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Clearing the Air: Assessing the Effectiveness of Emission Policy in Qinhuangdao's Key Industries

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Abstract: China has successively put forward ultra-low emission (ULE) transformation plans to reduce the air pollutant emissions of industrial pollutants since 2014. To assess the benefits of the ULE policy on regional air quality for Qinhuangdao, this study developed an emission inventory of nine atmospheric pollutants in 2016 and evaluated the effectiveness of the emission policy in Qinhuangdao's key industries under different scenarios with an air quality model (CALPUFF). The emissions of air pollutants in 2016 were as follows: Sulfur dioxide (SO_2) emitted 48.91 kt/year, nitrogen oxide (NOx) emitted 86.83 kt/year, volatile organic compounds (VOCs) emitted 52.69 kt/year, particulate matter (PM_{10} and $PM_{2.5}$) emitted 302.01 and 116.85 kt/year, carbon monoxide (CO) emitted 1208.80 kt/year, ammonia (NH_3) emitted 62.87 kt/year, black carbon (BC) emitted 3.79 kt/year, and organic carbon (OC) emitted 2.72 kt/year, respectively. The results showed that at the regional level in 2025, the iron and steel industry under the PPC (Peak Production Capacity) scenario had the highest potential for reducing SO_2 and NOx emissions, while the cement industry under the PPC scenario excelled in reducing PM_{10} emissions. As for the industrial level in 2025, the flat glass industry under the ULE scenario would reduce the most SO_2 emitted, while the iron and steel industry and the cement industry under the PPC scenario demonstrated the best reduction in NOx and PM_{10} emissions, respectively. Furthermore, the average annual contribution concentration of SO_2, NOx, and PM_{10} in the air monitoring stations of Qinhuangdao under the PPC scenario was significantly lower than that under the BAU scenario revealed by air quality simulation. It can be concluded that the emission policy in Qinhuangdao will help improve the air quality. This study can provide scientific support for policymakers to implement the ULE policy in industrial undeveloped cities and tourist cities such as Qinhuangdao in the future.

Keywords: emission inventory; the characteristics of air pollution; ultra-low emission (ULE); emission reduction scenarios; Qinhuangdao

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1. Introduction

Located in the Beijing-Tianjin-Hebei (BTH) region, one of China's key pollution control areas, Hebei Province has a large population and developed industries, and its output of various industrial products, especially heavy industries such as iron and steel, and flat glass, has ranked among the top in China for many years [1]. Human activities in Hebei produce a large number of air pollutants every year, which will decrease air quality, and endanger human health and the social economy [2,3]. Therefore, the government has been committed to controlling air pollution from all aspects, with the emission inventory being the most basic step. High-resolution emission inventories are vital to understanding the characteristics of air pollutants and taking corresponding measures and policies to control air pollution. The previous studies on the emission inventory of Hebei primarily focused on cities with BTH air pollution transmission channel cities (Section S1 explains which cities these transmission channel cities include), provincial level or the whole BTH region [4–7], and few studies on the industry-wide emission inventory of cities that are not transmission channels and tourist cities.

It is reported that the industrial sectors dominated the emission of air pollutants in China [8,9]. China's Ecological Environment Statistical Annual Report issued by the Ministry of Ecology and Environment showed that SO_2, NOx, $PM_{2.5}$, and PM_{10} emissions from the industrial sectors in 2016 accounted for 90.13%, 53.82%, and 85.58% of the national emissions, respectively [10]. Studies have shown that controlling pollutant emissions from the industrial sectors can significantly improve regional air quality [11–13], which means the industrial sectors have great potential for emission reduction. To reduce the emission of industrial pollutants, China has successively put forward ULE standards for the thermal power, coking, cement, flat glass, iron and steel industries, etc., since 2014 [14–18]. For high-polluting enterprises, various efficient pollutant control measures have been adopted to ensure the emission concentration of air pollutants (SO_2, NOx, and PM) meets the ultra-low emission limits of the industry [19]. Since the implementation of the ULE policy, studies have assessed the changes in pollutants from different industries, such as power plants, coking, and iron and steel, before and after the ULE policy [19–23]. For instance, Tang et al. [23] found that since the implementation of the ULE standards for thermal power plants in 2014, emissions of SO_2, NOx, and PM from China's thermal power plants had been reduced by 65%, 60%, and 72%, respectively, by 2017. The results of Bo et al. [19] showed that if China's iron and steel enterprises all meet the ULE standards in 2018, the emissions of SO_2, NOx, and PM from the iron and steel industry would be reduced by 50%, 37%, and 58% compared with the actual situation in 2018. However, most of these assessments were for the whole country or key polluted areas, and few studies have been conducted on tourist cities and non-transmission channel cities. For tourism areas with low levels of industrialization, pollutant emissions are considered to be lower than those of traditional industrial cities [24]. The main contributors of pollutants in tourism areas are power plants, industry, and transportation sectors, which are also the focus of emission reduction [25]. Xu et al. [25] assessed vehicle emission reduction policies in Hainan Province, a tourism-developed province. However, the impact assessment of the ULE policy on industry sectors for tourist areas is lacking.

To fill in these research gaps, this study selected Qinhuangdao, a representative tourist city in Hebei, as the research object. As a tourist city, the air pollution in Qinhuangdao brought by urban development is also serious, and the task of air quality improvement is particularly significant. From 2013 to 2016, the air quality in Qinhuangdao gradually improved, the compliance rate of excellent days increased from 57.3% to 76.8%, and the concentration of $PM_{2.5}$ decreased from 65 $\mu g/m^3$ to 46 $\mu g/m^3$, but it still failed to meet the average annual concentration standard (35 $\mu g/m^3$) stipulated by "Ambient Air Quality Standard" (GB 3095-2012) [26,27]. In 2016, its air quality ranked 53rd among 74 key cities in China (including the Beijing-Tianjin-Hebei region, Yangtze River Delta, Pearl River Delta, municipalities, provincial capital cities, and the cities with independent planning), in the last 30% [28–31]. Air pollution in Qinhuangdao includes pollution from itself and other cities of the BTH region, so there is great pressure on pollutant emission reduction and management [32,33]. According to the simulation results from the air quality model CAMx conducted by Bo et al. [32], the contributions of regional transport from SO_2, NOx, and $PM_{2.5}$ emitted by the iron and steel enterprises in the BTH region to Qinhuangdao during winter in 2012 were found to be 18.8%, 27.3%, and 10.1%, respectively. Liu [33] simulated the regional transport of $PM_{2.5}$ based on the CAMx model and found that in 2013, 60% of the annual average concentration of $PM_{2.5}$ in Qinhuangdao was attributed to regional transport from the BTH region. However, there are few studies analyzing the impact of Qinhuangdao's air pollutant emission policy on local air quality. To further improve the air quality in the BTH region and strengthen the emergency management of heavily polluted weather, it is necessary to develop an accurate and comprehensive emission inventory of multiple pollutants for Qinhuangdao. In addition, since 2018, Hebei has successively issued "The Plan for Deep Emission Reduction of Iron and Steel, Coking and Coal-fired Power Plants in Hebei Province", etc. [34–36], vigorously promoting the ULE transformation (deep treatment) and the construction of key environmental protection facilities in key industries. Some cities such as Qinhuangdao have taken the lead in completing ULE upgrading of key industries. In 2019, the "The Three-year Operational Plan for all Industrial Enterprises Complying with Discharge Standards in Qinhuangdao City" issued by the Qinhuangdao Municipal People's Government emphasized the active promotion of ULE retrofit measures and aimed to complete the ULE transformation of key industries across the entire city by the end of October 2020 [37]. By the end of 2020, Qinhuangdao had completed the ultra-low emission reconstruction project of key industries, so it is necessary to evaluate the emission reduction effect brought by this policy, which is of great significance to air pollution control.

Therefore, this study developed a high-resolution emission inventory of nine major atmospheric pollutants in 2016 and evaluated the effectiveness of the emission policy in Qinhuangdao's key industries under different scenarios with the air quality model (CALPUFF). The reliability of the results was also verified by comparing them with other emission inventories and using Monte Carlo Simulation to assess the uncertainties.

2. Methods and Data

2.1. Study Domain

Qinhuangdao City is located in the northeast coastal area of Hebei (118°33′–119°51′ E longitude and 39°22′–40°37′ N latitude, as shown in Figure 1), enjoying the reputation of a summer resort. There is rich natural scenery such as mountains, sea, lakes, and forests, and historical attractions in Qinhuangdao such as the Great Wall and "the First Pass Under Heaven" [38]. Fresh air and a good ecological environment have always been "a golden signboard" built by Qinhuangdao. The city in Figure 1 includes four municipal districts (Shanhaiguan, Haigang, Funing, and Beidaihe), two counties (Changli and Lulong), and one autonomous county (Qinglong Manchu Autonomous County), with a total area of 7750 square kilometers and a population of 2,975,000 in 2016 (shown in Figure S1). The gross domestic product (GDP) reached 134.94 billion yuan in 2016. In 2016, Qinhuangdao received 42.18 million domestic and foreign tourists. From 2016 to 2019, the total tourism income increased from 49.55 billion yuan (36.7% of the city's GDP in 2016) [39] to 101.40 billion yuan (62.9% of the city's GDP in 2019) [40].

2.2. Emission Inventory

According to the technical guideline and relevant literature [41–43], the main emissions in Qinhuangdao for 2016 were divided into ten first-level categories, including industrial process sources, mobile sources, fossil fuel combustion sources, and so on. Each category comprised multiple sub-categories. The detailed categorization of emission inventories is beneficial for providing a comprehensive understanding of air pollution control. The details of the classification of emission sources are provided in Table S1.

Activity levels primarily came from environmental statistics, statistical yearbooks of various departments, and pollution source surveys. The sections of engineering analysis in the Environmental Impact Assessment involve substantial key information, such as the location of the enterprise, the type of products, production and air pollutant emissions of each process, fuel use type and amount, etc. These data were compared with the same data provided by the enterprise. Environmental Permitting includes the capacity of products, type and amount of raw and auxiliary materials, end treatment facilities, and exhaust cylinder parameters (height, diameter, temperature, flow rate). Then, the data from Environmental Permitting were compared with the same data provided by the enterprise. Consequently, enterprises with an error rate of 60% or more are defined as suspect [44,45]. Then we launched field surveys in the selected problem enterprises and reviewed the data to gain a better understanding of the air pollution in Qinhuangdao.

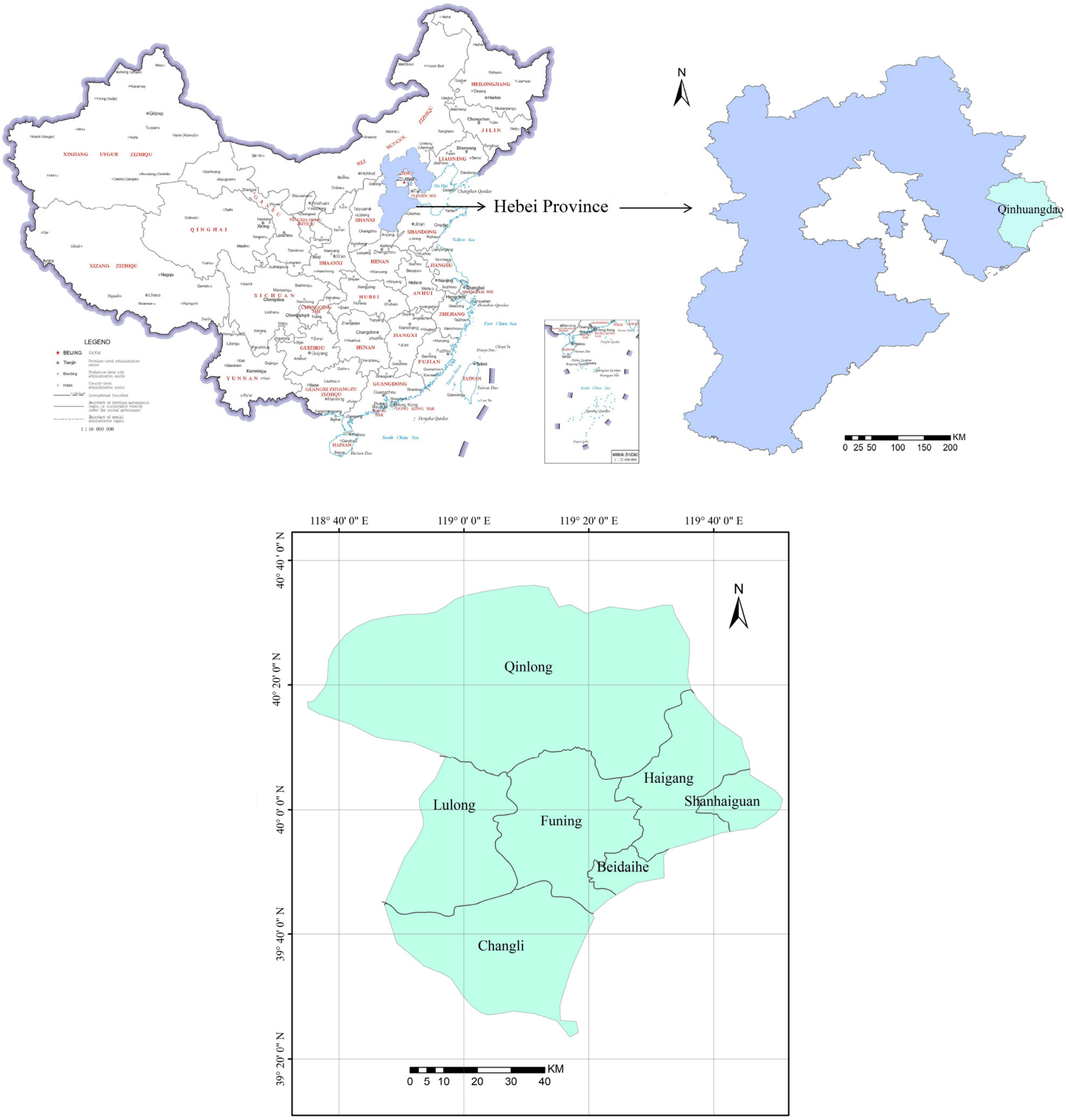


Figure 1. Map showing the study domain (Qinhuangdao City) and its localization within China.

After obtaining accurate activity-level data, pollutant emissions were calculated using the material balance algorithm and the emission factor method and then allocated to the 1 km grids of Qinhuangdao by the spatial allocation. For the industry sector, a bottom-up approach was used to calculate the emissions of different processes in each enterprise based on detailed facility-level activity-level data from approximately 400 enterprises. The data sources and calculation methods are listed in Sections S2 and S3 of the Supplementary Material. In addition, the details on spatial allocation are shown in Table S2 and Section S4. Besides, the uncertainty of air pollutant emission estimates for Qinhuangdao in 2016 was quantitatively evaluated using 10,000 Monte Carlo simulations with a 95% confidence interval, and the probability distributions of emission factors and activity level are shown in Tables S11–S20.

2.3. The Settings of Emission Reduction Scenarios

According to the ULE policies of Hebei Province [34–36], the focus of the transformation was concentrated on the thermal power plants, iron and steel, cement, and flat glass industries. Since the thermal power plants in Qinhuangdao had met the ultra-low emission standards in 2016 [46], they were not involved in the calculation of these scenarios. Based on the emission inventory in this study, the sum of pollutant emissions from the iron and steel, cement, and flat glass industries all accounted for more than 65% of emissions from industrial process sources. In addition, they were also the major above-scale industries [39]. Therefore, we selected the iron and steel, cement, and flat glass industries to set up different scenarios. Taking 2016 as the base year, the emission reduction in 2025 and 2030 was predicted by calculating the pollutant emissions under each scenario. In addition, the tourism industry in Qinhuangdao is considered to be developing steadily in these scenarios.

2.3.1. Business-as-Usual (BAU) Scenario

In this scenario, without the intervention of policy and equipment transformation, it was supposed that the annual output would increase with the growth of the secondary industry GDP [21,25,47–49]. Through the correlation analysis GDP of the secondary industry and the production of the three industries in recent years, a strong linear relationship has been observed among them (shown in Figures S2–S5). Therefore, the output was predicted by the GDP of the secondary industry.

2.3.2. Ultra-Low Emission (ULE) Scenario

In this scenario, the output of the industries would increase with the secondary industry GDP, as that in the BAU scenario. Since the plan issued by the Qinhuangdao Municipal People's Government in 2019 aimed to complete the ULE transformation of key industries across the entire city by the end of 2020 [37], the emissions from the iron and steel, cement, and flat glass industries were calculated by ultra-low emission factors of these industries after 2020. The details of the calculation method and the ULE standards are shown in Sections S2 and S3 and Tables S3–S8.

2.3.3. Peak Production Capacity (PPC) Scenario

In recent years, Hebei has consistently emphasized the strict prohibition of capacity expansion in key industries such as iron and steel, cement, and flat glass. From 2012 to 2021, the output of the three industries of Hebei has been fluctuating in the range of (−19.6%, 32.7%) (taking 2016 as the base year) (Tables S9 and S10). Therefore, this scenario assumed that the output of the iron and steel, cement, and flat glass industries would remain at the level of 2016 from 2016 to 2030, and at the same time, ULE transformation would be carried out to predict future annual emissions.

The detailed settings of the three scenarios are shown in Table 1.

Table 1. Scenarios parameter settings.

Scenario	Year	Industry	Output (kt) [1]
BAU	2016	Iron and steel	60,691.29
		Cement	5663.42
		Flat glass	726.75
	2025	Iron and steel	189,411.80
		Cement	14,635.83
		Flat glass	565.97
	2030	Iron and steel	248,703.52
		Cement	18,603.88
		Flat glass	489.60

Table 1. *Cont.*

Scenario	Year	Industry	Output (kt) [1]
BAU	2016	Iron and steel Cement Flat glass	60,691.29 5663.42 726.75
	2025	Iron and steel Cement Flat glass	189,411.80 14,635.83 565.97
	2030	Iron and steel Cement Flat glass	248,703.52 18,603.88 489.60
ULE	2016	Iron and steel Cement Flat glass	60,691.29 5663.42 726.75
	2025	Iron and steel Cement Flat glass	189,411.80 14,635.83 565.97
	2030	Iron and steel Cement Flat glass	248,703.52 18,603.88 489.60
PPC	2016	Iron and steel Cement Flat glass	60,691.29 5663.42 726.75
	2025	Iron and steel Cement Flat glass	60,691.29 5663.42 726.75
	2030	Iron and steel Cement Flat glass	60,691.29 5663.42 726.75

[1] For industrial sectors, annual output of product is generally regarded as activity-level data to calculate pollutant emissions.

3. Results and Discussion

3.1. Spatial Emission Characteristics of Air Pollutants

As shown in Table 2, the total emissions of SO_2, NOx, VOCs, $PM_{2.5}$, PM_{10}, CO, NH_3, BC, and OC in Qinhuangdao for 2016 were calculated to be 48.91, 86.83, 52.69, 116.85, 302.01, 1208.80, 62.87, 3.79, and 2.72 kt, respectively.

Table 2. Emission inventory of nine pollutants in Qinhuangdao City for 2016 (Unit: kt).

Sources	SO_2	NOx	CO	PM_{10}	$PM_{2.5}$	BC	OC	VOCs	NH_3
Fossil fuel combustion	12.16	12.26	184.80	18.29	9.21	1.41	0.27	7.12	0.46
Industrial processes	35.33	34.34	926.20	233.65	92.33	0.83	1.64	21.63	1.45
Mobile	0.45	39.79	31.15	2.40	2.26	0.68	0.52	6.79	0.26
Solvent use	0	0	0	0	0	0	0	5.20	0
Agriculture	0	0	0	0	0	0	0	0	59.95
Fugitive dust	0	0	0	42.55	8.41	0	0	0	0
Storage and transportation	0	0	0	0	0	0	0	5.40	0
Biomass burning	0.97	0.43	66.66	4.93	4.59	0.87	0.18	5.78	0.37
Waste treatment	0	0	0	0	0	0	0	0.63	0.38
Others (catering)	0	0	0	0.18	0.15	0.003	0.10	0.13	0
Sum	48.91	86.83	1208.80	302.01	116.85	3.79	2.72	52.69	62.87

The contributions of each subcategory to the total emissions are shown in Figure 2 and the contributions of each county can be found in Figure S1.

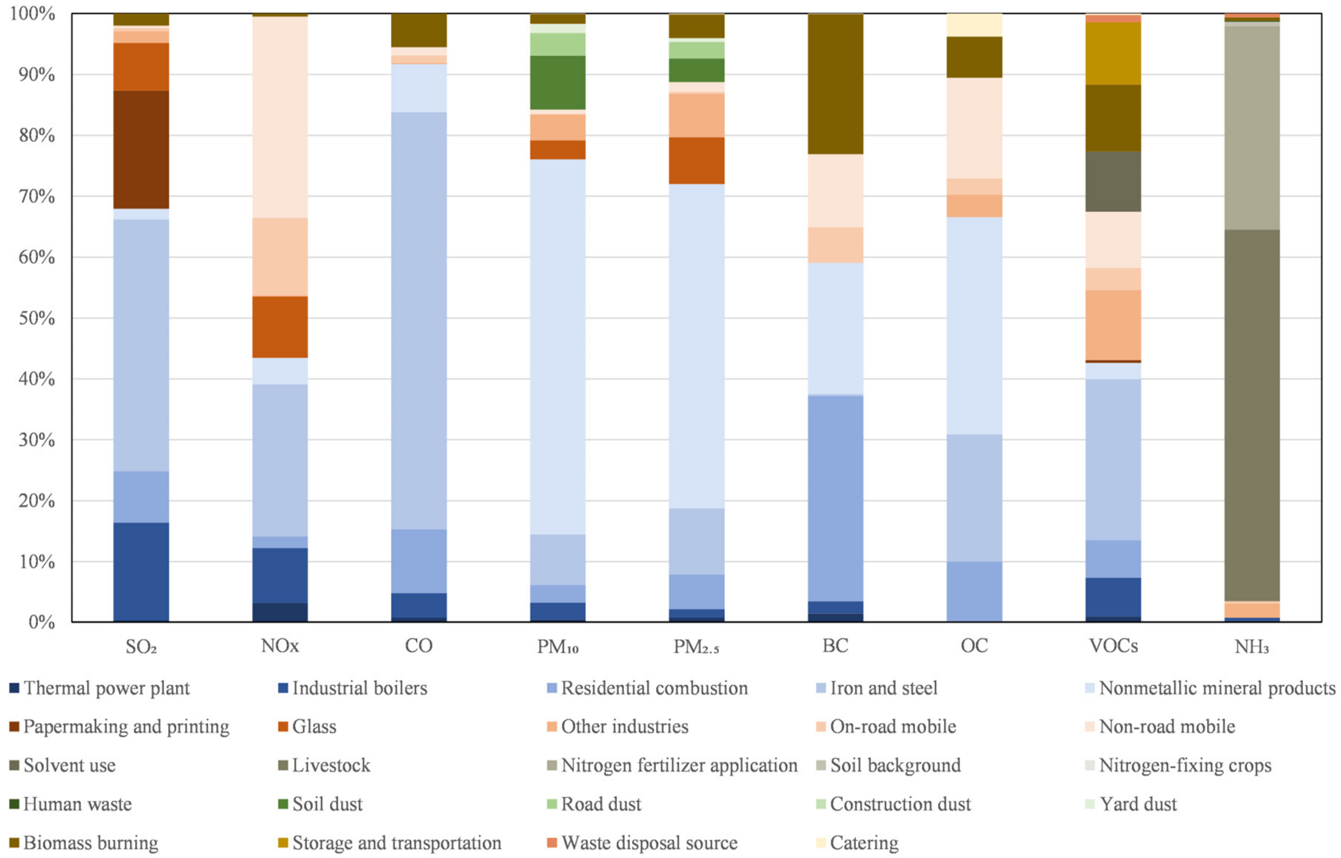
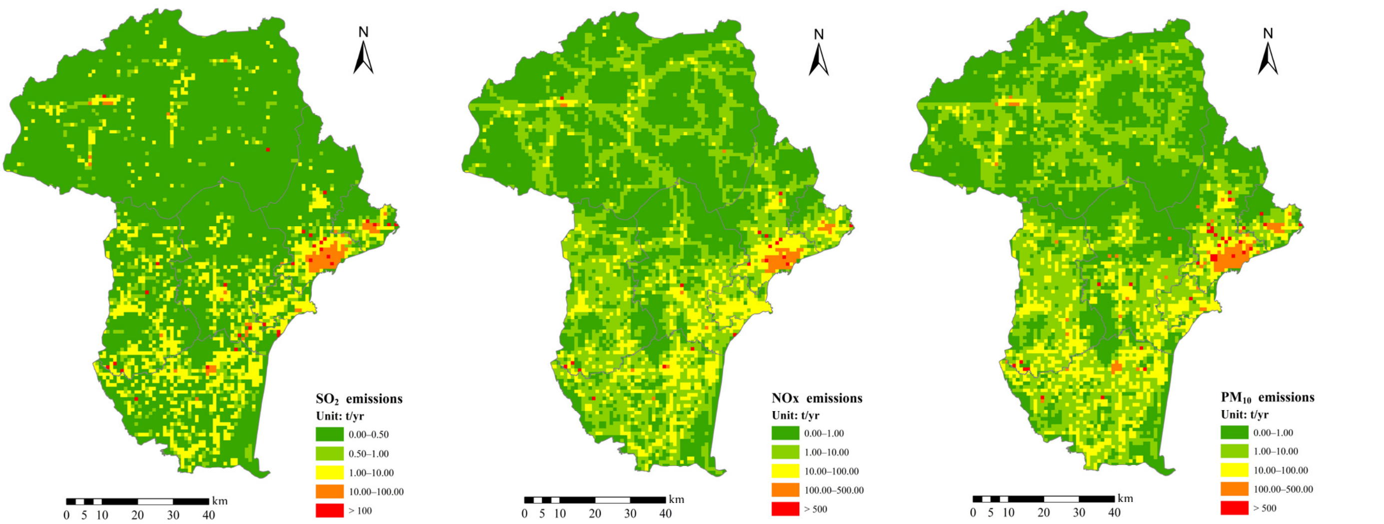


Figure 2. Emission contributions by subcategory for Qinhuangdao in 2016.

According to the contributions of various sources to SO_2 emissions, the industrial process sources had the largest contribution to total SO_2 emissions at 72.2%, followed by fossil fuel combustion sources at 24.9%. In the industrial process sources, the iron and steel industry was the main emission source, and the emission contribution rate was 41.4% (of the total SO_2 emissions). The SO_2 emissions in Qinhuangdao City for 2016 were allocated into 1 km × 1 km grids (Figures 3a and S6a). The eastern region of Qinhuangdao, similar to Haigang District, was characterized by the highest emissions of SO_2.

The key emission sources of NOx were mobile sources, accounting for 45.8% of the total emissions, and ships and agricultural transport vehicles among them emitted 10.9% and 10.7% of the total NOx, respectively. It also reflected the regional characteristics of developed agriculture and sea transportation in Qinhuangdao. Industrial process sources accounted for 36.67% of the total emissions, among which the iron and steel industry (25.0% of the total) and glass manufacturing industry (10.1% of the total) were the major contributors. The eastern and southern regions of Qinhuangdao, specifically the Haigang District and Changli District, stood out as the primary sources of elevated NOx emissions (shown in Figures 3b and S6b). In addition, the distribution of NOx also showed some spatial similarities with the road network.



(**a**) (**b**) (**c**)

Figure 3. Spatial distribution characteristics of air pollutant emissions in Qinhuangdao for 2016. (**a**) Spatial distribution characteristics of SO_2 emissions in Qinhuangdao for 2016; (**b**) spatial distribution characteristics of NOx emissions in Qinhuangdao for 2016; (**c**) spatial distribution characteristics of PM_{10} emissions in Qinhuangdao for 2016.

PM (PM_{10} and $PM_{2.5}$) emissions in Qinhuangdao primarily came from industrial process sources and dust sources. The contribution of industrial process sources to PM_{10} and $PM_{2.5}$ emissions accounted for 77.4% and 78.9%, and nonmetallic mineral products had a contribution rate of 61.6%. Because there were many small stone slag factories, lime kilns, and brick factories, most of them had few pollution control facilities, which caused serious pollution to the regional environment. As for dust sources, the contribution to PM_{10} and $PM_{2.5}$ emissions accounted for 14.1% and 7.2%, respectively. Soil dust was the main contributor to dust sources. Due to the land and sea breeze in Qinhuangdao being frequent, and some enterprises digging soil around the mountains to destroy the mountain vegetation environment, the wind erosion phenomenon was serious and produced a large amount of soil dust. As depicted in Figures 3c, S6 and S7, Haigang District exhibited the highest emissions of PM primarily due to the presence of numerous construction material enterprises, which generated fugitive dust within the area.

The industrial process sources were the largest emission sources of VOCs, accounting for 40.55% of the total emission of VOCs, of which the VOCs emissions from the iron and steel industry accounted for 26.4% of the total. Fossil fuel combustion sources and mobile sources contributed 13.5% and 12.9% of the total VOC emissions, respectively. The reason for the high emission of VOCs was that most enterprises did not install VOC treatment equipment. Changli District and Haigang District emitted the most VOCs, primarily caused by the most iron and steel plants in Changli and many industrial points in Haigang. Additionally, the spatial distribution of VOC emissions also exhibited a high consistency with the road network, primarily due to storage and transportation sources (Figures S6e and S7b).

The dominant sources of CO emissions were industrial process sources (76.6% of the total CO emissions), followed by fossil fuel combustion sources (15.3%). For industrial sources, CO emissions primarily came from the iron and steel industry, with a contribution rate of 68.5% (of the total), and fugitive emissions contributed the most. Residential combustion sources were the largest source of CO emissions among fossil fuel combustion sources (68.9%). This was primarily due to the fact that bulk coal was still mainly used for cooking and heating in many rural areas of Qinhuangdao City. Similar to the spatial distribution of NOx, the high-value zones of CO emissions were concentrated in the Haigang District and Changli District (Figures S6f and S7c).

The primary source of NH_3 emission was agricultural sources, with a contribution rate of 95.4%. The livestock and poultry industry was the main source of NH_3 emissions, accounting for 61.1% of the total NH_3 emissions, followed by nitrogen fertilizer application (33.4%). Qinhuangdao's NH_3 emissions were concentrated in Changli, Haigang, and Qinglong (Figures S6g and S7d). Because these areas are not only industrial agglomerations in Qinhuangdao but also important agricultural economic zones, they form a complete modern agricultural industrial system, with several districts and counties being named as advantageous areas for agricultural products with special characteristics in Hebei and even China [50].

BC primarily came from fossil fuel combustion sources with a contribution rate of 37.2%, followed by biomass combustion sources (23.0% of the total BC emissions) and industrial process sources (21.9% of the total BC emissions). The primary source of OC was the industrial process sources with a contribution rate of 60.2%, followed by the mobile sources with a contribution rate of 19.3%. Haigang District was the main contributor to the emissions of BC and OC (shown in Figures S6 and S7).

3.2. Emission Analysis under the Three Scenarios

The total emissions of SO_2, NOx, and PM_{10} in 2025 would be 2.08, 1.99, and 2.04 times higher than those in 2016, and in 2030 would be 2.60, 2.47, and 2.54 times higher than those in 2016, respectively. Given the slight disparity in the emission reduction effect between 2025 and 2030, this section took 2025 as a representative example to quantify the impact of various scenarios on emission reduction and assess the influence of implementing the ULE policy on atmospheric pollutant emissions in key industries (iron and steel, cement, and flat glass), as shown in Figure 4.

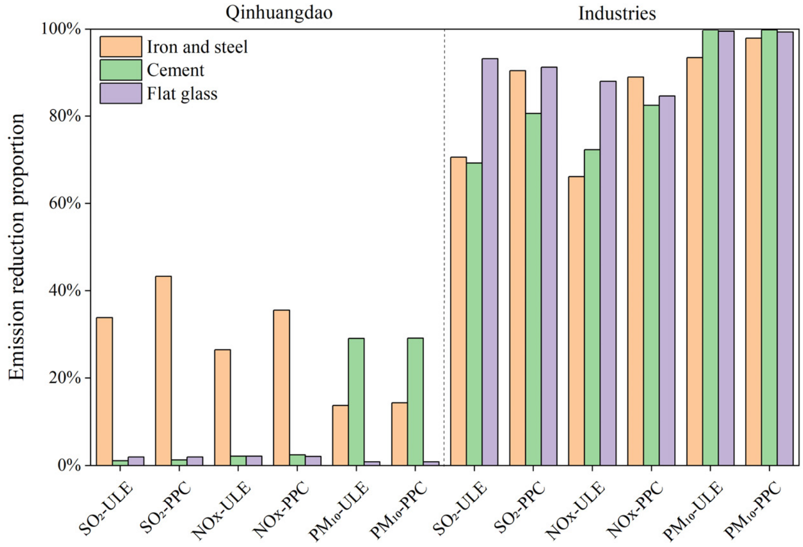


Figure 4. The emission reduction ratio of SO_2, NOx, and PM_{10} under different scenarios in 2025. The left part shows the emission reduction proportion of typical industries on the total emission of air pollutants in Qinhuangdao under different scenarios; the right part shows the emission reduction proportion of typical industries on their respective industries under different scenarios.

In the ULE scenario, by 2025, the SO_2, NOx, and PM_{10} emitted from the iron and steel industry in Qinhuangdao would be reduced by 29.12 kt (70.65% of the emissions from the industry), 44.83 kt (66.21%), and 70.10 kt (93.44%), respectively, compared to the BAU scenario by 2025. Emission reduction accounted for 33.82%, 26.43%, and 13.70% of the total emissions of SO_2, NOx, and PM_{10} in 2025, respectively. For the cement industry, the emission reduction of SO_2, NOx, and PM_{10} were 0.93 kt (69.33%), 3.59 kt (72.37%), and 149.03 kt (99.70%), respectively, and the reduction rates of total emissions were 1.08%, 2.12%, and 29.12%, respectively. As for the flat glass industry, the emissions of SO_2, NOx, and PM_{10} would be reduced by 1.68 kt (93.21%), 3.60 kt (88.06%), and 4.35 kt (99.44%), respectively, corresponding to the total emission reduction rate of 1.95%, 2.12%, and 0.85%.

Under the PPC scenario, compared with the BAU scenario, the reduction of SO_2, NOx, and PM_{10} in the iron and steel industry in 2025 was 37.29 kt (90.48% of the industry), 60.27 (89.02%), and 73.44 (97.88%) kt, respectively, with the total reduction rate of 43.31%, 35.54%, and 14.35%, respectively. In the cement industry, compared with BAU, the emission reduction of SO_2, NOx, and PM_{10} was 1.09 kt (80.64%), 4.10 kt (82.56%), and 149.19 kt (99.81%), accounting for 1.26%, 2.42%, and 29.15% of the corresponding total emissions, respectively. In addition, SO_2, NOx, and PM_{10} emissions of flat glass would be reduced by 1.64 kt (91.28%), 3.46 kt (84.67%), and 4.34 kt (99.28%), respectively, and the corresponding total emission reduction rates were 1.91%, 2.04%, and 0.85%, respectively.

Therefore, due to the declining production of the flat glass industry in the ULE scenario, the emission reduction effect of the other two industries in the PPC scenario was always better than that in the ULE scenario except for the flat glass industry. At the city level, the iron and steel industry contributed the most to the emission reduction of SO_2 and NOx under the PPC scenario, while the cement industry contributed the most to the emission reduction of PM_{10}. This was primarily due to the significant emissions generated by these industries for their respective pollutants. At the industrial level, the emission reduction proportion of the three industries that implemented the ULE policy exceeded 60%, and the cement industry under the PPC scenario made the largest contribution to PM_{10} reduction. This was primarily due to the absence of dust removal devices in some cement plants in 2016, indicating significant potential for emission reductions.

Furthermore, we compared the emission reduction of this study with other emission reduction studies (shown in Table 3). Among them, the city of Tangshan exhibited the lowest reduction rate in the iron and steel and cement industries. This can be primarily attributed to the fact that in its assumed scenario, the industrial emission concentrations did not fully meet the ultra-low emission standards.

Table 3. Comparison of emission reduction in this study with other studies.

Reference	Base Year	Region	Reference Policy	Industry	SO_2 Emission Reduction (%)	NOx Emission Reduction (%)	PM_{10} Emission Reduction (%)
Bo et al. [51]	2013	Tangshan	Air Pollution Prevention and Control Action Plan	Iron and steel	2.28	5.97	37.02
				Cement	0	7.55	25.00
This study	2016	Qinhuangdao	ULE	Iron and steel	70.65	66.21	93.44
				Cement	69.33	72.37	99.70
				Flat glass	93.21	88.06	99.44
Tang et al. [52]	2018	China	ULE	Iron and steel	82.98	88.61	85.69

3.3. Comparisons with Other Emission Inventories

The emission inventory for Qinhuangdao in this study was compared with the Qinhuangdao part included in the BTH region [6], the Multi-resolution Emission Inventory for China (MEIC) [9] and China High-Resolution Emission Database 3.0 A (CHRED 3.0A) [8] (shown in Table 4). Compared to these inventories, our work has a higher spatial resolution of 1 km × 1 km and comprehensive data, which strengthens the accuracy of the results.

Table 4. Comparison of estimated emissions in this study with previous studies (unit: kt).

Reference	Year	Region	SO_2	NOx	PM_{10}	$PM_{2.5}$	CO	VOCs	NH_3	BC	OC
Qi et al. [6]	2013	Qinhuangdao	87.9	116.7	47.7	32.9	694.1	48.1	24.3	3.3	5.7
MEIC [9]	2016	Qinhuangdao	39.3	76.6	33.9	25.1	578.5	70.2	23.1	4.3	6.3
CHRED 3.0A [8]	2018	Qinhuangdao	26.2	40.8	22.6	18.1	763.6	59.9	26.2	2.7	5.7
This study	2016	Qinhuangdao	48.9	86.8	302.0	116.8	1208.8	52.7	62.9	3.8	2.7

The results showed that the emissions of PM in the other three studies were much lower than those in this study since dust sources were included in this study, which were also the main sources of PM emissions. The point data in the emission inventory for 2013 were detailed and comprehensive and could reflect the interannual variation of pollutant emissions from point sources in Qinhuangdao. The emissions of SO_2 and NOx in 2013 were significantly higher than those in 2016, which was primarily caused by the introduction of the ULE policy on power plants in 2014 and the adjustment of the energy structure. As for other pollutants, the differences in the estimates were primarily from emission factors and activity levels in different years.

Compared to the MEIC for 2016, the emissions of SO_2 and NOx were close to those in this study. Except for VOCs, BC, and OC, the emissions of other pollutants from MEIC and CHRED 3.0 A were lower than those calculated in this study, which may be due to the fact that the activity level in this study for Qinhuangdao was more comprehensive and reliable than the statistics from the other two emission inventories. Furthermore, as two national-level inventories, MEIC (27 km $\times$ 27 km) and CHRED 3.0 A (10 km $\times$ 10 km) had lower resolutions, which cannot accurately represent pollutant emissions at the city level. In addition, there were differences in the classification of emission sources between MEIC (five source categories) and this work (ten source categories). In summary, we believe that the new emission inventory in this study can describe a more reliable feature of Qinhuangdao's pollutant emissions.

3.4. Impact Analysis of the PPC Scenario on the Atmosphere of Qinhuangdao

In this section, the CALPUFF model and the Weather Research and Forecasting (WRF) meteorological model were used to simulate the air pollution in Qinhuangdao for 2025 under BAU and PPC scenarios. Emission inventories under different scenarios in 2025 were used as input for source data. WRF data and other parameters input for different scenarios were consistent. The details of model parameters are described in Table S21. The simulation results are shown in Figure 5.

The simulation results indicated that under the BAU scenario, the high concentrations of SO_2, NOx, and PM_{10} were primarily distributed in the south of Qinhuangdao, including Haigang, Funing, Lulong, and Changli Districts. In the PPC scenario, the distribution of pollutants was generally consistent with the BAU scenario, but there was a significant decrease in concentration in the high-value areas (shown in Table 5).

Table 5. The average annual contribution concentrations of pollutants to the air monitoring stations in Qinhuangdao.

The ID of the Air Monitoring Station	The Contribution of Average Annual Concentration under the BAU Scenario (μg/m^3)			The Contribution of Average Annual Concentration under the PPC Scenario (μg/m^3)		
	SO_2	NOx	PM_{10}	SO_2	NOx	PM_{10}
1	11.64	50.07	118.52	6.04	29.39	52.28
2	9.74	63.27	117.66	4.73	35.70	55.32
3	10.21	52.08	96.89	4.48	31.12	42.25
4	4.42	28.45	36.95	2.35	15.40	18.99
5	5.02	10.84	117.78	2.72	6.57	53.91

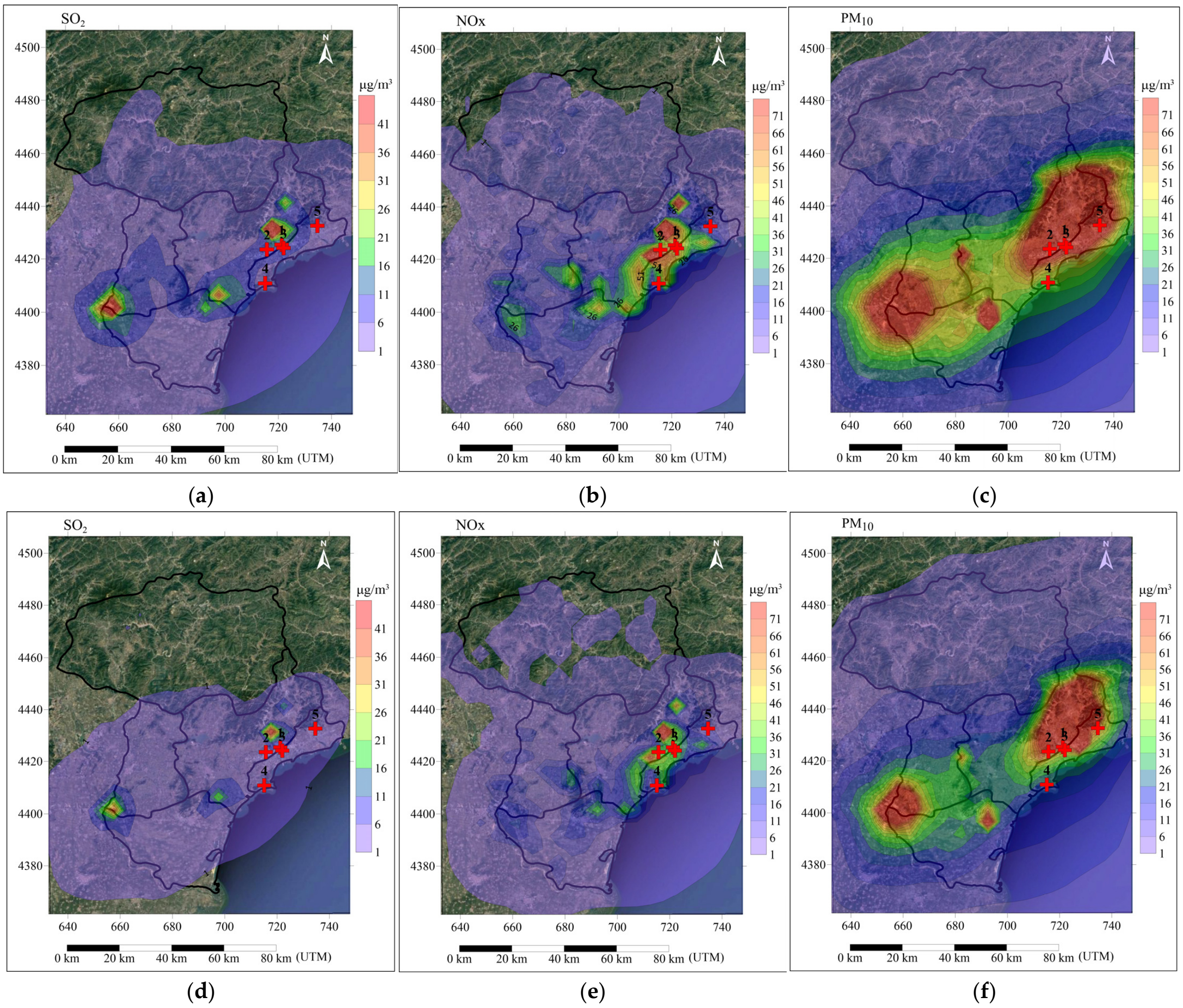


Figure 5. The contribution of average annual concentration of SO_2, NOx, and PM_{10} in Qinhuangdao for 2025 modeled by CALPUFF under BAU (**a**–**c**) and PPC (**d**–**f**) scenarios. The red plus signs represent the location of the air monitoring stations, and the numbers near the plus signs represent the ID of the monitoring stations.

3.5. Policy Implications

According to Section 3.2, the iron and steel industry contributed the most to the emission reduction of SO_2 and NOx under the PPC scenario, while the cement industry contributed the most to the emission reduction of PM_{10} at the city level. Therefore, targeted emission reduction efforts in the iron and steel industry and the cement industry are more likely to significantly improve the air quality in Qinhuangdao. In fact, since the ULE policy of key industries was implemented by the Qinhuangdao Municipal People's Government in 2018, there has been an overall downward trend in the concentrations of SO_2, NOx, and PM_{10} in Qinhuangdao in the case of industrial output growth. In 2021, compared to 2016, the concentrations of SO_2, NOx, and PM_{10} decreased by 60.71%, 33.33%, and 27.59%, respectively [53]. Thus, the PPC scenario focusing on output control and adopting ULE measures could offer the additional potential to reduce the emission of air pollutants, building upon the positive trend observed since the implementation of the ULE policy.

On the one hand, the ULE policy not only has a significant emission reduction effect for traditional industrial cities but also applies to tourist cities and non-transmission channel cities, which shows the broad applicability, remarkable effect, and huge potential of this policy. It also has a guiding significance for undeveloped industry regions and tourist cities to implement the ULE policy. Therefore, the reduction effect of ULE may be underestimated, and policymakers should be aware of the effectiveness of this policy and reevaluate its effect. On the other hand, although the ULE policy has made remarkable achievements [19] in pollutant emission reduction, the current ULE standards still have an improvement in pollutant emission reduction policies and technologies. In the future, the Chinese government should devote itself to promoting more advanced and environmentally friendly emission reduction technologies and corresponding standards, so as to ensure the continuous cleanliness of air and reduce the harm to the social economy and people's health. In addition, the Chinese government should regularly update the emission inventory of regional air pollution sources and comprehensive emission characteristics as a study basis for the migration, transformation, and traceability of air pollutants to support regional air quality control policies.

3.6. Uncertainty Analysis and Limitations

Monte Carlo simulations were frequently employed to quantitatively evaluate uncertainty in emission inventories [25]. Based on the probability distribution of emission factors and activity levels, Monte Carlo simulation randomly sampled a group of emission factors and activity levels to generate random parameter values. These random values were then substituted into the emission inventory model to calculate the emissions for each sampling, and this sampling and calculation process was repeated n times. The uncertainty of emission inventory was quantified by statistical analysis of the results from these repeated samples [54].

Table 6 summarizes the range of uncertainty in pollutant emissions. For SO_2, NOx, CO, PM_{10}, $PM_{2.5}$, and VOCs, the uncertainties were relatively lower since their contributors were primarily point sources such as industry sources with detailed and reliable data at the plant level. The high uncertainty of NH_3 largely came from agriculture sources, whose activity-level data at the city level were affected by factors such as fertilization time, weather, and incomplete statistics. In addition, area sources such as non-road mobile and dust sources also had large uncertainties. Non-road mobile sources are primarily based on a top-down calculation of pollutant emissions based on parameters such as fuel consumption, mileage, and holding capacity, which lacked the support of actual monitoring data and therefore had a large uncertainty. In addition, the selection of emission factors also led to some uncertainties. Similar to non-road mobile sources, the uncertainties for the fugitive dust sources were also related to the lack of actual monitoring data. The dust was widely distributed and constantly changed with time and weather, making it difficult to obtain more accurate emission data.

Table 6. Uncertainty ranges in the estimated pollutant emissions.

Pollutant	SO_2	NOx	CO	PM_{10}	$PM_{2.5}$	VOCs	NH_3	BC	OC
Uncertainty	−6% to 6%	−7% to 7%	−6% to 6%	−6% to 6%	−7% to 7%	−7% to 7%	−37% to 39%	−17% to 19%	−16% to 19%

In addition to the aforementioned uncertainties, there were also some limitations in the inventory established in this study. The emission factors selected for this study were derived from the guidelines issued by the Ministry of Ecology and Environment [41,55–63] and existing research [41,59]. However, local emission factors specific to Qinhuangdao have not been established, which may result in discrepancies with the actual emission factors in Qinhuangdao. For the three emission scenarios set in this study, factors such as capacity replacement and factory relocation were not considered. As a result, there may be discrepancies between the predicted output and the actual production in the future. Additionally, the ultra-low emission factors used in this study were derived from the industry ultra-low standards rather than actual monitoring data. This can introduce errors when estimating the actual emissions in the future. In addition, for other air contaminants, such as heavy metals and PM_1, the impact on air quality and human health cannot currently be assessed due to the lack of reliable localization emission factors. Addressing these limitations will be a crucial aspect of our future research endeavors.

4. Conclusions

In this work, we established a high-resolution (1 km × 1 km) emission inventory for Qinhuangdao City in 2016 to evaluate the impact of the ULE policy on Qinhuangdao's air quality. The inventory showed that industrial process sources were regarded as the main sources of SO_2, $PM_{2.5}$, PM_{10}, VOCs, CO, and OC, respectively. The main contributor to SO_2, CO, $PM_{2.5}$, and PM_{10} emissions was industrial processes while the main contributor to NOx emissions was mobile sources. Fossil fuel combustion sources were the main sources of BC. NH_3 emissions originated mostly from agricultural sources such as livestock and N-fertilizer. In terms of spatial distribution, high emissions of pollutants were concentrated in the southern and eastern regions of Qinhuangdao City.

Based on this, three scenarios (BAU, ULE, and PPC) were established for key industries to evaluate the reduction effect of the emissions and the average annual contribution concentration brought by the ULE policy in Qinhuangdao. The results indicated that the ULE policy had a promoting effect on the reduction of air pollutants and the improvement of air quality in Qinhuangdao. For example, at the regional level, the iron and steel industry under the PPC scenario excelled in reducing SO_2 and NOx emissions, while the cement industry had the greatest potential for reducing PM_{10} emissions in 2025. Air quality simulations revealed a significant decrease in pollutant concentrations under the PPC scenario in 2025. Therefore, the ULE policy in Qinhuangdao is significant for the improvement of local air quality in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14081218/s1, Section S1. Beijing-Tianjin-Hebei (BTH) air pollution transmission channel cities; Section S2: Emission factors; Section S3: Calculation formula; Section S4: Spatial allocation of the emission sources; Table S1: Emission source categorization in Qinhuangdao City; Table S2: Spatial distribution surrogates of each emission source; Table S3: Emission concentration and theoretical flue gas rate for sintering; Table S4: Emission concentration and theoretical flue gas rate for pelletizing; Table S5: Emission concentration and theoretical flue gas rate for blast furnace (BF); Table S6: Emission concentration and theoretical flue gas rate for basic oxygen furnace (BOF); Table S7: Emission concentration and theoretical flue gas rate for flat glass; Table S8: Emission concentration and benchmark displacement for cement; Table S9: The product output of the three industries in the past decade (unit: 10^4 t/a; for flat glass: 10^4 boxes/a); Table S10: The fluctuating range of the three industries in the past decade; Table S11: The uncertainties of activity level; Table S12: The uncertainties of emission factors for SO_2. 95% CIs are provided in the parentheses; Table S13: The uncertainties of emission factors for NOx. 95% CIs are provided in the parentheses; Table S14: The uncertainties of emission factors for CO. 95% CIs are provided in the parentheses; Table S15: The uncertainties of emission factors for $PM_{2.5}$. 95% CIs are provided in the parentheses; Table S16: The uncertainties of emission factors for PM_{10}. 95% CIs are provided in the parentheses; Table S17: The uncertainties of emission factors for VOCs. 95% CIs are provided in the parentheses; Table S18: The uncertainties of emission factors for NH_3. 95% CIs are provided in the parentheses; Table S19: The uncertainties of emission factors for BC. 95% CIs are provided in the parentheses; Table S20: The uncertainties of emission factors for OC. 95% CIs are provided in the parentheses; Table S21: CALPUFF model parameter settings; Figure S1: Distribution of population density in Qinhuangdao; Figure S2: The prediction of the secondary industry GDP; Figure S3: The relationship between the output of iron and steel and the secondary industry GDP; Figure S4: The relationship between the output of cement and the secondary industry GDP; Figure S5: The relationship between the output of flat glass and the secondary industry GDP; Figure S6: County-level contributions to the total emissions for nine pollutants in Qinhuangdao; Figure S7: Spatial distribution characteristics of air pollutant emissions in Qinhuangdao for 2016. (a) $PM_{2.5}$; (b) VOCs; (c) CO; (d) NH_3; (e) BC; (f) OC. References [15–17,21,25,41,55–63] are cited in the supplementary materials.

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