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LIFE CYCLE POLLUTION AND CLIMATE IMPACT FROM URBAN POWER SYSTEMS: A CASE STUDY OF FOUR MUNICIPALITIES IN CHINA

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ABSTRACT

To control global mean temperature at the levels proposed by the Paris Agreement, energy systems need to be net-zero emission systems by mid-century. In 2014, global carbon emissions increased by only 0.5%, and China had contributed to the reduction in emissions. Therefore, a discussion of greenhouse gas emissions and air pollutant emissions in China for 2014 is important, as China is one of the world's largest emitters. Taking Shanghai, Beijing, Tianjin and Chongqing as examples, we identified 251 power plants with a capacity of greater than 6,000 kW in these four municipalities. In addition, we calculated carbon emissions and air pollutant emissions of five types of power generators in China based on a life cycle assessment. The results illustrate that the thermal power plants and biomass power plants account for most of the emissions (including SO_2, CO_2, and NO_x emissions, 1.87E+09 kg) in the power sector, and the emissions of new energy power generation (2.68E+06 kg) are concentrated in Chongqing. According to the analysis, emissions of CO_2 markedly exceed the emissions of SO_2 and NO_x, with carbon emissions being 156 times that of air pollutants. These results provide new insights into the reduction of carbon emissions and air pollutant emissions for governments and stakeholders.

Keywords: LCA; Carbon emissions; Air pollutant emissions; China; Power plants

1. INTRODUCTION

With the growing energy consumption demand, which is mainly driven by a booming economy and population, emissions from power generation have surged[1,2]. The power sector is one of the most important contributors to greenhouse gas and other air pollutant emissions. It accounts for more than 40% of energy-related CO_2 emissions, more than 48% of SO_2 emissions, and more than 28% of NO_x emissions worldwide in 2010[3,4,5]. CO_2 emissions from the power sector that pose threats to the environment are largely contributed by China: In 2016, nearly 42% of global carbon dioxide emissions came from power generation, of which 30.69% came from China[6]. Furthermore, the massive amounts of SO_2 and NO_x emissions from China has also raised extensive concerns internationally[7,8]. Due to the prominence of China in emissions from the power sector, studies have placed a greater emphasis on China[9]. As clusters of population and industry, cities are highly dependent on the power sector; therefore, the urban power sector is tightly related to the city's energy security and ecological environment.

At present, the city's power sector has received widespread attention. Auffhammer et al. estimated the urban industrial carbon dioxide emissions and growth rates in 287 cities in China from 1998 to 2009[10]. Shi et al. applied Defense Meteorological Satellite Program's Operational Linescan System data and statistical energy consumption data for evaluating spatial and temporal changes of China's urban carbon dioxide emissions for the years from 1997 to 2012[11]. Bo and other coauthors provided a detailed list of emissions for 337 Chinese

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cities (333 prefecture-level cities and Beijing, Tianjin, Shanghai, and Chongqing) in 2013[12], and Guan et al. mapped the carbon footprint of 13 cities in China by an input-output model[13]. However, studies usually focus on emissions at the urban level, and few researchers have studied emissions of each power plant in Chinese cities in detail up until now. In addition, previous studies have emphasized changes in carbon dioxide emissions at the urban level in China, with little attention being given to sulfur dioxide emissions and nitrogen oxide emissions, which are also important to the environment[14]. In addition, many studies only concentrate on the impact of thermal power and do not address other types of power generation; however, in the next few decades, clean energy generation will account for a larger share in the power sector of the world[15,16,17].

This paper focuses on different emissions including CO_2, NO_x, and SO_2 emissions from power plants in four municipalities in China in 2014. In this paper, five categories of power generation (thermal power, wind power, biomass, photovoltaics, and hydropower) were analyzed, and precise positions were determined by the latitudes and longitudes of 251 power plants in Shanghai, Chongqing, Beijing, and Tianjin operating in 2014 were determined. Meanwhile, through life cycle assessment (LCA) factors, the total emissions of CO_2, NO_x, and SO_2 generated by different power generation categories in four municipalities in China in 2014 were analyzed. In addition, because of the uneven power generation in China and large regional differences, we also assessed the pollution situation in various regions and the distribution of power generation emissions; we then proposed emission reduction strategies for the different regions. The paper is conducive to energy conservation and emission reduction in the power sector, forming a sustainable urban energy system.

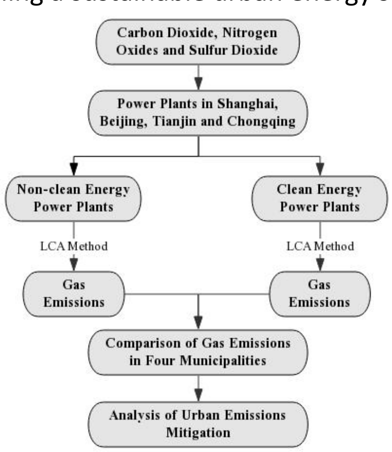
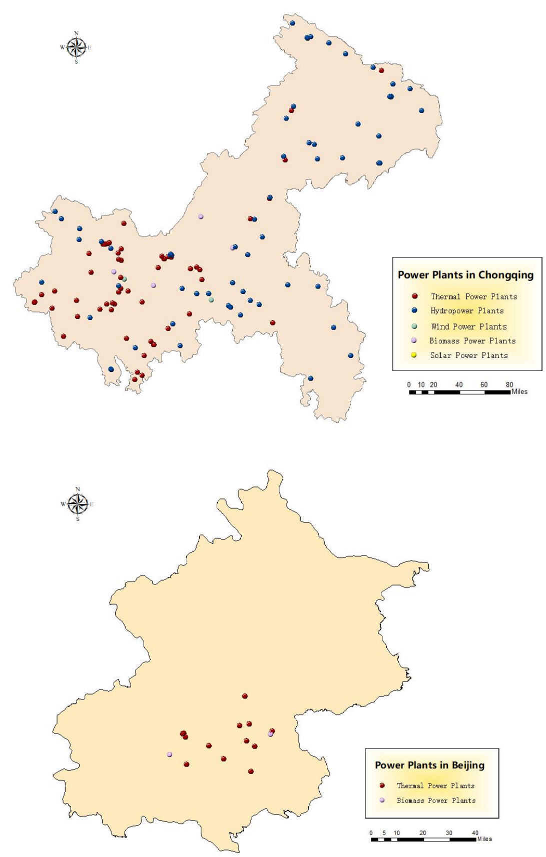


Fig 1 The framework of this study

2. DATA SOURCES AND METHODS

2.1 Data sources

We established a database of air pollutants in China using 251 power plants with a capacity greater than six kilowatts. This database contained categories of power plant, power generation capacity (kW), power generation (10,000 kWh), utilization hours (hours), plant power consumption rate (%), power generation standard coal consumption (g/kWh), power supply standard coal consumption (g/kWh), and the amount of raw coal consumed in power generation (ton). Part of the data came from the China Industrial Database[18]. In addition, locations of over two hundred power plants were accurately found by Google Earth and the Chinese corporate credit network. Figure 2 shows the geographical distribution and power generation types of power plants operating in Shanghai, Chongqing, Beijing and Tianjin in 2014, which in turn consist of 251 generating units with a combined installed capacity of 60.24 GW. Chongqing owned the largest number of power plants with a capacity of over 6,000 MW, specifically referring to 129 power plants. In the contrast, Beijing had the smallest number of power plants, of which 67.9% where coal-fired power plants.



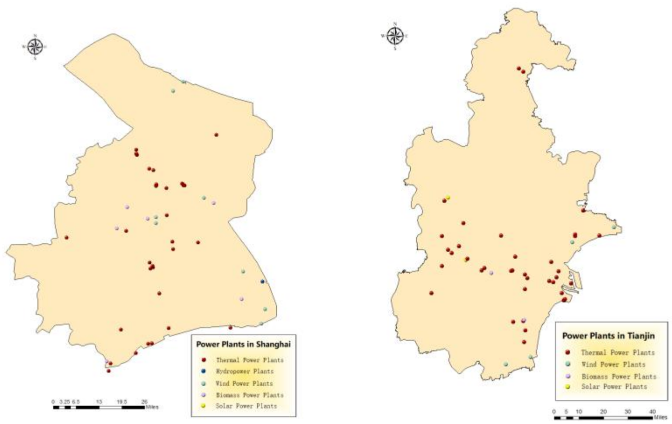


Fig 2 Distribution of 251 power plants in Shanghai, Tianjin, Chongqing, and Beijing.

2.2 *Unit-based CO_2, NO_x, and SO_2 emission estimation*

CO_2 has been recognized as a representative greenhouse gas, whereas NO_x and SO_2 contribute more to acidification and eutrophication. Therefore, researchers decided to study the emissions of these three gases. To calculate emissions for each category in each province, we introduced the life cycle assessment factor calculation. The method calculates the amount of gas emitted during the entire power generation cycle, from which the emission factor of the gas can be derived. The emission factors in this paper are derived[15]. This article counted more than one hundred current LCA studies on power generation, where emission factors are universal and more representative of the 2014 emissions levels. Due to the difficulty of the methods used in each study, the various geographical situations of the studies, the degree of cleanliness of the power plant, etc., the emission factors of these gases when obtained by the different studies are not entirely the same but fall within a range. Table 1 shows the range of life cycle emission factors for electricity generation. For the convenience of calculation, the average value of the range of emission factor ranges was used in this paper. Then, the corresponding emission factors were multiplied by the annual power generation per power plant to measure the total emissions of a single power plant. The total emissions of each province were equal to the total emissions of all power plants in the province, and the total emissions of China in 2014 were equal to the total emissions of the provinces.

Table 1 Life cycle emission factors for electricity generation from selected technologies.

Energy source	CO_2		NO_x		SO_2	
Electricity output $\left[kg / MWh_{out}\right]$						
	Reference range	Average value	Reference range	Average value	Reference range	Average value
Hard coal	660-1050	855	0.3-3.9	2.1	0.03-6.7	3.37
Biomass	8.5-130	69.25	0.08-1.7	0.89	0.03-0.94	0.485
Hydropower	2-20	11	0.004-0.06	0.032	0.001-0.03	0.0155
Solar power	13-190	101.5	0.15-0.4	0.275	0.12-0.29	0.205
Wind power	3-41	22	0.02-0.11	0.065	0.02-0.09	0.055

2.3 *Monte Carlo uncertainty method*

When greenhouse gas emissions are calculated, evaluating and quantifying the uncertainties of the estimates are necessary. Uncertainty analyses help analysts and decision makers identify how accurate the estimations are and the likely range in which the true value of the emissions fall. The Monte Carlo approach involves the repeated simulation of samples within the probability density functions of the input data[19]. First, the normal distribution was used to fit both the activity level and the emission factor; thus, each of the 1000 numbers matching the distribution was randomly generated by Excel. The average of the respective 1000 numbers was obtained and then multiplied by the average of the 1000 random activity levels by the average of 1000 random emission factors to get 1000 average emissions. Then, the software EasyFit was used to simulate the distribution of the average emissions, with a 95% confidence interval to find the left (2.5) and right endpoint (97.5) values of the confidence interval. The confidence width was the difference between the left (2.5) and the right endpoint (97.5) values. After that, we used Formula (1) to obtain the uncertainty:

$$uncertainty = \frac{0.5 \times a \times 100}{b} \tag{1}$$

where a represents the confidence interval width, and b is the estimated emission.

3. RESULTS AND DISCUSSION

3.1 *Carbon Emissions and Air Pollutant Emissions*

In 2014, the total emissions of the four municipalities were 1.86E+09 kg CO_2, 4.58E+06 kg NO_x, and 7.32E+06 kg SO_2 in 2014. We found that most of the air pollutant emissions and carbon emissions are generated by thermal power generating units. For example, nearly 99% of China's primary emissions from the coal-fired power plants were produced by 89% of their total capacity.

Shanghai was responsible for the highest amount of power generation (8.07E+06 MW). CO_2, NO_x, and SO_2 emissions of the power sector in Shanghai were, respectively, 6.77E+08 kg, 1.67E+06 kg, and 2.66E+06 kg, which were the highest among the four cities in 2014. Therefore, power generation in Shanghai leads to huge emissions. In the face of such a grim situation, the Shanghai Municipal Government actively adopted various policies to save energy and reduce emissions[20]. According to relevant data, the emissions of pollutant gases decreased from 2015 to 2018. The declines in the rates of nitrogen oxide emissions and sulfur dioxide emissions over the four years, sequentially, were 1%, 5%, 4%, and 4%. Apart from the thermal power, emissions of wind power, biomass, photovoltaics and hydropower were also the highest compared with other cities. In the sector of nonfossil fuel emissions, Shanghai was the only city possessing all four kinds of renewable power generation. Shanghai accounted for 62% of the total emissions from wind power stations of the four cities. Wind power stations required an annual average wind speed of 5.8 m/sec or more, an average spacing of each machine, a good grid connection condition, and a distance of more than 300 m from a residential area. Therefore, the coastal location, which has wind as a resource enables Shanghai to develop more wind power than any other alternative energy.

Following Shanghai, Tianjin had the second highest emissions. It released 5.15E+08 kg carbon emissions and 3.30+06 kg air pollutant emissions, including SO_2 and NO_x emissions. The CO_2 exhausted by the thermal power plants in Tianjin, which accounted for 82% of all power plants, had a dominant position. Nearly 99% of the power generated in 2014 was from thermal power plants, which were responsible for main emissions. Tianin, which was one of the two cities that owned photovoltaic power stations in 2014, had the highest number of photovoltaic power stations. These power stations were named the Xinyi Glass Photovoltaic Power Generation and Sino-Singapore Eco-City Photovoltaic Power Generation.

In spite of the 123 power plants in Chongqing, this city had relatively lower emissions of 3.69E+08 kg CO_2, 9.13E+05 kg NO_x, and 1.45E+06 kg SO_2. Because of the abundant hydropower resources and policy support in Chongqing, 66 hydropower plants were operating there in 2014. They generated 2.03E+08 kWh of electricity, accounting for 31.7% of the total power generation, and exhausted 2.24E+06 kg CO_2, 6.51E+03 kg NO_x, and 3.15E+03 kg SO_2. In addition, except for one hydropower station operating in Shanghai, the other two municipalities did not have any hydropower stations operating in 2014. Furthermore, the performance of biomass generation was conspicuous with annual electricity of 68,829 mw. The thriving renewable power generation resulted in lower emissions and guaranteed the electricity need.

Beijing was the city with the lowest emissions among the four municipalities, exhausting 2.98E+08 kg CO_2, 7.36E+05 kg NO_x, and 1.18E+06 kg SO_2. Fifteen thermal power plants accounted for 99.83% of the total carbon emissions, and the remaining 0.17% of the carbon emissions came from two biomass power plants. Beijing, like Shanghai, is a modern city dominated by thermal power generation. The reason for the huge difference in emissions between the two is the small number of power plants and the lower power generation (3.53E+10 kWh) in Beijing. Biomass power plants released 2.77E+05 kg carbon emissions and 5.50E+03 kg air pollutant emissions. The carbon emissions are insignificant relative to the total emissions for the four municipalities (1.87E+09 kg).

The total power generated by Shanghai ranked first in the four cities, whereas Beijing generated the least amount of power. The main function of Beijing is as the capital city of China, rather than for industrial purposes, so it resulted in the lowest annual power generated in 2014[21]. Unlike Beijing, Shanghai which holds many industrial parks, especially for energy, is the largest metropolitan city in China and is seeking more opportunities to prosper[22]. Hence, the speed of urbanization could be the reason for the emission discrepancy that exists between those two cities[23]. Compared with Shanghai, Beijing has performed poorly in the development of renewable energy. Beijing only owned two biopower plants, which accounted for merely 1% of Beijing's annual power generation, whereas Shanghai possessed many plants that used renewable energy. Reducing the emissions of power generation by shutting down thermal power plants is more effective than developing the renewable energy to replace them in the short term when the power is extra. Apart from this, the emissions from the industry will likely bring obstacles when the city begins to mitigate the carbon dioxide emissions[16]. Therefore, Shanghai will meet later challenges during the process of cutting emissions. Tianjin, with CO_2 emissions

1.64E+08 kg less than those of Shanghai, exhausted the second highest emissions of the four cities, followed by Chongqing. Nevertheless, in Chongqing, whose emissions were 71.7% of those in Tianjin, more power was generated. This greater production can be attributed to abundant hydropower resources[24]. Under the circumstances of the essential need to generate power, renewable energy should be the only solution to reduce the emissions.

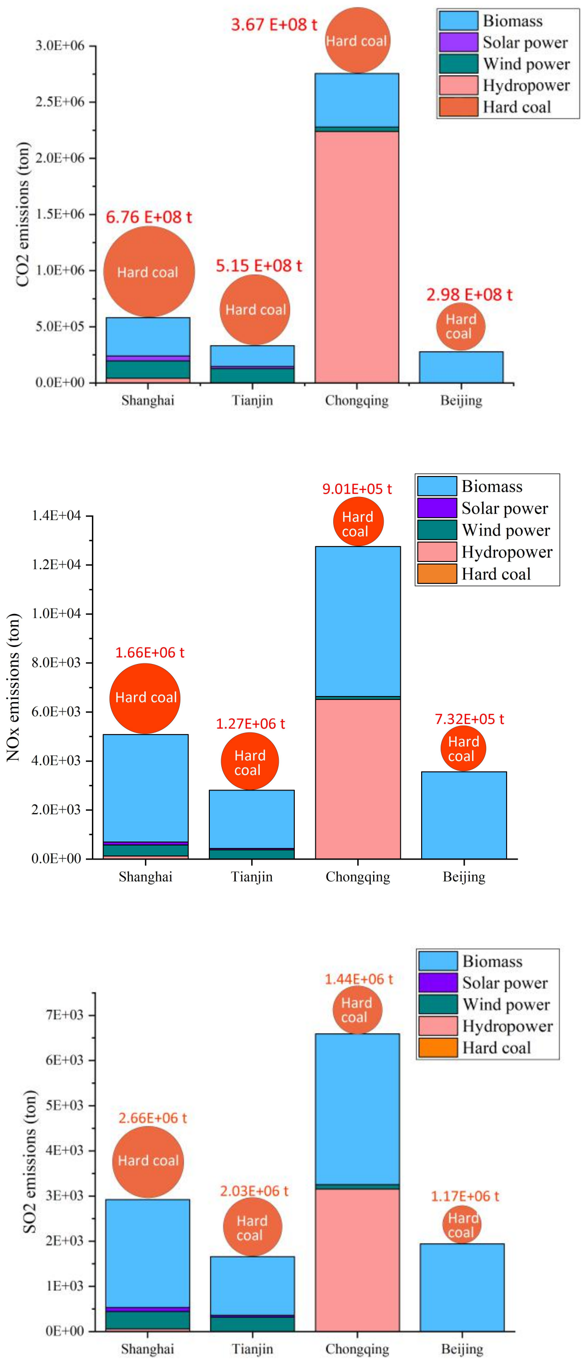


Fig 3 Carbon emissions and air pollutant emissions in Shanghai, Tianjin, Chongqing, and Beijing.

3.2 Uncertainty analysis and verification

The Monte Carlo uncertainty analysis results for thermal power generation of all categories of emissions are shown in Table 2. Because of the limited sample of other kinds of the power generation, the Monte Carlo method is not suitable for them. Therefore, only the uncertainty of thermal power generation is analyzed. Table 2 shows that the uncertainty of all categories of emissions from thermal power generation is close to that of the other kinds of emissions, which may be explained by the activity level being the same during the study period. This finding might lead to the conclusion that the importance of the activity level outweighed the importance of the emission factor when calculating the uncertainty. The accuracy of the activity data crucially determined the certainty. The results shown illustrate that the total emissions estimated herein are reliable because the uncertainty was relatively small and acceptable. The accidental loss of a small group of activity data and the variation in the range of emission factors are responsible for the final uncertainty.

Table 2 Results of Monte Carlo Uncertainty Analysis

Emissions	Confidence interval	Average of emissions estimation	Uncertainty
CO_2	2.77E+06	1.33E+07	10.44%
NO_x	7.79E+03	3.26E+04	11.95%
SO_2	1.31E+04	5.22E+04	12.53%

4. CONCLUSION

This study builds a detailed database of power plants in China's four municipalities and analyze the uncertainty of the emissions releasing from power plants operating in 2014. The main conclusions are as follows:

(1) The characteristics of the locations of the power plants vary from one city to another. Power plants are highly centralized in Beijing and are mostly gathered in the North of Tianjin, whereas the power plants in Chongqing and Shanghai are evenly distributed.

(2) The emissions of thermal power plants take the lead in all sorts of power generation. The substitution and advanced cleaning technology of thermal power plants is essential. Regardless of the kind of power generation, CO_2 emissions are always far greater than the other emissions; however, the levels of NO_x and SO_2 emissions show less of a difference.

(3) Applying the Monte Carlo method to analyze the uncertainty of thermal power plants verifies that

the large emissions shown by the results are reasonable.

The study shows emissions of different power generation types of four cities. However, our study only considers three types of emissions, ignoring other potentially harmful emissions. Further research will incorporate other pollutants into the model.

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