DOI: 10.54254/2755-2721/58/20240730

# Establishment of multi-pollutant emission inventory for coal-fired power plants in Guangdong province: A comprehensive approach to air quality management

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**Abstract.** Emissions of heavy metals from coal-fired power plants pose significant environmental and health risks. This study focuses on quantifying the point-source emissions of heavy metal elements from coal-fired power plants in Guangdong Province, a major economic region with numerous power plants. A bottom-up approach was used to calculate the emissions of mercury (Hg), arsenic (As), and other elements in 2018, along with scenario assumption analyses. The total emissions of Hg, As, Pb, Cd, Cr, and Ni were estimated at 2305, 7443, 7891, 298, 3039, and 7131 kg in 2018, respectively. In addition, the Pearl River Delta (PRD) region, due to its economic development and demand for electricity, has the highest levels of heavy metals emitted from coal-fired power plants in the region, accounting for 42.17-48.60% of the provincial emissions. Scenario simulations showed that the installation of advanced dust removal methods (e.g., LLT-ESP) significantly reduces heavy metal emissions compared to the baseline. It is crucial to continue investing in advanced dust removal technologies and enforce stricter regulations to further mitigate heavy metal emissions from coal-fired power plants.

**Keywords:** Heavy Metal, Coal Fired Power Plants, Emission Inventory, Guangdong Province.

## 1. Introduction

Air pollution has become a pressing environmental issue in recent years, especially in countries undergoing rapid development such as China [1, 2]. The growing demand for energy has led to an increase in coal-fired power plants, which release pollutants such as sulfur dioxide ($SO_2$), nitrogen oxides (NOx), particulate matter (PM), and heavy metals, causing air pollution [3, 4]. Anthropogenic emissions of hazardous trace elements in the atmosphere pose a serious threat to human health and ecosystems. According to the 1990 amendments to the United States Clean Air Act, several trace elements, such as Sb, As, Cr, Pb, Cd, Hg, Ni, Se, Be, Mn, and Co, were recognized as toxic air pollutants due to their negative impacts on public health and the environment [4, 5]. Similarly, the European Union (EU) identifies arsenicals, Pb, Cd, Hg, and Ni as the primary toxic air pollutants responsible for environmental issues [6].Trace elements are usually released as suspended particulate matter and in gaseous form at high temperatures and can remain in the atmosphere for 5-8 days attached to fine particles or up to 30 days if combined with very small particles, causing serious effects on human health [6, 7].

Coal-fired power plants are significant contributors to anthropogenic trace element pollution in China [7, 8]. By the end of 2010, 1,591Mt of coal was used for power generation, accounting for about 50% of the country's total coal consumption, generating various trace element emissions [6]. Studies have focused on pollutant emissions from coal-fired power plants in other provinces as well as nationwide [9-11].

Guangdong Province, located in southern China, is a densely populated and economically developed area that heavily relies on coal-fired power plants to meet its energy demands. The potential environmental consequences of these power plants on air quality have raised concerns among policymakers, researchers, and the general public. However, there has been a lack of specific data regarding heavy metal emissions from point sources in Guangdong Province's coal-fired power plants. To address this gap, a study was conducted using a unit-based bottom-up approach to calculate a comprehensive emission inventory for these plants within the province. The study also examined the variability of emissions across different municipalities and analyzed how economic, industrial, and other human factors affected emissions levels. Additionally, future heavy metal emissions from these power plants were predicted based on scenario assumptions. The findings of this study offer valuable insights into the spatial distribution and temporal patterns of emissions from coal-fired power plants in Guangdong Province, which can inform air quality management strategies and evaluate the efficacy of emission control measures.

## 2. Data and methods

### *2.1. Study domain and basic method*

Located in southern China, Guangdong Province is the largest provincial economy in the country with a land area of 180,000 square kilometers and a population of over 110 million. With a strategic geographical location, Guangdong is situated in the southeastern part of China and shares borders with Hong Kong and Macau. Renowned for its vibrant cities, coastal landscapes, and rich cultural heritage, Guangdong is also a key player in China's energy sector. With a significant number of coal-fired power plants, Guangdong stands at the forefront in terms of both power plant count and coal consumption (Fig 1). According to a report by Guangdong Development and Reform Commission, as of 2019, the province had a total of 206 coal-fired power plants, accounting for approximately 25% of China's total coal-fired power plants. Moreover, these power plants consumed an estimated 120 million tons of coal annually, making Guangdong a leading coal consumer in the country.

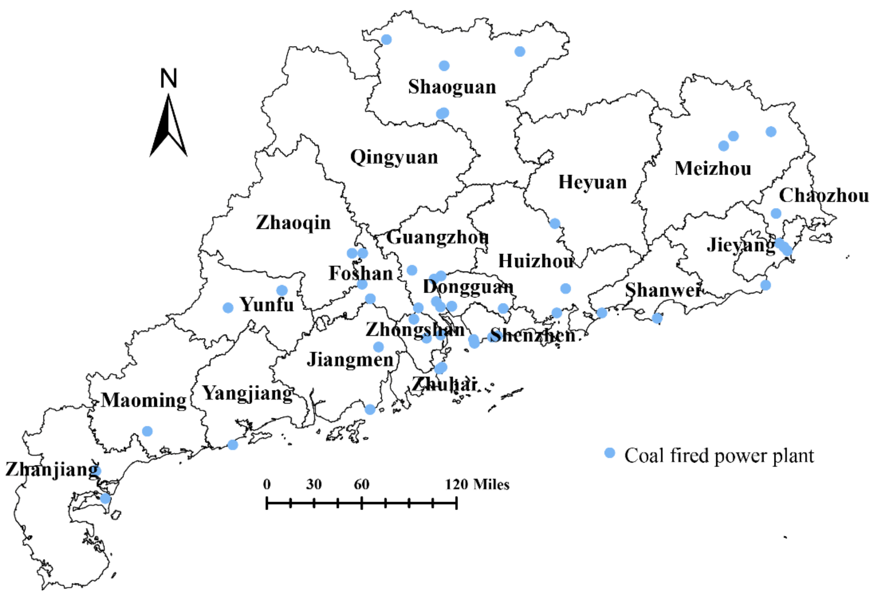


**Figure 1.** Distribution of installation locations of coal-fired power plants in Guangdong Province.

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In this study, emissions of heavy metals including Hg, As, Pb, Cd, Cr, and Ni from coal-fired power plants are calculated by a unit-based bottom-up method. Calculations were made by collecting the concentrations of each metal in the raw coal, the coal consumption of each power plant in Guangdong Province, and the removal rate of each heavy metal by the power plant's non-useful devices (including desulfurization, denitrification, and dust collector).

$$E_{total} = \sum_i E_i \tag{1}$$

$$= \sum_i C \times M \times R \times (1 - \eta_{PM}) \times (1 - \eta_{SO_2}) \times (1 - \eta_{NO_x}) \tag{2}$$

In this study, the researchers calculated the emissions of Hg, As, Pb, Cd, Cr, and Ni (in kilograms) in Guangdong Province in 2018. The calculation took into account several factors: the average concentration of each heavy metal in the feed coal (in micrograms per gram), the amount of coal consumption (in tons), and the average release ratio of each heavy metal in the flue gas compared to its concentration in the feed coal for pulverized coal boilers, which were the boiler types used in all coal-fired power plants in Guangdong Province. The specific release rates for Hg, As, Pb, Cd, Cr, and Ni were determined as 99.42%, 98.46%, 96.25%, 94.54%, 84.50%, and 56.53% respectively. $\eta_{PM}$, $\eta_{SO_2}$, and $\eta_{NO_x}$ represent the averaged fraction of one heavy metal cobenefit removed from flue gas by the conventional PM/$SO_2$/$NO_x$ emission control devices, respectively.

### 2.2. *Parameters for the calculation of atmospheric emissions*

*2.2.1. Coal consumption.* Since the beginning of the 21st century, coal consumption by coal-fired power plants has shown a high growth rate. According to the established coal-fired power plant database, China's coal-fired power plants consumed 1.9 billion tons of coal in 2018. Among them, Inner Mongolia ranked first in terms of coal consumption, with 240.9 million tons (Mt), and Shandong province, which has the largest number of coal-fired power plants, consumed 186.9 Mt. The remaining provinces with greater than 100 Mt were Jiangsu (139.5 Mt), Shanxi (136.8 Mt), Guangdong (116.9 Mt), and Henan (109.7 Mt). The coal consumption of each power plant used in this study is based on the total coal combustion data of Guangdong Province, which is accounted for according to the installed capacity of each power plant.

*2.2.2. Average content of heavy metals in coal.* The content of hazardous trace elements in coal plays a key role in pollution control during coal combustion and utilization. Even if the amounts of hazardous elements in coal is only one part per million, it can result in tons of pollutants being released into the environment. In China, the geological conditions vary from region to region, resulting in significant differences in the coal rank, mineral and trace element composition of each region. Previous studies have demonstrated that cadmium, chromium, and lead occur in different ways, in different amounts, and in different distributions in different provinces, from different sources, and even within the same coal seam. In addition, due to the unbalanced geographic distribution of coal resources in China, Guangdong Province has fewer coal fields of its own and therefore needs to transport coal from other provinces. In this study, the concentrations of heavy metals in raw coal were calculated from the data of previous studies using the national coal transportation matrix as well as the concentrations of heavy metals in the coal produced in each province, obtained from the concentrations of coal consumed in each province. Since the source of coal used in each power plant could not be obtained, the raw coal concentrations were consistent across power plants, as shown in Table 1.

**Table 1.** Contents of Cd, Cr, and Pb in raw coals consumed (unit: mg/kg).

| Items | Concentration (μg/g) |
|---|---|
| Hg | 5.19 |
| As | 17.72 |
| Pb | 36.00 |
| Cd | 1.04 |
| Cr | 26.96 |
| Ni | 26.01 |

*2.2.3. Removal efficiencies of PM and $SO_2$ control devices.* The facility's boilers emit flue gas containing Hg, As, Pb, and related compounds, as well as fine fly ash particulate matter. To mitigate these emissions, various control mechanisms are employed, including electrostatic precipitators (ESPs), baghouses (FFs), electrostatic baghouse combi-filters (ESP-FFs), low-temperature electrostatic precipitators (LLT-ESPs), wet electrostatic precipitators (WESPs), and wet flue gas desulfurization (WFGD) systems [4, 12, 13]. These mechanisms help remove a portion of the emissions as ash and FGD slurry. The remaining flue gas is released into the atmosphere through a stack. Previous studies have shown that the efficiency of different flue gas control equipment in removing various heavy metals can vary significantly [11, 14, 15]. For this study, the average removal efficiencies of the different PM and $SO_2$ control devices were determined based on mean values reported in relevant literature, as outlined in Table 2 [14, 16, 17].

**Table 2.** Removal efficiency of heavy metals by various devices in power plants (%).

| Category | Hg | As | Pb | Cd | Cr | Ni |
|---|---|---|---|---|---|---|
| ESP | 33.17 | 86.2 | 97.17 | 96.47 | 98.54 | 92.92 |
| FF | 67.92 | 99 | 99 | 97.63 | 95.13 | 94.83 |
| ESP-FF | 95.2 | 96.32 | 99.16 | 97.32 | 98.12 | 96.31 |
| WESP | 91.1 | 97.26 | 99.49 | 98.87 | 99.7 | 99.51 |
| LLTESP | 90 | 99.8 | 99.9 | 99 | 99.9 | 99.6 |
| WFGD | 57.22 | 80.38 | 78.4 | 80.5 | 86 | 80 |
| SCR | 11.92 | | | | | |

### *2.3. Scenario projections*

Dust removal methods are an important factor affecting heavy metal pollution in the atmospheric emissions of coal-fired power plants. In the context of reducing atmospheric pollutants, China began promoting the installation of air pollution control equipment in coal-fired power plants in 2005, issued ultra-low emission standards nationwide in 2014, and achieved an 80% installation rate of ultra-low emission technology by 2018. As a typical technology of ultra-low emission, the low-temperature electrostatic precipitator installed before the electrostatic precipitator with a low-temperature economizer is considered to significantly increase the removal efficiency of atmospheric pollutants in the dust removal device. The lower the temperature of the low-temperature economizer, the greater the adsorption of heavy metals on the fly ash. Therefore, the further installation of low-temperature electrostatic precipitators in future control strategies will foreseeably reduce the emissions of atmospheric pollutants. Based on this background, the study sets up three hypothetical scenarios for the installation of low-temperature electrostatic precipitators in future coal-fired power plants: Scenario 1: Power plants currently using electrostatic and bag dust collectors are converted to low-temperature

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electrostatic dust removal; Scenario 2: On the basis of Scenario 1, the electric bag composite dust collector is converted to low-temperature electrostatic dust removal; Scenario 3: All dust removal methods are converted to low-temperature electrostatic dust removal. The consumption of raw coal and the concentration of heavy metals in raw coal remain unchanged, in order to explore the impact of changes in dust removal methods.

## 3. Results and discussions

### *3.1. Annual heavy metal particle emissions from coal-fired power plants in Guangdong province*

As shown in Fig 2, the annual emissions of heavy metals from coal-fired power plants vary drastically. The total emissions of Hg, As, Pb, Cd, Cr, and Ni were estimated at 2305, 7443, 7891, 298, 3039, and 7131 kg in 2018, respectively. To be specific, Pb emissions summing up to 7891 kg contrasting cadmium emissions accumulating to 298 kg, this difference can be attributed to the chemical composition of coal [11]. In response to high Pb emissions from coal-fired power plants, by blending low-lead coal with high-lead coal, the overall lead content in the fuel mixture can be reduced. Additionally, coal washing techniques can help to remove impurities, including lead, before the coal is utilized in power plants. By calculating the heavy metal emissions from coal-fired power plants in all provinces of China in 2010, Tian et al. [16] found that Pb emissions in Guangdong province in 2010 were 22.3 t. In contrast, the Pb emissions in Guangdong in this study in 2018 were 7,891.3 kg (7.89 t), which is lower than other literature calculations. The reason for this result is mainly because the ultra-low emission retrofit of coal-fired power plants has improved the removal efficiency of power plants for various pollutants [18]. All coal-fired power plants in Guangdong Province are installed with wet flue gas desulphurization devices (WFGD) and selective catalytic reduction denitrification devices (SCR). In addition, ESP-FF, WESP, and LLTESP have been installed in increasing proportions in recent years, compared to pre-2010 when electrostatic precipitator and bag filter were the dominant dust removal processes in China [19]. As depicted in Figure 3, dust collectors with certain ultra-high retention efficiencies are installed in various regions of Guangdong Province, which are useful for the removal of heavy metals.

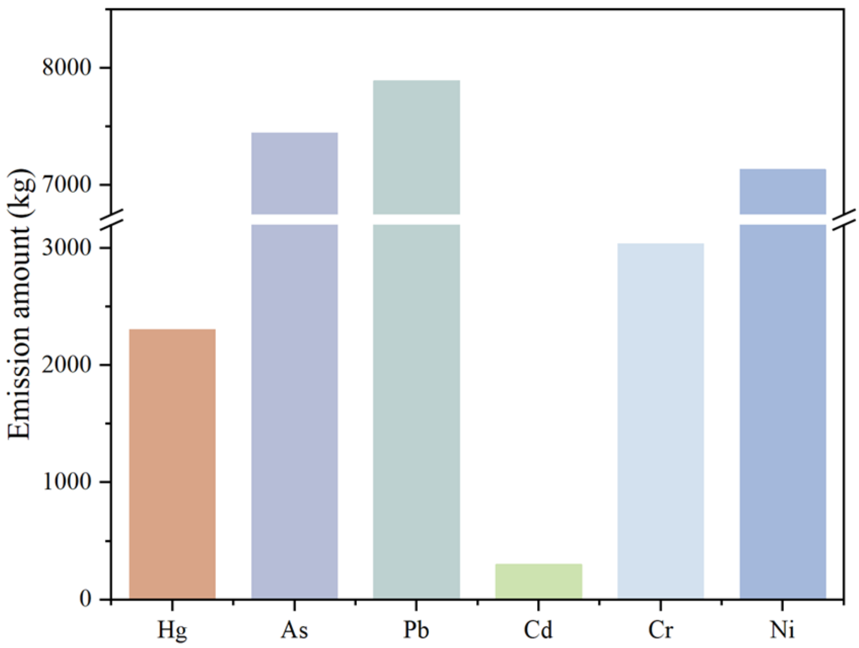


**Figure 2.** HMs emissions from CFPPs in Guangdong Province.

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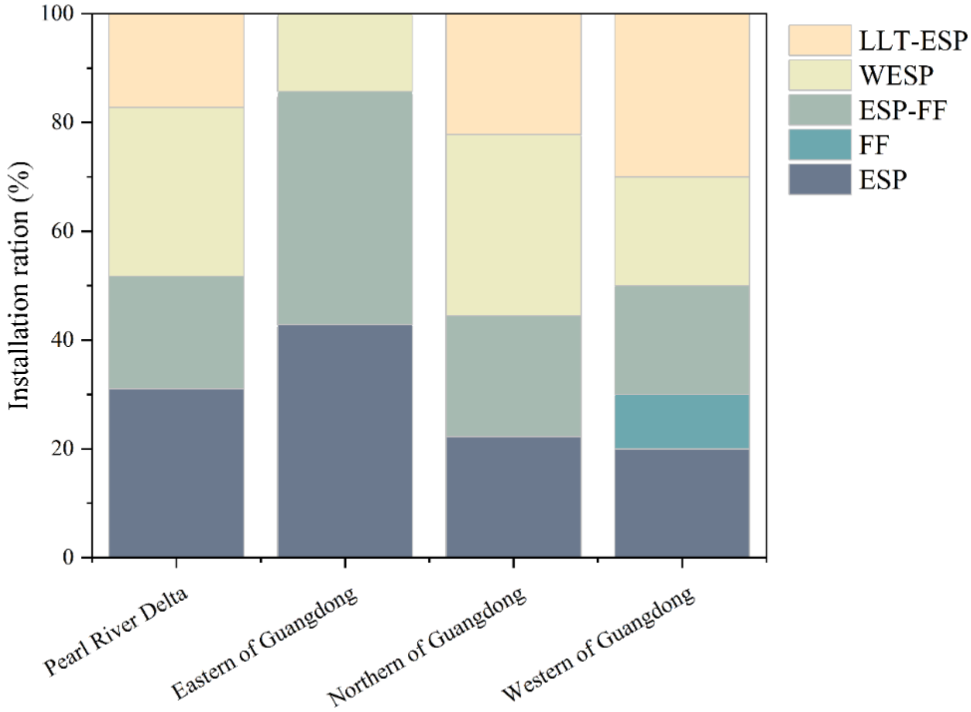


**Figure 3.** Installation ratio of dust collector in each region of Guangdong Province.

### *3.2. Distribution of HMs in Guangdong Province*

Comparing the number of emissions by regions in Guangdong, the Pearl River Delta stands out with the highest coal consumption and consequently the highest emission of heavy metals, followed by East of Guangdong, West of Guangdong, and lastly the North of Guangdong in order (Table 3). The Pearl River Delta—consisting of Guangzhou, Foshan, Zhaoqing, Shenzhen, Dongguan, Huizhou, Zhuhai, Zhongshan, Jiangmen— is also the region installed with 29 CFPPs, the largest among the regions of Guangdong, suggesting a greater demand for electricity which is the basis of all modern industrialization and residence. At the same time, the Pearl River Delta is an economically developed and vibrant region in Guangdong Province compared to the rest of the country. Its favorable geographic location and strong industrial base have contributed to the demand for electricity on the one hand, and on the other hand, it has taken the lead in retrofitting coal-fired power plants with ultra-low emissions. Chen et al., [20] calculated mercury emissions from coal fly ash from coal-fired power plants across the country and found that the amount of mercury produced by coal-fired power plants in the provinces that were the first to implement ultra-low-emission (ULE) retrofits (e.g., Zhejiang, Jiangsu, and Guangdong, etc.) was greatly reduced. In addition, Xiong et al., [10] calculated emissions of $PM_{2.5}$, $SO_2$ and other pollutants from coal-fired power plants in Shandong province and found that cities with relatively developed economies and desulphurization plants (WFGD or FGD) emit relatively fewer pollutants.

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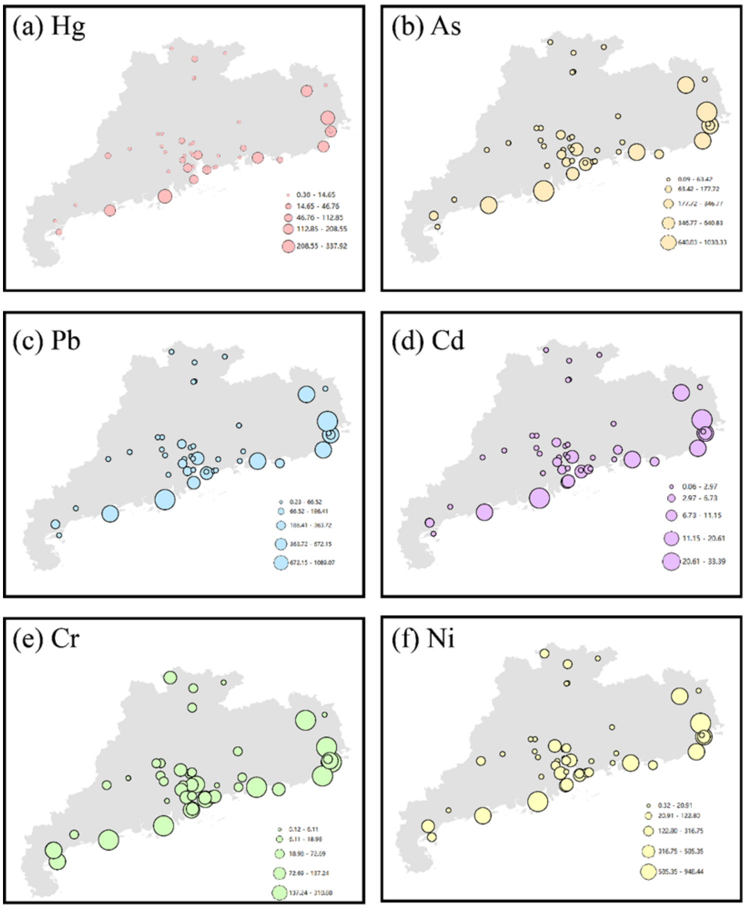


**Figure 4.** Distribution of different HMs from CFPPs in Guangdong Province.

Furthermore, West of Guangdong with similar amounts of CFPPs and coal consumption as East of Guangdong emitted fewer heavy metals than the latter (Fig. 4). The reason lied behind the difference in installation ratio of advanced deducting systems. To be specific, for West of Guangdong, the installation rate of LLT-ESP and WESP in CFPPs were 30% and 20% respectively. On the contrary, East of Guangdong had only 14% of the power plants installed with WESP (Fig. 3). WESP generally offers the highest collection efficiency among the three technologies, especially for submicron particles and those with high resistivity [21]. ESP and LLT-ESP also have high efficiency but may have slightly lower collection efficiencies for specific particle sizes or resistivities [8]. ESP is effective in capturing larger particles, typically above 1 micron in size. LLT-ESP is designed to perform well in capturing fine particles ranging from submicron to a few microns [22]. WESP is suitable for capturing both fine and submicron particles, including those that are difficult for dry ESPs to capture [15,23]. Therefore, to capture finer particles and increase collection efficiency, CFPPs in East of Guangdong should acquire more WESP and LLT-ESP to reduce heavy metal emissions.

**Table 3.** Emission amounts of various heavy metals in each region of Guangdong Province (kg).

| Region | Hg | As | Pb | Cd | Cr | Ni |
|---|---|---|---|---|---|---|
| Pearl River Delta | 1120 | 3521 | 3713 | 137 | 1282 | 3268 |
| Eastern of Guangdong | 646 | 2137 | 2266 | 81 | 876 | 2128 |
| Northern of Guangdong | 78 | 298 | 316 | 18 | 175 | 283 |
| Western of Guangdong | 461 | 1487 | 1597 | 63 | 707 | 1453 |

### 3.3. *Scenario analysi*

Mainly, the aim of the scenario analysis is to examine the effects of installing relatively advanced dust removal techniques (LLT-ESP) and to explore the capacity for future improvement in pollutant reduction of power plants in Guangdong. Although each scenario has changes in the types of removal methods, every power plant in the three scenarios hold the same amount of coal consumption and quantity of dust removals (difference in each type) as the 2018 inventory. Overall, all of the scenarios suggest a reduction in the emission of every HMs (Hg, As, Pb, Cd, Cr, and Ni) from measurements of 2018, but the trend of Hg emission from scenario 1 to 3 is shown inconsistent with other heavy metals: Hg in the three scenarios show less progressive reduction in emission than the other heavy metals. For instance, in scenario 1–when power plants currently using electrostatic and bag dust collectors are converted to low-temperature electrostatic dust removal, Hg emission drops by 1761.38kg, and As decreases by 6236.35kg, compared to the controlled 2018 data. Then, in scenario 2 in which on the basis of Scenario 1, the electric bag composite dust collector is converted to low-temperature electrostatic dust removal, Hg emission merely drops by 1705.54kg, unlike As having reduced more than scenario 1 with a decrease of 6792.45kg in scenario 2. In fact, Hg emission goes up as more low temperature electrostatic dust removals replace other removal methods, further supported by the reduction of 1691.92 kg in scenario 3, which is lesser than the previous two scenarios with less LLT-ESP displacements. The reason lies in the difference in types of removal method's removal efficiency for each heavy metal. Specifically, LLT-ESP captures 1.1% and 5.2% less mercury than WESP and ESP-FF (Table 2). Mercury has low particle affinity and tends to exist in the gas phase or small particulate form, making its capture more challenging for electrostatic precipitation [8,21]. It is noted that mercury has a low sorption capacity onto collection surfaces, leading to poor capture efficiency in dry electrostatic precipitators. Accordingly, there is still a large space for improvements in even the most advanced removal technologies. Researchers could work on developing more efficient electrostatic dust removal systems. This could involve improving the electrostatic charge generation and distribution methods, as well as optimizing the geometry of the electrostatic plates or grids to maximize dust collection.

**Table 4.** Reduction of heavy metals under different scenarios (kg).

| Elements | 2018 | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| Hg | 2305.22 | -1761.38 | -1705.54 | -1691.92 |
| As | 7443.16 | -6236.35 | -6792.45 | -7260.64 |
| Pb | 7891.34 | -6433.22 | -7038.04 | -7424.57 |
| Cd | 298.59 | -147.094 | -180.846 | -183.859 |
| Cr | 3039.25 | -1871.68 | -2676.66 | -2780.98 |
| Ni | 7131.876 | -5516.37 | -6452.4 | -6481.94 |

## 4. Conclusion

In this study, a bottom-up approach was used to quantify the emissions of heavy metal elements such as Hg, As, and Pb, and to establish a multi-pollutant emission inventory of CFPPs in Guangdong Province in 2018. The results of the study showed that heavy metal emissions from CFPPs in Guangdong Province are mainly dominated by Pb, As, Ni, and Cr, and the emissions are mainly influenced by raw coal. It is worth noting the effectiveness of advanced dust removal methods in reducing heavy metal emissions, with LLTESP and WESP having high removal efficiencies compared to outdated dust removal methods, such as ESP and FF. As well, scenario modeling provided evidence that implementation of these technologies could result in significant emission reductions. Therefore, this study concluded that prioritizing investment in advanced dust removal technologies and strengthening regulation can help further reduce heavy metal emissions from coal-fired power plants. It is essential for improving air quality and protecting the environment and public health.

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