo simulation was then repeated 10000 times to estimate the emissions with a 95 % confidence interval. The uncertainty on the total emission per species was obtained by combining values obtained by subsector by province.

3 Results and discussion

3.1 Trends of air pollutants and CO_2 emissions

Figure. 1 shows the trends of air pollutants and CO_2 emissions from 2005 to 2021 in China. It can be seen that the emissions of air pollutants have declined since 2013. At the same time, the growth rate of CO_2 emissions has significantly decreased and has decoupled with GDP. In 2021, China's emissions of SO_2, $PM_{2.5}$, NOx, VOCs, NH_3, and CO_2 are 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 have also compared our emission inventory with other published datasets, such as MEIC (Zheng et al., 2018), CHRED (China High Resolution Emission Gridded Data; Gao et al., 2022), CEDS (Community Emissions Data System; O'Rourke et al., 2021), EDGAR (Crippa, M. et al., 2020), and IEA (International Energy Agency; IEA, 2022) datasets (Fig. S1). The emission trends of air pollutants and CO_2 are generally consistent among different emission datasets. Due to the differences in emission source frameworks (taking CO_2 emission sources for example in Table S4), there are some differences among the absolute emissions of various datasets.

However, the emission trends of air pollutants and CO_2 are quite different. The change in CO_2 emissions shows a continuously increasing trend, but the annual growth rate significantly slowed since 2011 (from 9 % during 2005–2011 to 2 % during 2011–2021), when the CO_2 emission intensity was included in the national five-year plan (CPGPRC, 2008). The emissions of SO_2 and $PM_{2.5}$ have continuously decreased since 2005 when the total emission control of SO_2 and particle was required in the 11th five-year plan. After 2013, almost all air pollutant emissions have begun to decrease since the "Action plan for the prevention and control of air pollutants" was issued (CPGPRC, 2013). It can be seen that the emission change of air pollutants and CO_2 in China is closely affected by the policies implemented.

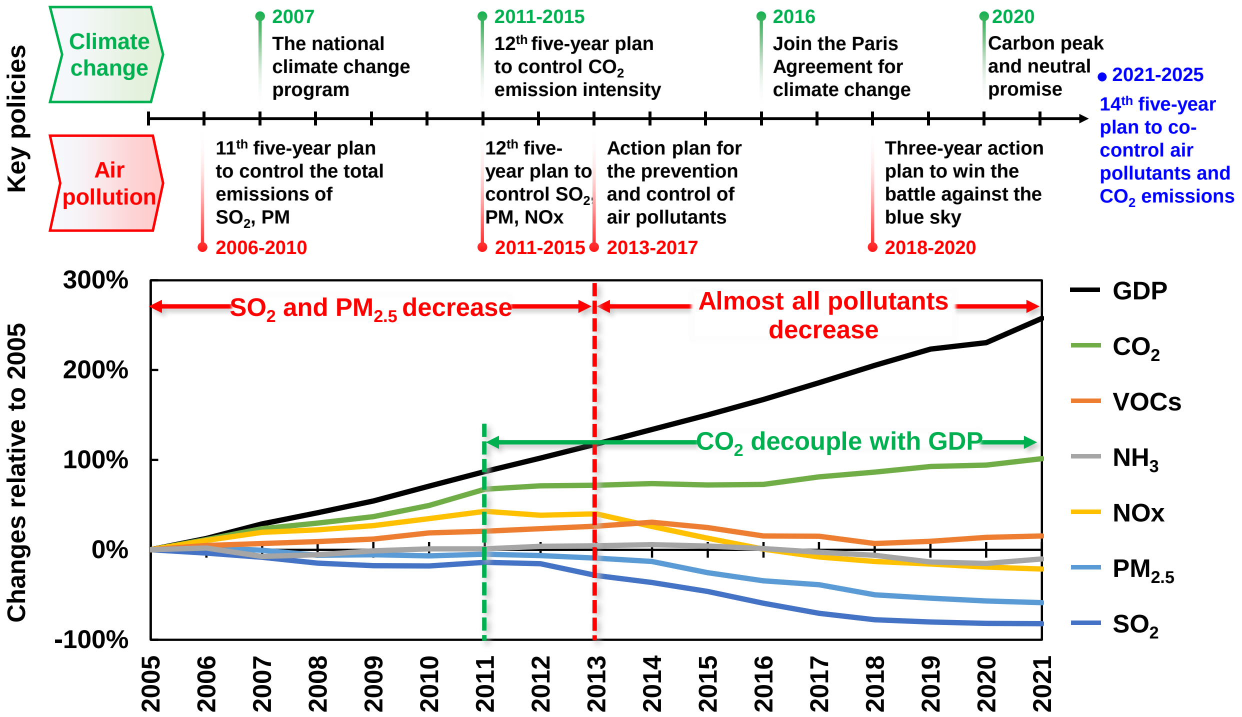

Figure 1: Interannual variations of GDP, and emissions of air pollutants and CO_2 relative to 2005 in China.

https://doi.org/10.5194/essd-2022-464
Preprint. Discussion started: 10 January 2023

3.2 Sectoral contributions to emissions of air pollutants and CO_2

3.2.1 Sectoral emission changes

To identify key emission reduction sectors in the past, this study has further analysed subsector emissions changes in detail; and 15 subsectors are totally introduced here (Fig. 2). Before 2013, SO_2 emissions were mainly reduced from power plants, while $PM_{2.5}$ and VOCs emissions were mainly reduced from cement industry and on-road vehicles, respectively, which is closely related to the sector-specific emission standards implemented around 2005 (MEE, 2003a, b, 2004). Besides, with the socio-economic development, the spontaneous phase-out of residential biofuel also contributed to some emission reductions of $PM_{2.5}$ and VOCs.

After 2013, air pollutant emissions of almost all sectors began to decline with the implementation of “Action plan for the prevention and control of air pollutants” (CPGPRC, 2013) and “Three-year action plan to win the battle against the blue sky” (CPGPRC, 2018). For SO_2, the sectors of power plant, industrial boiler, and residential fossil fuel combustion are the major reduction contributors, which accounted for more than 75 % of SO_2 emission reductions during 2013–2021 in China. End-of-pipe control on the first two played a huge role. The proportion of coal-fired generator units completing ultra-low emission retrofit has 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 largely approached that of coal-fired generator units. By contrast, considerable SO_2 emission decline in the residential sector is 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 tons of standard coal (Mtce) in 2013 to 98 Mtce in 2021. For NOx, power plant and industrial boiler also contributed the largest (almost 70 %) reductions during 2013–2021 in China because of their ultra-low emission retrofit. Besides, cement industry and on-road vehicle contributed an additional 17 % of NOx emission reductions. For the cement industry, some provinces in China have taken the lead in implementing ultra-low emission standards without national mandatory requirements in recent years; and the proportion of production lines equipping with higher-efficiency removal facilities (e.g., the combination of low NOx combustion technology and selective non-catalytic reduction technology) have increased from less than 1 % in 2013 to about 25 % in 2021. Meanwhile, the proportion of on-road vehicles under China IV–VI standards has a 50 % increase from 2013 (16 %) to 2021 (65 %), whose NOx emission factors after exhaust gas treatment are 82 %–96 % lower than China II vehicles and 44 %–87 % lower than China III vehicles (Wen et al., 2021). For $PM_{2.5}$, iron and steel industry, open burning, cement industry and are the major reduction contributors, which accounted for 29 %, 20 %, and 12 % of $PM_{2.5}$ emission reductions during 2013–2021 in China, respectively. End-of-pipe control measures still led to reductions. After the related policy was issued (MEE et al., 2019), the proportion of steel production capacity having completed or carrying out ultra-low emission retrofit sharply increased to about 60 % nationwide within three years. Thanks to the “no-open burning” policy, the proportion of open burning of straw in China has averagely fallen from about 25 % in 2013 to 10 % in 2021. For VOCs, the “no-open burning” policy also contributed to 1.8 Mt VOCs emission reductions during 2013–2021 in China, though its contribution has been offset by the increased use of solvents with high VOCs content. For NH_3, the fertilizer sector has 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. It is not hard to find that end-of-pipe control measures led to air pollutants emission reductions during 2013–2021 in China. A preliminary assessment based on the control variate method (Zhang et al., 2019) quantified that end-of-pipe control measures contributed about 74 % (51 %–98 %) of total emission reductions.

For CO_2, power plant is always the dominant contributor to its emission increase, accounting for 47 %–77 % of the total CO_2 incremental emissions from 2005 to 2021. This is likely due to the continuous increase in fossil fuel consumption with the share of coal consumption remaining above 90 % in the power plant sector. However, despite a 2.4-fold increase in power generation from 2005 to 2021, sectoral CO_2 emissions only have a 1.0-fold increase. Energy mix transformation and energy efficiency improvement measures have offset half of the CO_2 emission increase due to the growth of electricity generation. On the one hand, the non-fossil fuel generation proportion has a 16 % increase during 2005–2021, especially after 2013 (a 10 % increase during 2013–2021); on the other hand, the coal consumption rate for electricity supply has declined from 370 gce kWh^{-1} in 2005 to about 303 gce kWh^{-1} in 2021. At the same time, similar types of measures have also been 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. Energy efficiency during 2013–2021 in the industrial boiler, iron and steel industry, cement industry, and on-road vehicle sectors has increased by 12 %, 10 %, 10 %, and 22 %, respectively.

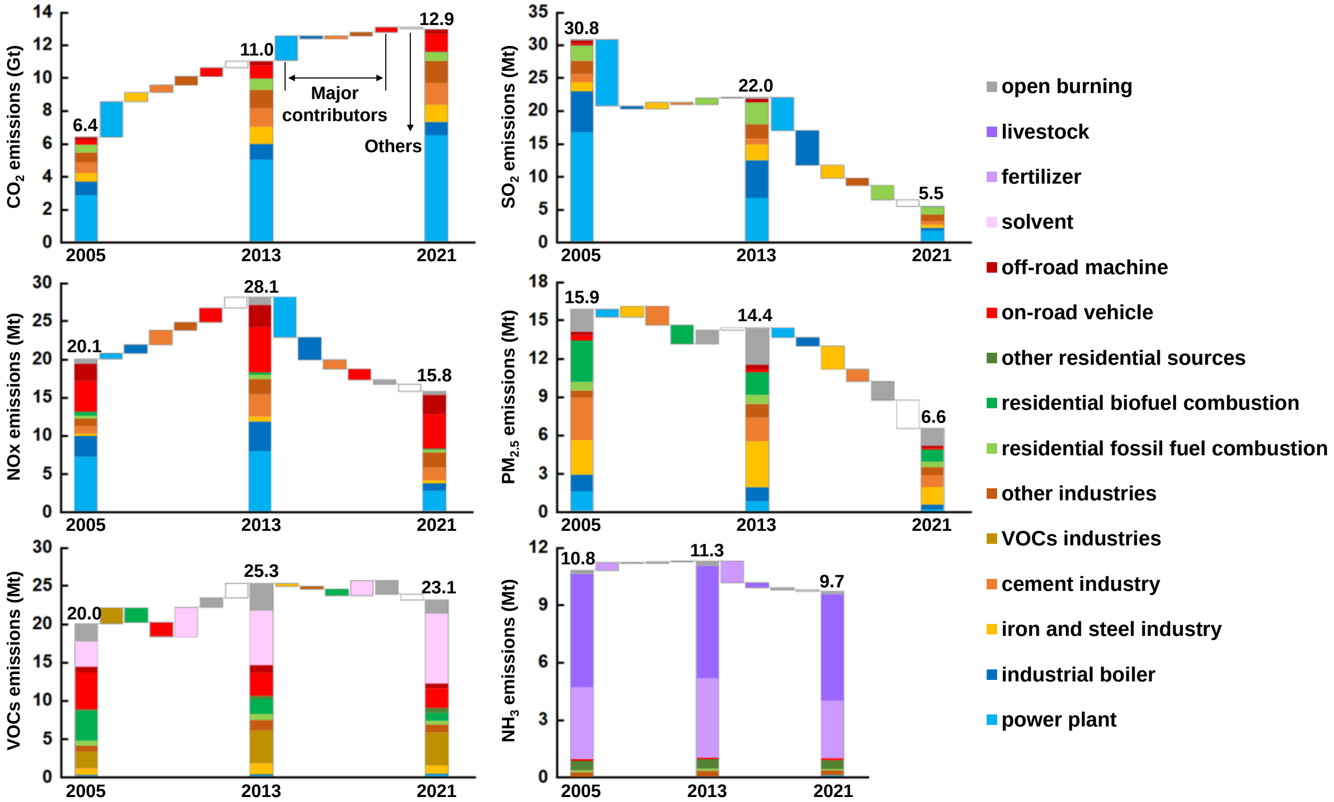

Figure 2: Sectoral contributions on the emission changes of air pollutants and CO$_2$ from 2005 to 2021 in China.

3.2.2 Sector-specific synergy of air pollutants and CO$_2$ emissions

The sector-specific emission changes of air pollutants (NH$_3$ excluded) and CO$_2$ are shown in Fig. 3. The seven sectors included in Fig. 3 account for 89 % of CO$_2$ emissions and 22 %–84 % of air pollutants emissions in 2021 in China (Fig. S2). We have found that industrial boilers and residential fossil fuel combustion have firstly achieved the simultaneous reduction of air pollutants and CO$_2$ emissions from 2013 to 2021, which likely benefits from the energy structure adjustment in these two sectors as discussed above. There was no significant change in CO$_2$ emissions from the iron and steel industry and off-road machine between 2013 and 2021 when their air pollutant emissions gradually decreased. This is mainly the result of the combination of energy & material saving measures and end-of-pipe control measures. On one hand, the decrease in energy and material consumption rate has offset the effects of increased activity on sectoral emissions of air pollutants and CO$_2$. For instance, the coal and coke consumption rate in blast furnace have decreased from 148 kg t^{-1} and 553 kg t^{-1} in 2013 to 145 kg t^{-1} and 461 kg t^{-1} in 2021, largely curbing coal consumption in the iron and steel industry; the oil consumption rates have a 2 %, 3 %, 17 %, and 19 % decline for agriculture machinery, construction machinery, railway transport, and inland waterway transport, respectively. On the other hand, end-of-pipe control, such as ultra-low emission retrofit in the iron and steel industry and emission standard upgrade for off-road machines, brought additional air pollutants emissions reductions for these two sectors. However, CO_2 emissions from the power plant, cement industry, and on-road vehicle sectors are still increasing, indicating their great carbon reduction challenge in the following decade.

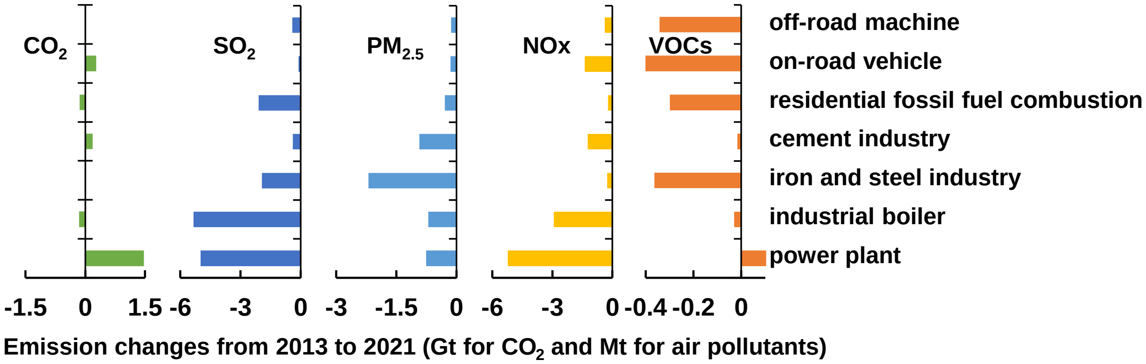

Figure 3: Sectoral contributions to the emission changes of air pollutants and CO_2 in China during 2013–2021.

Several studies have pointed out that with the exhaustion of end-of-pipe control reduction effects in the future, more ambitious carbon reduction measures are needed to collaboratively mitigate air pollutants emissions to finally achieve the WHO air quality guideline (Cheng et al., 2021; Xing et al., 2020). In this study, to find out the sectors having larger air pollutant reduction potential per unit CO_2 emission reduction, ratios of air pollutant emission to CO_2 emission have been calculated for each sector. The larger the ratio, the greater the potential for synergistic reducing air pollutants emissions under the same CO_2 reduction level. It must be clarified that the ratio only represents the potential of synergistic reduction rather than the real ability; the latter may be needed to be further discussed from the reduction measure perspective in future studies.

From 2013 to 2021 in China, the ratios of all air pollutants to CO_2 for all sectors have decreased (Fig. 4), revealing the faster reduction progress of air pollutants than that of CO_2 in recent years; in other words, the synergistic reduction potential of all sectors has weakened. For SO_2/CO_2 ratio, the industrial boiler has the largest value of 6.0, followed by residential fossil fuel combustion of 4.8 in 2013; however, the highest-ratio sector turned to residential fossil fuel combustion (2.1) in 2021, more than 4 times larger than other sectors, indicating the potential priority of this sector to synergistic reduce SO_2 and CO_2 emissions in the future. For $PM_{2.5}/CO_2$ ratio, the iron and steel industry always has the highest $PM_{2.5}/CO_2$ ratio in both 2013 (3.4) and 2021 (1.3); however, its superiority has decreased from 2013 to 2021, other sectors with comparable ratio level, such as residential fossil fuel combustion (0.8), off-road machine (0.8), and cement industry (0.7), are also suggested to be noticed in future synergistic reduction of particle and CO_2. For NOx/CO_2 and $VOCs/CO_2$ ratio, transport sectors including on-road vehicle and off-road machine are always the focus with more than 2 times higher values than other sectors. It is worth noticing that as the largest CO_2 contributor in China (Fig. S2), the potential for power plant to synergistically reduce air pollutants and CO_2 emissions has become limited and less effective than in other sectors.

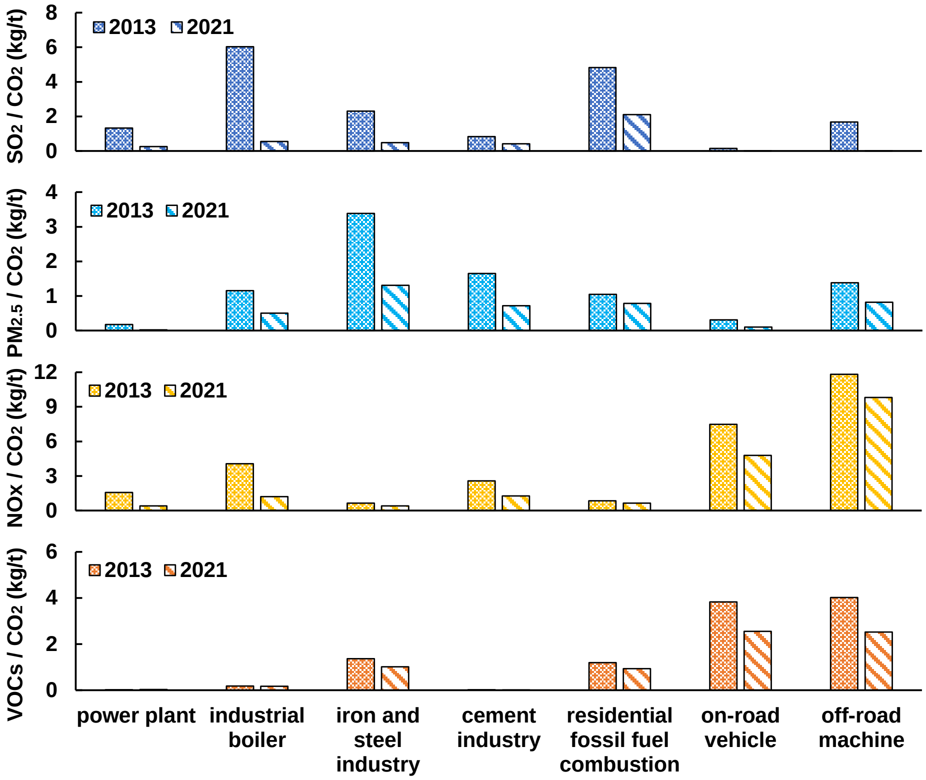

Figure 4: Emission ratios of air pollutants to CO_2 in 2013 and 2021 in China.

3.3 Regional contributions to air pollutants and CO_2 emissions

3.3.1 Provincial emission changes

Figure. 5 shows the provincial emission changes of air pollutants and CO_2 during 2005–2013 and 2013–2021. Before 2013, only Beijing just achieved reductions of both air pollutants and CO_2 emissions. Nearly two-thirds of provinces have achieved reductions in SO_2 and $PM_{2.5}$ emissions, while CO_2, NOx and, VOCs emissions still increased in over 90 % of provinces. Guangdong, Zhejiang, Jiangsu, and Shandong were the major contributors to reducing national SO_2 and $PM_{2.5}$ emissions, which are all located in the regions with heavier air pollution in China (Jiang et al., 2022), such as Pearl River Delta (PRD; including some cities located in Guangdong), Yangtze River Delta (YRD; including Shanghai, Jiangsu, Zhejiang, and Anhui), and 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 of 450 Mt in China during 2005–2013, due to its higher coal consumption (top 3 in 2013) and the largest increase in coal consumption (210 Mt coal during 2005–2013) among provinces in China.

After 2013, the number of provinces reaching the co-control achievement has become seven, including Beijing, Tianjin, Shanghai, Jilin, Henan, Sichuan, and Qinghai; most provinces only contributed to the air pollutants emission reductions with increased CO_2 emissions. Among provinces, Hebei, Shandong, and Henan contributed the largest national air pollutant emission reductions, which are all regions located in the BTHs region with the more comprehensive and tougher reduction measures in recent years in China (CPGPRC, 2013, 2018). Inner Mongolia, Xinjiang, and Shandong accounted for the largest increases in CO_2 emissions in recent years, which are the top thermal power generators with the faster increase of thermal power generation and faster increase of coal consumption in China during 2013–2021. It is worth noting that one-third of the provinces, especially Liaoning, Jiangsu, and Fujian, are still under pressure to reduce both CO_2 and VOCs emissions.

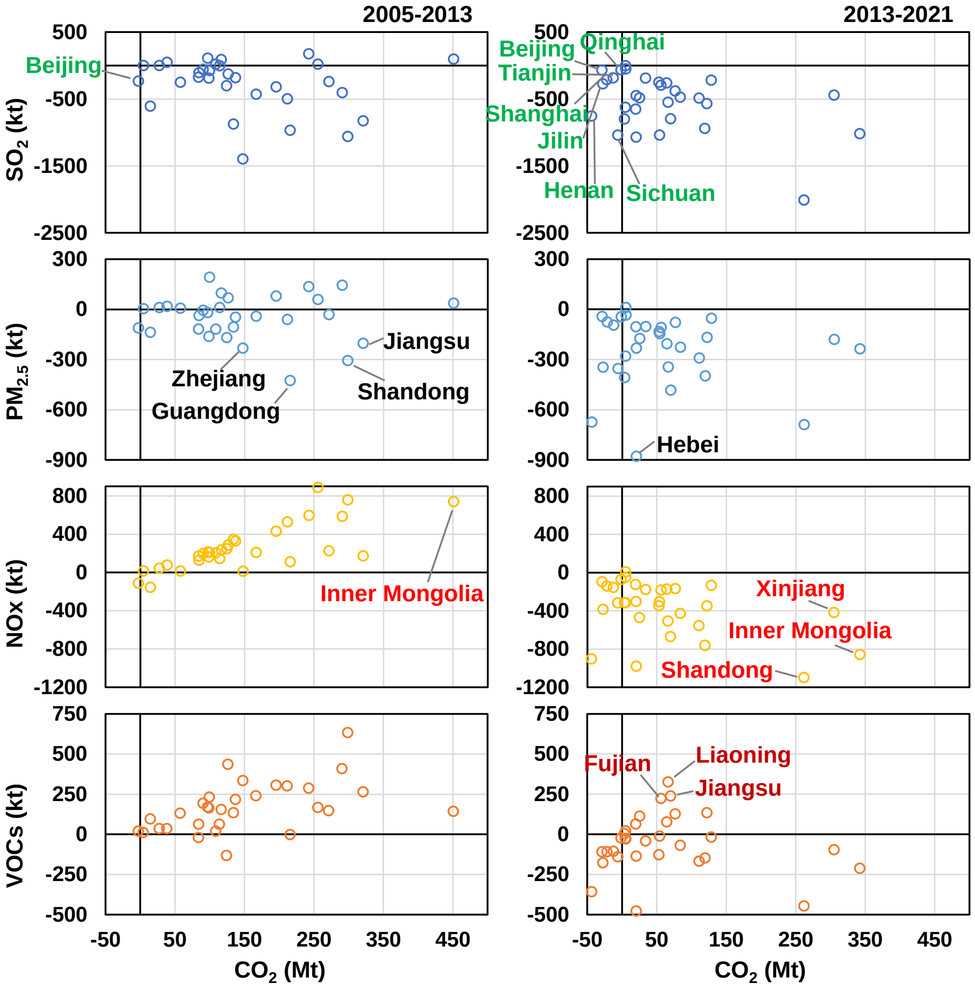

Figure 5: Provincial emission changes of air pollutants and CO_2 during 2005–2013 and 2013-2021.

3.3.2 City performance on the co-control of air pollutants and CO_2

Air pollutants and CO_2 emissions are always concentrated in the central and eastern parts of China due to their dense population and more developed economy (Fig. S3). To identify the hotspots with a larger potential for synergistic reduction of air pollutants and CO_2, cities with higher CO_2 emissions are selected to calculate the ratios of air pollutant emission to CO_2 emission. Finally, 160 cities of 29 provinces (except for Hainan and Xizang provinces) are picked out in this study, which accounts for 80 % of national CO_2 emissions. The ratios in 2013 and 2021 have been calculated for each city, respectively (Fig. 6). There is generally a nationwide decline in the ratios of all air pollutants to CO_2. City ratios of SO_2/CO_2 have the largest decrease of 78 % on average, followed by $PM_{2.5}/CO_2$ (61 %) and NOx/CO_2 (51 %). This result is consistent with the result of analysis from the perspective of emission sectors, implying that the potential for cities to reduce these three air pollutants and CO_2 synergistically may have fallen by more than half on average. However, the ratios of $VOCs/CO_2$ only decreased by 21 % on average; what's more, there are still 32 cities where the ratios have increased by 1 %–24 %. Considering that the current level of VOCs controls in China is still weak, there is still a large potential for co-control VOCs and CO_2 emissions in the future, especially in the transportation sector as discussed in section 3.2.2.

The average city ratio of SO_2/CO_2 was 2.0 in 2013; while cities with a ratio > 2.0 have almost disappeared in 2021; target cities with higher values in 2021 included 5 cities (including Guiyang city, Liupanshui city, Zunyi city, Bijie city, and Qiannan zhou) in northwest Guizhou provinces and 3 cities (Kunming city, Qujing city, and Honghe zhou) in northern Yunnan provinces. The average city ratio of $PM_{2.5}/CO_2$ was 1.3 in 2013 with 70 cities above the average; however, the number of cities has been down to just 4 in 2021, including Harbin city and Qiqihar city of Heilongjiang province, Songyuan city of Jilin province, and Guilin city in Guangxi province. For NOx/CO_2 ratio, more than 95 % of cities had a ratio > 2.0 in 2013, while only 6 of them were left in 2021. The cities are all within the Yangtze River Economic Belt, including Chongqing city, Chengdu city and Deyang city of Sichuan province, Wuhan city and Huangang city of Hubei province, and Anqing city of Anhui province. For $VOCs/CO_2$ ratio, some separated hotspots located in Yunnan, Xinjiang, and the BTHs region have gradually disappeared from 2013 to 2021; at the same time, the ratios of some cities located in Liaoning province and eastern coastal areas had a slight increase. In 2021, only 12 cities also within the Yangtze River Economic Belt remained with a $VOCs/CO_2$ ratio > 3.0, including 2 cities (Chengdu city and Deyang city) of Sichuan province, 4 cities (Huanggang city, Jingzhou city, Xiangyang city, and Yichang city) of Hubei province, and 6 cities (Taizhou city, Zhoushan city, Jinhua city, Shaoxing city, Ningbo city, and Hangzhou city) of Zhejiang province.

Summing up the target cities having a higher emission ratio of air pollutants to CO_2, it can be inferred that city clusters within the Yangtze River Economic Belt are facing the opportunity with relatively high potential to carry out demonstrations of synergistic reducing NOx, VOCs, and CO_2 emissions, especially Chengdu city, Chongqing city, and Huanggang city. Cities with higher potential to co-control SO_2 and CO_2, and $PM_{2.5}$ and CO_2 are separately located in southern and northeast China.

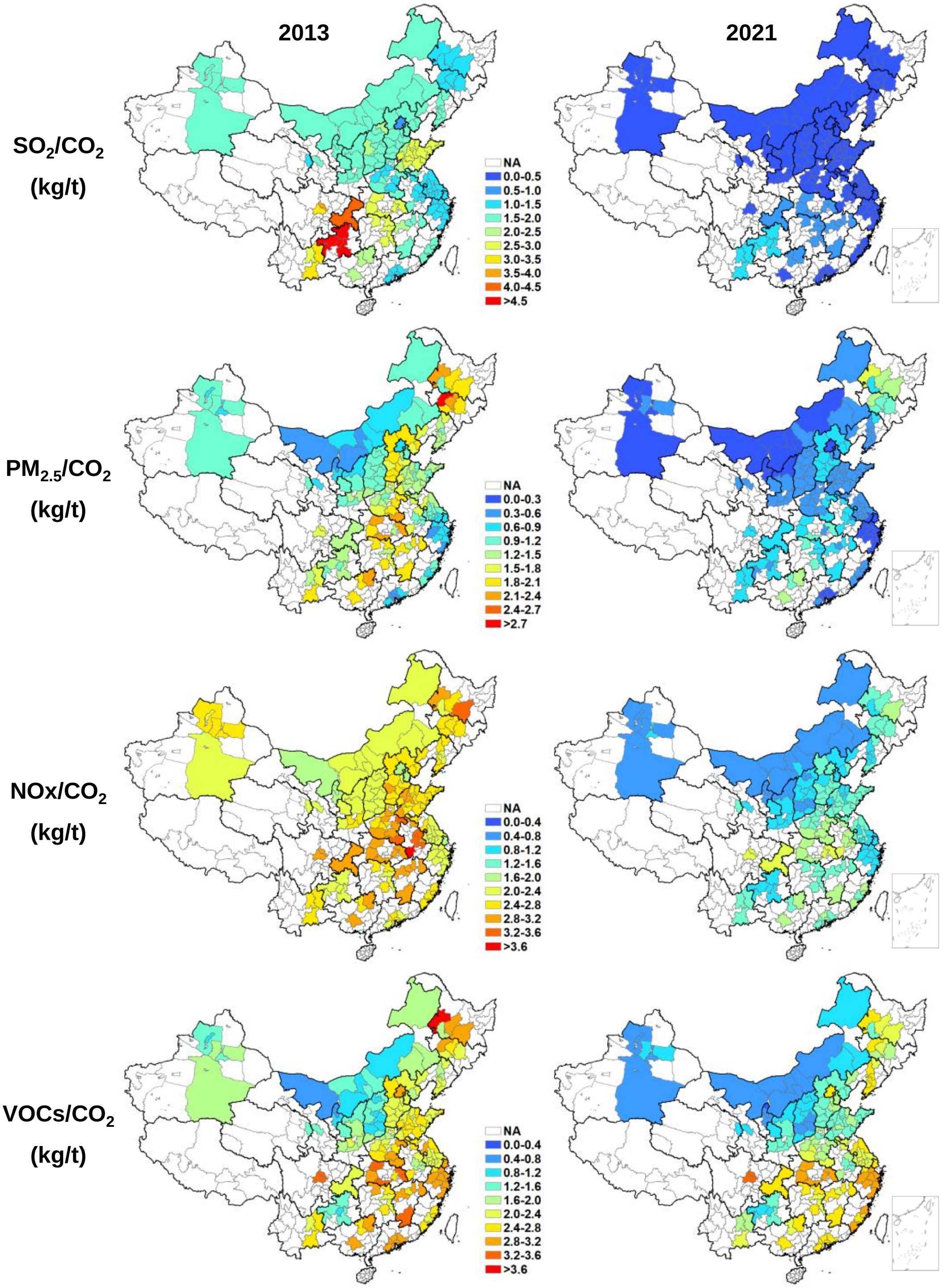

Figure 6: City's ratios of air pollutant emission to CO_2 emission in 2013 and in 2021 in China. (NA: data not analysed)

3.4 Implication for future air pollutants and CO_2 emission reduction

According to the policies guiding future emission mitigation (MEE et al., 2022), structure adjustment of energy, industry, and transport are the key measures to promote the synergistic reduction of air pollutants and CO_2. Therefore, we carried out a detailed analysis of these sectors to further explore future synergistic emission reduction measures.

Power plant, residential combustion, and industrial boiler are the major energy combustion sectors, which consumed 64 % of total fuel consumption in 2021. From Fig.7 we can see that coal is still the dominant fuel in 2021 in China, which accounted for 78 % of the total fuel consumption of energy sectors and contributed 91 % of CO_2, 88 % of SO_2, 33 % of $PM_{2.5}$, and 83 % of NOx emissions from energy sectors; power plant is still the major coal-fired sector with 86 % consumption. It is still a key control policy for the energy sectors to limit total coal consumption in the future. It is worth noting that although biomass only accounted for 7 % of the total fuel consumption of energy sectors, it contributed 66 % of $PM_{2.5}$ emissions since residential combustion is almost without control measures. In view of the difficulty of equipping residential biomass use with de-dusting equipment, it is suggested that biomass fuels, as a "zero-carbon" energy, be concentrated in power plants or industrial sectors that are in a position to install end-of-pipe measures.

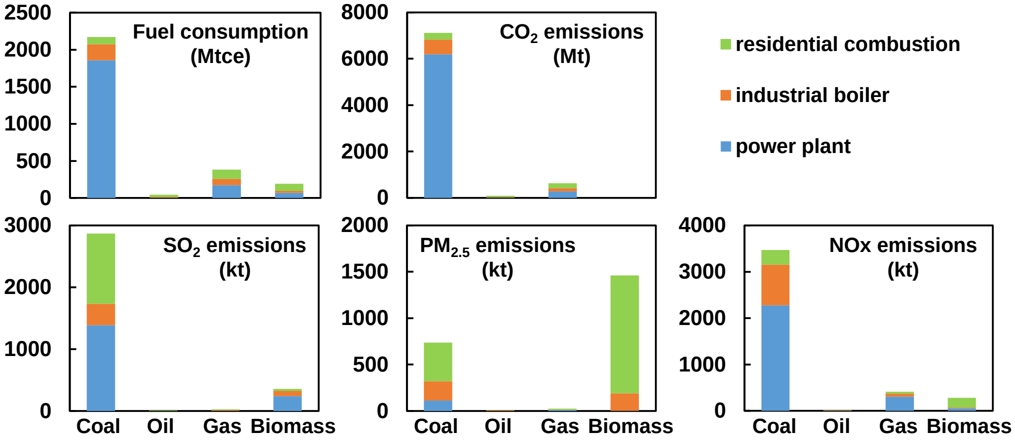

Figure 7: Fuel consumption and related emissions from energy sectors in 2021 in China.

The iron and steel industry and cement industry are the major industrial sectors contributing 51 %–79 % of industrial CO_2 and most emissions of air pollutants in 2021 in China. To achieve a synergistic reduction in these two sectors, clean energy promotion and technology reform are considered ideal control measures for the future (Wei et al., 2022). Therefore, this study further analysed the sectoral emissions of the energy-related and process-related parts to clear the focus of measure implementation (Fig. 8).

For the iron and steel industry, coal is the dominant fuel mostly used in the links such as coking, sintering, and blast furnace ironmaking. Emissions related to coal consumption are recognized as energy-related emissions here; at the same time, emissions produced from other processes, such as iron ore treatment, steel making, casting, and steel rolling, are recognized as process-related emissions. The emission proportions of each part are either calculated by our emission inventory or collected from the literature (Ning and Qin, 2006; Zhang et al., 2012; Wang et al., 2014). There is an interesting result that more than 90 % of CO_2 is related to energy consumption but more than 60 % of air pollutants emissions are related to production technology and process in 2021. This contradiction point brings a great challenge for the iron and steel industry to carry out synergistic emission reduction of air pollutants and CO_2. It indicates that only replacing coal with clean energy (e.g., natural gas and biofuel) is not enough to effectively mitigate sectoral air pollutants emissions; instead, promoting innovative technologies (e.g., H_2-based direct reduced iron technology), that have low air pollutant emission intensity and the co-benefit to reduce or avoid coal consumption, is more recommended.

For the cement industry, coal is also the major fuel used for cement clinker calcination. Process-related emissions happened during the links such as raw material processing, material grinding, and cement grinding. The emission proportions of each part are either calculated by our emission inventory or collected from the literature (Bai et al., 2019). Coal consumption contributed 34 % of CO_2, 22 % of SO_2, and 65 % of NOx emissions in 2021, which indicates that promoting clean energy has considerable potential and value to achieve synergistic reduction. As for process-related emissions, CO_2 is mainly from the use of limestone, SO_2 is mainly from the use of raw materials containing sulphate, and $PM_{2.5}$ is closely related to the grinding process. It indicates that improving material structure or quality has the potential to co-control CO_2 and SO_2 emissions, while specific control measure is needed to reduce sectoral $PM_{2.5}$ emissions with limited synergistic reduction potential.

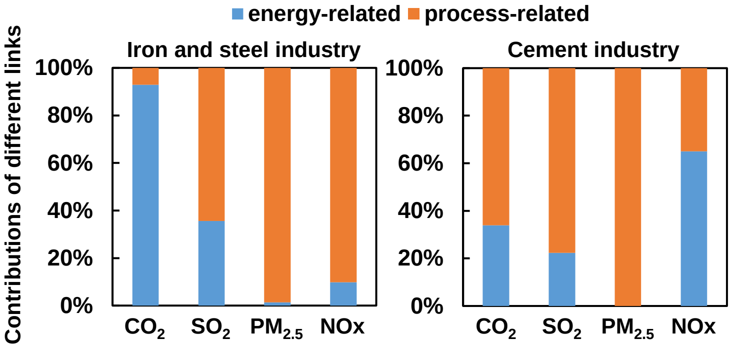

Figure 8: Deconstruction of emissions from major industrial sectors in 2021 in China.

Nine types of on-road vehicles and four types of off-road machines are included in the transport sector in our study (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). For the on-road vehicle sector in 2021, light-duty passenger vehicles contributed 43 % of CO_2 and 49 % of VOCs emissions, and heavy-duty trucks contributed 33 % of CO_2 and 65 % of NOx emissions. This result suggested that emission reduction measures are applied priority to the light-duty passenger vehicle and heavy-duty truck. For the off-road machine sector, 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.

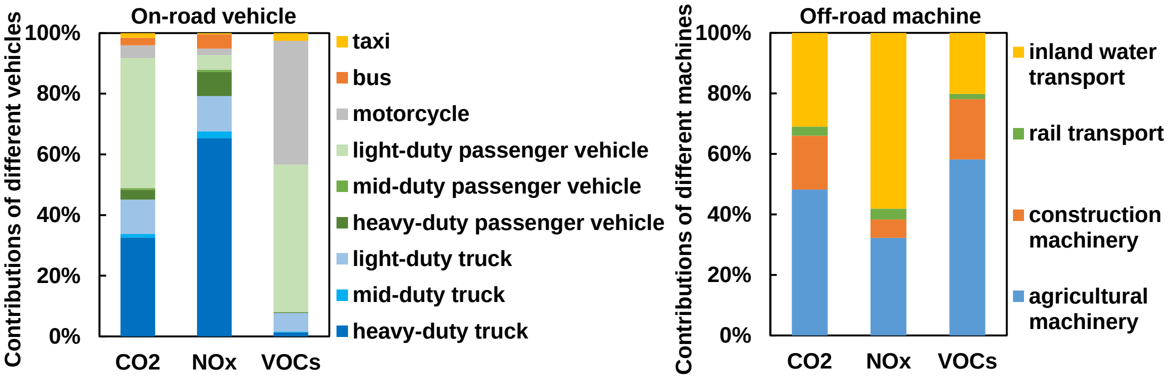

Figure 9: Emission contributions from different types of transport facilities in 2021 in China.

4. Data availability

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

5. Conclusions and implication

To support the co-control of air pollutants and CO_2 emissions in the future in China, we have introduced the ABaCAS-EI v2.0 dataset in this study, which is a coupled emission inventory of air pollutants and CO_2 based on a unified emission source framework. Analysis of interannual emission trends from 2005 to 2021 revealed that China's air pollutants and CO_2 emissions have decoupled from economic development. Implementation of reduction measures is the major driver affecting emission change in the past decade or so in China. Exploration of sectoral emission changes shows that the mitigation process of air pollutants emissions is faster than that of CO_2 emissions in China. Generally, the implementation of structure adjustment measures and energy & material saving measures have significantly slowed the increase rate in CO_2 emissions; end-of-pipe control measures dominantly contributed to the emission reductions of air pollutants for most sectors. During 2013–2021, the power plant, cement industry, and on-road vehicle sectors are still in the phase of decreased air pollutant emissions but increased CO_2 emissions. Analysis of regional emission changes found that the number of provinces achieving emission reduction of both air pollutants and CO_2 has increased from one (Beijing) during 2005–2013 to seven (including Beijing, Tianjin, Shanghai, Jilin, Henan, Sichuan, and Qinghai) during 2013–2021. However, more than three-quarters of the provinces are still in a phase of reduced air pollutant emissions and increased CO_2 emissions. Based on the emission status and an emission ratio method of air pollutant to CO_2, we have preliminarily explored the emission reduction directions in the future in China. The discussion is under the policy preference of reducing more air pollutants per unit CO_2 emission reductions. Among sectors, residential fossil fuel combustion has a greater potential for synergistic emission reduction of SO_2 and CO_2, corresponding effects of the iron and steel industry on $PM_{2.5}$ and CO_2, and those of the transport sectors on NOx, VOCs, and CO_2. Among cities, city clusters with relatively higher potential to synergistic reduce NOx, VOCs, and CO_2 emissions are mostly located within the Yangtze River Economic Belt; those with higher potential to co-control SO_2 and CO_2, and $PM_{2.5}$ and CO_2 are separately located in southern and northeast China. Considering measure implementation, the mitigation potential of measures to optimize filed structure and save energy and material, are suggested to be further unlocked to achieve synergistic emission reductions of air pollutants and CO_2. For example, controlling total coal combustion and promoting new energy will remain the focus of future synergistic emission reduction in the energy sector, with attention 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 profit in the iron and steel industry. The promotion of new energy and pollutant-specific emission reduction technologies are both suggested for cement industry. Light-duty passenger vehicle, heavy-duty truck, agricultural machinery, and the inland waterway are the focus of synergistic emission reduction in the transport sector.

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 current emission status can provide some experiences and ideas for the future planning and formulation of synergistic emission reduction policies and paths. It should be noted that the simultaneous reduction of sectoral air pollutants and CO_2 emissions can result from different measures, which does not mean that the emission sector has achieved truly synergistic reduction; at the same time, it is also not synergetic when one measure has the opposite effect on air pollutants and CO_2 emissions (Zhang et al., 2019; Shi et al., 2022). More detailed studies on emission reduction measures of their synergistic reduction effects and potential are yet to be conducted.

Author contributions

Shengyue Li, Shuxiao Wang, Qingru Wu, and Jiming Hao designed the study. Shengyue Li developed the emission inventory; Yanning Zhang, Daiwei Ouyang, Haotian Zheng, Licong Han, Kaiyun Liu, Xionghui Qiu, Yifan Wen, and Min Liu helped to improve the emission inventory. Yueqi Jiang and Dejia Yin did the spatial distribution of the emission inventory. Shengyue Li wrote the original draft; all the co-authors revised the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

Acknowledgements

This work was supported by National Key Research and Development Program (2022YFC3700602, 2022YFC3702900), National Natural Science Foundation of China (22188102, 92044302), and Tsinghua-Toyota Joint Research Center.

Financial support

This study was jointly funded by National Key Research and Development Program (2022YFC3700602, 2022YFC3702900), National Natural Science Foundation of China (22188102, 92044302), and Tsinghua-Toyota Joint Research Center.

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