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Original Research

Overlooked CO_2 emissions induced by air pollution control devices in coal-fired power plants

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ABSTRACT

China's efforts to mitigate air pollution from its large-scale coal-fired power plants (CFPPs) have involved the widespread use of air pollution control devices (APCDs). However, the operation of these devices relies on substantial electricity generated by CFPPs, resulting in indirect CO_2 emissions. The extent of CO_2 emissions caused by APCDs in China remains uncertain. Here, using a plant-level dataset, we quantified the CO_2 emissions associated with electricity consumption by APCDs in China's CFPPs. Our findings reveal a significant rise in CO_2 emissions attributed to APCDs, increasing from 1.48 Mt in 2000 to 51.7 Mt in 2020. Moreover, the contribution of APCDs to total CO_2 emissions from coal-fired power generation escalated from 0.12% to 1.19%. Among the APCDs, desulfurization devices accounted for approximately 80% of the CO_2 emissions, followed by dust removal and denitration devices. Scenario analysis indicates that the lifespan of CFPPs will profoundly impact future emissions, with Nei Mongol, Shanxi, and Shandong provinces projected to exhibit the highest emissions. Our study emphasizes the urgent need for a comprehensive assessment of environmental policies and provides valuable insights for the integrated management of air pollutants and carbon emissions in CFPPs.

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1. Introduction

China has the world's largest fleet of coal-fired power plants (CFPPs), contributing to over 60% of its domestic electricity supply [1]. In 2020, the installed capacity of CFPPs in China was 1095 GW, accounting for over half of the global total installed capacity [2,3]. Moreover, CFPPs are the main sources of many kinds of air pollutant emissions in China. In 2017, CFPPs were responsible for 17% of SO_2, 19% of NOx, 8% of primary $PM_{2.5}$, and 11% of atmospheric mercury emissions [4,5], which have enormous adverse effects on both humans and the ecosystem [6–9].

Mitigating air pollutants from CFPPs has become a priority for the Chinese government. In the early 1990s, the 1991 Emission Standard of Air Pollutants for Coal-fired Power Plants was implemented [10]. For the first time, this standard stipulated a specific limit for dust emissions from CFPPs. Since then, a series of regulations and policies have been implemented to reduce dust, SO_2, NOx, and atmospheric Hg emissions [11–14]. Generally, three types of measures have been implemented: shutting down small coal-fired power generation units, improving power generation efficiency, and installing air pollution control devices (APCDs) [5,8]. During the 11th and 12th Five Year Plan periods (2006–2015), more than 100 GW of small units with low power generation efficiency or without APCDs were decommissioned [15]. The energy efficiencies of China CFPPs have largely improved, reducing the average coal consumption intensity from 370 to 318 gce KWh^{-1} [16]. In addition, the proportions of CFPP units with the desulfurization and denitration APCDs have increased from 34.8% to 93.0% and 1.5% to 85.8%, respectively [17]. These measures have successfully controlled air pollutant emissions from power generation, bringing great environmental and health benefits [18,19]. For example, Wu et al. [20] estimated that more than 1,400,000 premature deaths were

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avoided by emission control policies on China CFPPs from 2005 to 2020. The success of air pollutant abatement was largely due to the wide applicability of APCDs in CFPPs [20–24], including electrostatic precipitators (ESPs), wet limestone–gypsum flue gas desulfurization (WFGD), selective catalytic reduction (SCR), and selective noncatalytic reduction (SNCR).

While APCDs offer significant benefits, it is essential to note that they require a substantial amount of electricity from the CFPPs [25–27]. Jiang and Li [27] reported that desulfurization and denitration APCDs collectively have average station service power consumption rates of 1.29%, indicating their high carbon intensity. Anthropogenic CO_2 emissions are the main cause of global climate change, which features higher frequency and intensity of extreme weather events such as heatwaves, heavy precipitation, droughts, and tropical cyclones [28]; global climate change has been confirmed to exacerbate ill health and premature deaths [29,30], inflict economic losses [31,32], and pose a severe threat to biodiversity [18,33]. Currently, to achieve the carbon peaking and carbon neutrality targets [34], China is taking every measure to reduce carbon emissions [35]. Since coal-fired power will continue to play an important role in China's power generation structure over the next 20 or 30 years [15,36,37], CO_2 emissions induced by APCDs (hereinafter referred to as APCD CO_2 emissions) should not be ignored. Therefore, it is of great importance to quantify the historical CO_2 emissions induced by APCDs and to estimate future emissions, which can provide quantitative information for implementing carbon reduction measures.

To date, existing studies mainly focus on the cobenefits of environmental regulation measures on climate mitigation and air quality [38,39]. These studies have revealed that, under certain conditions, the two goals of reducing air pollutants and mitigating climate change can be simultaneously achieved [40–44]. However, little attention has been given to the conflict between these two goals. Ignoring this conflict can be misleading when formulating environmental policies, as it may result in policies prioritizing one environmental objective while inadvertently undermining other environmental objectives not considered. A few life cycle assessment-based studies have quantified CO_2 emissions from APCDs in CFPPs [25,26,45–54], demonstrating that desulfurization devices are the largest electricity consumers among APCDs [26,45]. However, these previous studies have assessed a small number of power plants and APCDs, which are far from sufficient to portray a holistic picture of China's CFPPs and diversified APCDs.

Therefore, this study aims to answer the following questions: How many CO_2 emissions have been induced by APCDs in China CFPPs? How many CO_2 emissions will APCDs cause in the future? What measures can be implemented to enhance the synergetic mitigation effects between air pollutants and carbon emissions? Specifically, by establishing a plant-level CFPP–APCD dataset, we have quantified, for the first time, the historical CO_2 emissions induced by the electricity usage of APCDs in China CFPPs. Furthermore, we have projected future emissions under different climate pathways through scenario analysis. Our study unveils the CO_2 emissions induced by the fast-changing APCDs in China CFPPs by compiling a high-resolution emission inventory based on plant-level information. Consequently, this study provides insights into formulating synergetic strategies to mitigate air pollutants and CO_2 emissions in China CFPPs. Various measures are proposed to reduce APCD CO_2 emissions, including improving the energy efficiencies of APCDs and powering them with low-carbon electricity. Moreover, our analysis framework is also applicable to other emission-intensive sectors, such as steel production and waste incineration.

2. Methods and data

In this study, the accounting scope includes the CO_2 emissions induced by the electricity consumption of APCDs in China CFPPs (hereafter referred to as APCD CO_2 emissions). CO_2 emissions from other life cycle stages, such as the production of equipment and consumables (adsorbents and catalysts), are not included. In the established plant-level CFPP–APCD dataset, there are more than 30 kinds of APCD technologies used for dust removal, desulfurization, and denitration. In this study, the electricity consumption rates of the four most widely used APCD technologies (e.g., ESP, WFGD, SCR, and SNCR + SCR) [26] are available (a list of the rates can be found in Table S1). ESP and WFGD are used for dust removal and desulfurization, respectively. SCR and SNCR + SCR are used for denitration. The installed capacities of other APCD technologies are relatively small, and their electricity consumption rates are not available in the dataset. Therefore, to provide a rough estimate, we have calculated the CO_2 emissions of other APCD technologies based on the electricity consumption rates of the above four APCDs.

2.1. Plant-level CFPP–APCD dataset

Data from multiple sources were integrated to construct our plant-level CFPP–APCD dataset. We obtained power plant information, including installed capacity, commissioning year, annual average operation hour, annual power generation, location, and coal consumption, from the China Electricity Council [55–58]. Additionally, data on APCDs used in CFPPs, including the CFPP name, APCD type, and the year of APCD installation, were derived from China's Ministry of Ecology and Environment [59]. Information about CFPPs built in 2019 and 2020 was derived from publicly available sources [60,61]. By matching the aforementioned data, we constructed the plant-level CFPP–APCD dataset. This dataset includes a total CFPP installed capacity of 199.9 GW in 2000, 340.2 GW in 2005, 632.7 GW in 2010, 768.1 GW in 2014, 893.4 GW in 2018, and 1038.3 GW in 2020, accounting for approximately 90% of the total installed capacity of China CFPPs. For CFPPs without coal consumption information, we made estimates based on previous studies [38,62] (see Supplementary Methods).

2.2. Plant-level CO_2 emissions from coal-fired power generation

Different types of coal exhibited different carbon emission factors. Due to the fact that the types of coal consumed in CFPPs were not reported in the data, we used the provincial weighted average carbon emission factor of coal consumed in power plants to calculate plant-level CO_2 emissions from power generation. The weighted average carbon emission factors $ef_{i,t}$ were calculated as follows:

$$ef_{i,t} = \sum_{k=1}^{4} \frac{w_{i,k}}{w_{i,\text{total}}} \times ef_k \tag{1}$$

where the subscripts i, t, and k refer to the province, year, and coal type, respectively; $w_{i,k}$ is the weight of the k type coal for power generation in province i; $w_{i,\text{total}}$ is the total weight of coal for power generation in province i; and ef_k is the emission factor of k type of coal. Four types of coal were included: raw coal, cleaned coal, briquette, and other washed coal. The carbon emission factor of coal used for power generation in each province is shown in Table S2.

Then, the emission factor method proposed by the Intergovernmental Panel on Climate Change (IPCC) was used to calculate the CO_2 emissions from power generation $EP_{n,t}$:

$$EP_{n,t} = Coal_{n,t} \times ef_{i,t} \tag{2}$$

where n is the number of the CFPP, $Coal_{n,t}$ is the total coal consumption of the CFPP in year t, and $ef_{i,t}$ is the carbon emission factor of coal in the corresponding province of the CFPP.

2.3. APCD CO_2 emissions from CFPPs

It's assumed that the APCDs use electricity supplied by the power plant where they are installed. To quantify APCD CO_2 emissions, a concept of APCD electricity consumption rate is introduced:

$$r_{n,t,l} = \frac{EC_{n,t,l}}{PG_{n,t}} \tag{3}$$

where the subscript l is the technology type of the APCD, $EC_{n,t,l}$ is the electricity consumption of the l type APCD in the nth CFPP in year t, and $PG_{n,t}$ is the annual power generation of the nth CFPP in year t. Due to data availability issues, we used the average electricity consumption rate for each kind of APCD technology (Table S3).

APCD CO_2 emissions in CFPP n can be calculated as follows:

$$\begin{aligned} E_{n,t} = \sum_l E_{n,t,l} = \sum_l EC_{n,t,l} \times ef_{n,t} = \sum_l \frac{EC_{n,t,l}}{PG_{n,t}} \times PG_{n,t} \times \frac{EP_{n,t}}{PG_{n,t}} \\ = EP_{n,t} \times \sum_l r_{n,t,l} \end{aligned} \tag{4}$$

where $ef_{n,t} = \frac{EP_{n,t}}{PG_{n,t}}$ is the CO_2 emissions from producing one unit of electricity in CFPP n.

2.4. Uncertainty and sensitivity analysis

In this study, the major sources of uncertainty originate from three variables: the activity data of coal consumption in CFPPs, the emission factors of coal used, and the electricity consumption rates of APCDs. The first step is to assume the probability distributions for the input variables. Following the approach of previous studies [62,63] and IPCC standards [64], we adopt normal distributions for the activity data and emission factors. In addition, we employ a coefficient of variation (CV) of 5% for activity data (coal consumption of CFPPs) and a CV of 3% for CO_2 emission factors of coal based on Guan et al. [63] and Liu et al. [65]. Regarding the electricity consumption rates of APCDs, we assume a normal distribution with a CV of 20%, considering the limited observation data. Monte Carlo simulation is performed to characterize the uncertainties of APCD CO_2 emissions. The uncertainty analysis is carried out using Crystal Ball, a statistical software. We adopt the 95% confidence interval (CI) for the estimations, and the simulation is configured to run 1000 times. Unless otherwise specified, uncertainty in this manuscript refers to a 95% CI around the central estimate.

Furthermore, a sensitivity analysis is applied to evaluate the impact of uncertainties in APCD electricity consumption rates on total emissions. Following previous studies [66,67], we quantify the range of uncertainty by considering the average, maximum, and minimum values of the electricity consumption rate, as presented in Table S1. Unless otherwise specified, the CO_2 emissions mentioned in the manuscript are calculated based on the average electricity use factors. The average, maximum, and minimum values of the electricity consumption rates of APCDs can be found in Table S3.

2.5. Scenario analysis

In this study, we have developed a plant-level scenario analysis to estimate future APCD CO_2 emissions. Our scenario analysis includes three factors: the power plant lifetime, climate mitigation target, and future APCD application, and each consists of three levels. Regarding the lifetime of each power plant, we assume three durations: 20, 30, or 40 years. Regarding the climate mitigation target, three scenarios — 1.5 °C, 2.0 °C, and business as usual (BAU) — are considered. The climate mitigation targets are represented by the corresponding annual average operation hours of CFPPs based on a previous study [68]. In addition, we assume that all CFPPs will be equipped with dust removal, desulfurization, and denitration APCDs in the next five or ten years. As a baseline scenario, we provide a BAU scenario, indicating that no new APCDs will be installed. Consequently, there are a total of 27 scenarios (Table S4). For example, the scenario “20-1.5 °C-5” represents that the lifetime of CFPPs is 20 years, the annual average operation hours of China CFPPs align with the 1.5 °C target, and all CFPPs are equipped with APCDs in the next five years. Detailed reasons and assumptions for scenario design can be found in the Supplementary Methods.

2.6. Data sources

Data on the CFPP installed capacity, power generation amount, coal consumption, geographic location, etc., were obtained from the Inventory of Power Plants in China published by the China Electricity Council [55–58]. Data about CFPPs built in 2019 and 2020 were collected from open sources [60,61]. Data about APCDs applied in CFPPs were derived from China's government reports [59]. To calculate the provincial weighted average carbon emission factors of coal, we employed energy balance tables for each province obtained from the Energy Statistical Yearbook [69] and carbon emission factors of different types of coal from a previous study [70]. The electricity consumption rates for different types of APCDs were derived from published studies and our on-site investigation. Our on-site investigation included six units across three CFPPs, with a total installed capacity of 2320 MW. The sources of the electricity consumption rates are shown in Table 1. A detailed specification on the electricity consumption rates can be found in Table S1.

3. Results

3.1. Fast-growing CO_2 emissions induced by APCDs from 2000 to 2020

From 2000 to 2020, CO_2 emissions induced by the four most widely used APCD technologies (i.e., ESP, WFGD, SCR, and

Table 1
Data sources for electricity consumption rates of APCDs.

APCD Type	Data Sources
ESP	Scientific literature [45]; on-site investigation.
WFGD	Scientific literature [45,71–76]; on-site investigation.
SCR	Scientific literature [47]; on-site investigation.
SNCR + SCR	On-site investigation.

Note: ESP, electrostatic precipitator. WFGD, wet limestone–gypsum flue gas desulfurization. SCR, selective catalytic reduction. SNCR, selective noncatalytic reduction.

SNCR + SCR) increased by approximately 34 times from 1.48 Mt (95% CI, 0.89–2.10 Mt) in 2000 to 51.70 Mt (95% CI, 34.74–69.67 Mt) in 2020 (Fig. 1a). By comparison, the total CO_2 emissions of Qinghai Province in 2019 were 51.75 Mt [77]. The proportion of APCD CO_2 emissions in the total emissions from coal-fired power generation also increased. Specifically, APCD CO_2 emissions accounted for 0.12% of the total emissions from coal-fired power generation in 2000; this proportion reached 1.19% in 2020 (Fig. 1b). This result reflects China's increasingly stringent control of air pollutant emissions from CFPPs over the past two decades.

The structure of APCD CO_2 emissions underwent dramatic changes (Fig. 1c). Initially, China's efforts to reduce air pollutants from CFPPs primarily focused on particulate matter emissions. In 2000, CO_2 emissions from dust removal APCDs (i.e., ESP) accounted for 97.4% of total APCD CO_2 emissions. Then, attention was given to the control of SO_2 emissions. From 2000 to 2005, the share of emissions from desulfurization APCDs (i.e., WFGD) in total APCD CO_2 emissions rapidly increased from 2.6% to 75.3%. The control of NOx emissions began comparatively later, with no CFPPs were equipped with APCDs for denitration in 2000. By 2005, CO_2 emissions induced by denitrification APCDs (i.e., SCR and SNCR + SCR) constituted 7.9% of the total APCD emissions. This proportion experienced an increase and reached 12.2% by 2014.

The changes in China's CFPP structure resulted in corresponding changes in the structures of APCD CO_2 emissions. Due to the relatively high-power generation efficiencies of large-generation units, the development of large-scale units was encouraged, and the retirement of small units was accelerated [78]. This shift towards larger CFPPs consequently increased the proportion of APCD CO_2 emissions from larger CFPPs. As shown in Fig. 1d, the ratio of APCD CO_2 emissions from power plants above 300 MW to the total APCD CO_2 emissions showed an increasing trend. In 2000, APCD CO_2 emissions from units above 300 MW accounted for 55.1% of total emissions, and this proportion increased to 90.2% in 2005 and 93.2% in 2020.

Among the four aforementioned APCD technologies, the desulfurization APCD (WFGD) consumed more electricity than the others, causing more CO_2 emissions. For example, the Qinbei Power Plant in Henan Province had an installed capacity of 4400 MW and was equipped with an ESP, WFGD, and SCR. In 2020, WFGD contributed 77% of the APCD CO_2 emissions of the Qinbei Power Plant; ESP and SCR contributed 10% and 13% of the emissions, respectively.

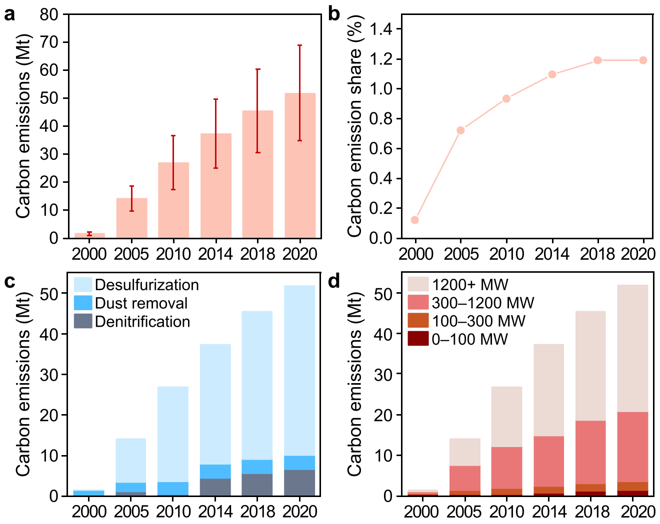

Fig. 1. National APCD CO_2 emissions 2000–2020 (**a**), their proportions to the total emissions from CFPPs (**b**), and emissions categorized by APCD type (**c**) and capacity size (**d**). (The error bars in panel **a** represent the 95% confidence interval.)

Both uncertainty and sensitivity analyses were conducted on the total APCD CO_2 emissions. The uncertainty range of the results is shown in Fig. 1a, and the sensitivity analysis results are shown in Fig. S1. The uncertainty mainly arose from the APCD electricity consumption rates because China's power plants do not generally publish detailed station service power consumption information, and only limited observations are collected.

In addition to the above four APCDs, numerous other APCD technologies are used for dust removal, desulfurization, and denitrification. In this study, we estimated the CO_2 emissions of other APCDs based on the electricity consumption rates of the four APCD technologies. Given the considerable disparity in electricity consumption rates among different APCDs designed to control the same pollutant emissions, it should be noted that the estimation provided in this study serves as a rough reference. The results showed that when the CO_2 emissions of other APCDs were included, the total APCD CO_2 emissions would grow by 11.2–24.7%; the total APCD CO_2 emissions increased to 57.5 Mt in 2020. More detailed results can be found in Fig. S2.

3.2. Spatial distribution of APCD CO_2 emissions

The APCD CO_2 emissions were unevenly distributed, with most of the emissions occurring in northern China and in coastal regions (Fig. S3). The northern regions of China, such as Nei Mongol, Shanxi, and Shaanxi, were the main coal-producing regions, and many pithead plants were built there. Consequently, a large amount of APCD CO_2 emissions were concentrated in these regions. The economically developed coastal region in China experiences a large electricity demand, which has led to the construction of an increasing number of CFPPs in this region. Consequently, extensive APCD CO_2 emissions were induced.

From 2000 to 2020, an increasing number of CFPPs with APCD CO_2 emissions surpassed 100 kt. In 2000, no power plants had APCD CO_2 emissions exceeding 100 kt. In 2020, there were 89 power plants with APCD CO_2 emissions exceeding 100 kt and 15 power plants exceeding 200 kt. Large CFPPs were the major contributors to APCD CO_2 emissions. Specifically, in 2020, there were 1981 CFPPs, and the top 20 power plants with the largest APCD CO_2 emissions accounted for 9.3% of the total emissions. In contrast, the 100 power plants with the smallest APCD CO_2 emissions collectively accounted for less than 0.01% of the total emissions. It's worth noting that many emissions were from CFPPs with relatively low annual average operation hours. In 2020, the annual average operation hours of China CFPPs were 4430 h $year^{-1}$. There were 234 power plants (41 GW in total) with average power generation hours of less than 2000 h $year^{-1}$ and total APCD CO_2 emissions of 480 kt. These 234 CFPPs accounted for 4% of the total national CFPP installed capacity, 4.4% of the coal combustion for power generation, and 1.1% of the coal-fired power output. The average coal consumption intensities of these 234 CFPPs reached 412 g kWh^{-1}, much higher than the national average of 304.5 g KWh^{-1}. In addition, many of these CFPPs were self-built power plants, with approximately one-fourth lacking denitration APCDs.

APCD CO_2 emissions at the provincial level are shown in Fig. S4. The top five provinces with the largest APCD CO_2 emissions in 2020 were Nei Mongol, Shanxi, Jiangsu, Shandong, and Henan, collectively accounting for 41.4% of the national total emissions. The growth rates of APCD CO_2 emissions among provinces from 2000 to 2020 showed great disparity. APCD CO_2 emissions in Nei Mongol increased by more than 220 times during the 20 years, followed by Xinjiang (125 times) and Ningxia (102 times). This phenomenon occurred mainly due to the rapid expansion of CFPPs in these regions. Generally, across all provinces, the growth rates of APCD CO_2 emissions outpaced those of coal-fired power generation, indicating China's increasingly higher requirements for pollutant emission control while developing coal-fired power generation.

3.3. Prospective APCD CO_2 emissions

The future APCD CO_2 emissions under the 27 scenarios vary greatly (Fig. 2a). Notably, the accumulated APCD CO_2 emissions under scenarios with a 20-year lifetime and 1.5 °C target are approximately one-fifth of the emissions under scenarios with a 40-year lifetime and the BAU climate target. Among the three factors considered, the lifetime of the power plant has the greatest impact on future APCD CO_2 emissions. When reducing the lifetime of the power plant to 20 years, the cumulative APCD CO_2 emissions are 298.2—391.2 Mt, which is much lower than the emissions under the 30-year (582.4—928.6 Mt) and 40-year (734.7—1517.6 Mt) lifetime scenarios. Climate policy has a relatively modest impact on APCD CO_2 emissions. For example, with a lifetime of 30 years, the APCD CO_2 emissions of power plants under the BAU climate policy scenario are approximately 1.6 times higher than those under the 1.5 °C climate policy scenario. Our results show that installing APCDs for power plants lacking desulfurization, denitrification, or dedusting equipment produces very little CO_2 emissions (Fig. 2a). This phenomenon occurs mainly because most of China CFPPs are already equipped with the required APCDs.

The longer the lifetimes of the power plants, the greater the disparities in the dynamic trajectories of APCD CO_2 emissions across different scenarios (Fig. 2b). When the lifetimes of the power plants are 20 years, annual APCD CO_2 emissions show similar trajectories. In addition, it is worth noting that a high portion, nearly 73%, of the existing CFPP capacity is decommissioned in the first ten years from 2020 to 2040. Therefore, there is a sharp decline in CO_2 emissions in the early stage. This phenomenon suggests that there will be more demand to accelerate CFPP decommissioning in the coming decade if the lifetime is set at 20 years. The velocity of power plant decommissioning in other scenarios is more even, indicating less stress.

The provincial APCD CO_2 emissions under different scenarios present great differences (Figs. 3 and S4). Among the 27 scenarios, Nei Mongol, Shanxi, Shandong, Jiangsu, and Henan have the largest APCD CO_2 emissions. Remarkably, these five provinces collectively account for approximately 30% of the total national APCD CO_2 emissions across all the scenarios. Nei Mongol always has the largest APCD CO_2 emissions due to its very high CFPP installed capacity. In contrast, the provinces with the lowest future APCD CO_2 emissions — Beijing, Hainan, Sichuan, Yunnan, and Qinghai—collectively account for approximately 1% of the total national APCD CO_2 emissions across the 27 scenarios. The gross installed capacity of newly built CFPPs after 2010 was approximately 280 GW. Xinjiang, Henan, Nei Mongol, Jiangsu, and Shanxi have the largest newly installed capacity, totaling 118 GW (Fig. S6). Therefore, as shown in Fig. 3, when extending the lifetimes of CFPPs, future APCD CO_2 emissions mainly occur in provinces with many newly built power plants.

We identify plants with the largest APCD CO_2 emissions under different scenarios, which helps develop targeted emission reduction measures. Under different scenarios, the top 20 power plants account for more than 9% of the total APCD CO_2 emissions, indicating the focus of improving the energy efficiencies of APCDs in these CFPPs. In addition, the list of the top 20 power plants almost overlaps when the lifetimes of the power plants are 30 and 40 years. However, when the lifetime is set at 20 years, the list undergoes substantial changes, primarily featuring newly constructed power plants within the last decade. This finding suggests that when accelerating the decommissioning of CFPPs, attention should be given to improving the energy efficiencies of APCDs of newly built power plants to reduce APCD CO_2 emissions.

4. Discussion

Over the past few decades, China has effectively reduced air pollutant emissions from CFPPs through the widespread installation of APCDs, bringing remarkable benefits to human health and ecosystems [18,21—24]. However, little is known about the CO_2 emissions induced by APCDs. Based on a plant-level CFPP—APCD dataset covering approximately 90% of China CFPPs, for the first time, we have quantified CO_2 emissions induced by APCDs in China CFPPs and predicted future emissions. The analysis framework employed in this study is applicable to other emission-intensive sectors, such as cement production, steel production, transportation, and waste incineration.

Traditionally, researchers have primarily focused on exploring

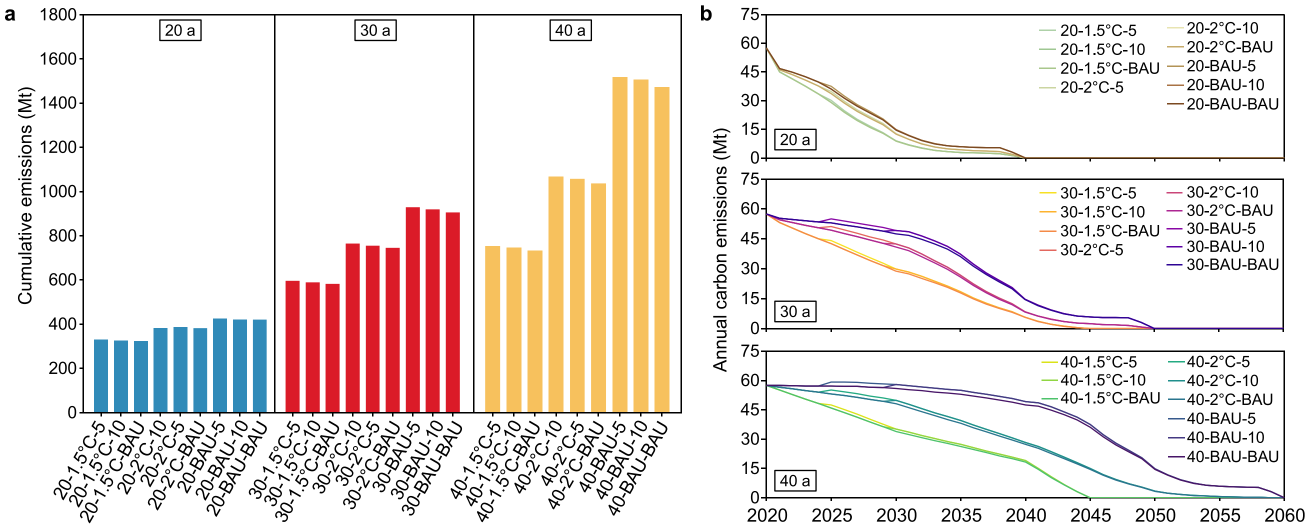

Fig. 2. The cumulative (**a**) and annual (**b**) APCD CO_2 emissions under different scenarios.

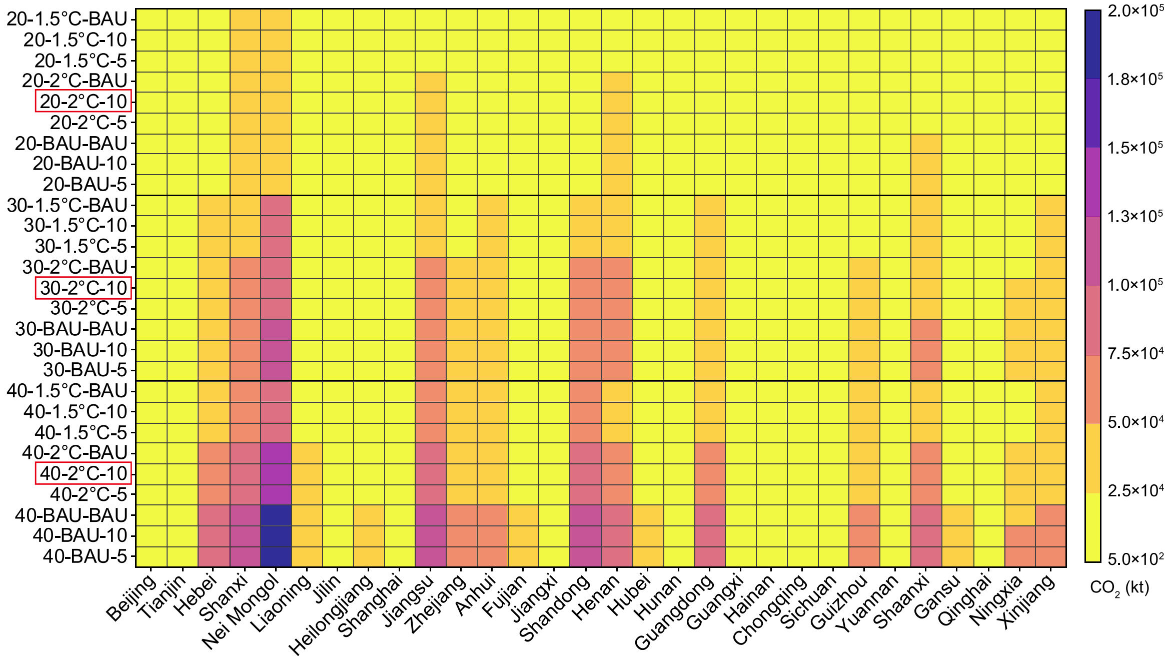

Fig. 3. Provincial cumulative APCD CO_2 emissions under different scenarios.

the synergistic effects of pollutant reduction and carbon reduction while largely overlooking the tradeoff between these two crucial objectives. Our study shows that measures to reduce pollutant emissions lead to substantial CO_2 emissions, revealing a tradeoff between carbon mitigation and air pollutant control. Therefore, we highlight the necessity of conducting a comprehensive environmental impact assessment prior to implementing policies to avoid the shifting of environmental problems. To date, the Chinese government attaches great importance to the synergistic effects of policy measures on pollutant emission reduction and climate change mitigation [79]. Policies with synergistic effects can simultaneously reduce air pollutants and carbon emissions at lower costs and higher efficiencies. Our study provides insights for formulating such policies.

Since APCD CO_2 emissions originally come from CFPP's coal combustion, there are several approaches to reduce APCD CO_2 emissions, including accelerating the decommissioning of CFPPs, employing the carbon capture, utilization, and storage (CCUS) technology, improving APCD energy efficiency, and providing APCDs with low-carbon electricity. However, since the first two approaches lie beyond the scope of the present study, we have focused our attention on the latter two. Due to outdated technology or lack of maintenance, some APCDs have low energy efficiency, resulting in wasting power [23]. To improve APCD energy efficiency, a range of measures are available, such as implementing APCD technical standards and updating APCD equipment. To provide APCDs with low-carbon electricity, one option is to reduce the emission intensity of coal-fired electricity produced in CFPPs. In China, there are more than 200 CFPPs with an average coal consumption intensity of 412 g KWh^{-1}, which is much higher than the national average. It is possible to decrease the overall emission intensity of coal-fired electricity by shutting down or reducing the operating hours of these CFPPs. In addition, co-firing biomass with coal in coal-fired units is recommended to decarbonize electricity. Biomass is regarded as CO_2 neutral, and hence, co-firing it with coal can reduce the carbon emission intensity of electricity [80]. Co-firing biomass with coal is a cost-effective approach to using biomass as fuel. Currently, most of the co-firing power plants are located in European countries, such as Germany and Finland [81,82]. China has abundant biomass resources, but only a small portion of them are utilized for power generation. Therefore, exploring this technology's potential to decarbonize China's power system is essential. Powering APCDs with photovoltaic (PV) power offers another option. Jiang et al. [83] proposed a cost-effective solution to produce PV power by installing PV panels on the roofs of CFPP buildings (the CFPP—PV system). Their study shows that the CFPP-PV system in Northern China has a lower levelized cost of electricity (LCOE) compared to typical PV systems (e.g., distributed PV systems, centralized PV systems, and standalone PV systems). This is because the CFPP—PV system avoids the additional costs associated with land rent, grid connection, and battery costs. In fact, the CFPP—PV system is economically competitive with fossil fuel power generation in most CFPPs. Therefore, it's possible to develop the CFPP—PV system in northern provinces in China to provide affordable solar power to APCDs during the daytime. This approach can help to reduce APCD CO_2 emissions as it reduces the demand for carbon-intensive coal-fired electricity.

Our results show that future APCD CO_2 emissions will have uneven spatial distributions, with certain provinces, including Shanxi, Nei Mongol, Jiangsu, and Shandong, having larger emissions than others. Indeed, installing and operating APCDs in these provinces yield positive environmental spillover effects. This implies that APCDs can improve the local air quality and reduce air pollutants' transportation to surrounding regions through atmospheric transport [8,84]. Therefore, it is recommended that CFPPs in these provinces be allocated a higher carbon emission quota in the carbon emission trading market. In addition, financial subsidies should be provided for upgrading APCDs in these provinces to improve their pollutant removal efficiency and energy efficiency.

This study is subject to several limitations. One of the primary limitations is the lack of a comprehensive inventory of APCD electricity consumption rates, which is essential for obtaining more accurate APCD CO_2 emission accounting. Currently, the electricity consumption rates for APCD technologies other than ESP, WFGD, SCR, and SNCR + SCR are not available. In addition, we use average APCD electricity consumption rates to estimate emissions in this study, which may lead to some uncertainties. Therefore, a sensitivity analysis is conducted to help us better understand its impact on the results.

5. Conclusion

In this study, we quantified CO_2 emissions induced by APCDs in China's CFPPs from 2000 to 2020 using a plant-level CFPP–APCD dataset covering approximately 90% of China CFPPs. China's APCD CO_2 emissions experienced a rapid increase of approximately 34 times, surging from 1.48 Mt in 2000 to 51.70 Mt in 2020. Concurrently, their proportion to the total emissions from coal-fired power generation also witnessed an increase, rising from 0.12% to 1.19%. In comparison to the dust removal and denitration devices, the desulfurization devices have higher carbon intensity and were responsible for approximately 80% of APCD CO_2 emissions in 2020. The spatial distribution of APCD CO_2 emissions was uneven. Specifically, Nei Mongol, Shanxi, Jiangsu, Shandong, and Henan provinces were the main contributors, collectively accounting for over 40% of the total APCD CO_2 emissions in 2020. Furthermore, using scenario analysis, we estimated future APCD CO_2 emissions. Our results indicate that the lifetimes of CFPPs will substantially impact future APCD CO_2 emissions, and Nei Mongol, Shanxi, and Shandong provinces are projected to have the largest emissions due to their large-scale newly built CFPPs. Overall, this study enhances the current understanding of the complex interaction between carbon mitigation and air pollutant control in CFPPs, and highlights the necessity of conducting thorough environmental impact assessments of environmental policies to avoid the shifting of environmental problems.

CRediT author contribution statement

Pengfei Zhang: Methodology, Writing - Original Draft, Visualization, Formal Analysis. **Kuishuang Feng**: Writing- Reviewing and Editing, Formal Analysis. **Li Yan**: Investigation. **Yaqin Guo**: Methodology, Data Curation. **Bei Gao**: Methodology, Data Curation. **Jiashuo Li**: Conceptualization, Supervision, Funding Acquisition, Writing - Reviewing and Editing, Project Administration, Resources.

Declaration of competing interest

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

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Appendix A. Supplementary data

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