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Improving the Air Quality Management: The Air Pollutant and Carbon Emission and Air Quality Model for Air Pollutant and Carbon Emission Reduction in the Iron and Steel Industries of Tangshan, Hebei Province, China

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Abstract: Currently, Tangshan confronts the dual challenge of elevated carbon emissions and substantial pollution discharge from the iron and steel industries (ISIs). While significant efforts have been made to mitigate air pollutants and carbon emissions within the ISIs, there remains a gap in comprehending the control of carbon emissions, air pollutant emissions, and their contributions to air pollutant concentrations at the enterprise level. In this study, we devised the Air Pollutant and Carbon Emission and Air Quality (ACEA) model to identify enterprises with noteworthy air pollution and carbon emissions, as well as substantial contributions to air pollutant concentrations. We constructed a detailed inventory of air pollutants and CO_2 emissions from the iron and steel industry in Tangshan for the year 2019. The findings reveal that in 2019, Tangshan emitted 5.75×10^4 t of SO_2, 13.47×10^4 t of NO_x, 3.55×10^4 t of PM_{10}, 1.80×10^4 t of $PM_{2.5}$, 5.79×10^6 t of CO and 219.62 Mt of CO_2. The ACEA model effectively pinpointed key links between ISI enterprises emitting air pollutants and carbon dioxide, notably in pre-iron-making processes (coking, sintering, pelletizing) and the Blast furnace. By utilizing the developed air pollutant emission inventory, the CALPUFF model assessed the impact of ISI enterprises on air quality in the Tangshan region. Subsequently, we graded the performance of air pollutant and CO_2 emissions following established criteria. The ACEA model successfully identified eight enterprises with significant air pollution and carbon emissions, exerting notable influence on air pollutant concentrations. Furthermore, the ACEA outcomes offer the potential for enhancing regional air quality in Tangshan and provide a scientific instrument for mitigating air pollutants and carbon emissions. The effective application of the ACEA model in Tangshan's steel industry holds promise for supporting carbon reduction initiatives and elevating environmental standards in other industrial cities across China.

Keywords: air pollutant; carbon; emission inventory; iron and steel industry; model; Tangshan

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Citation: Chen, S.; Li, J.; You, Q.; Wang, Z.; Shan, W.; Bo, X.; Zhu, R. Improving the Air Quality Management: The Air Pollutant and Carbon Emission and Air Quality Model for Air Pollutant and Carbon Emission Reduction in the Iron and Steel Industries of Tangshan, Hebei Province, China. *Atmosphere* **2023**, *14*, 1747. https://doi.org/10.3390/atmos14121747

Academic Editors: Hung-Lung Chiang and Vivien How

Received: 25 September 2023
Revised: 17 November 2023
Accepted: 23 November 2023
Published: 28 November 2023

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1. Introduction

The iron and steel sector occupies a pivotal role in economic progress. According to the World Steel Association, global crude steel production reached 1.869 billion tons in 2019, with China contributing 53.3% of this total [1]. In the same year, Hebei Province generated 242 million tons of crude steel, constituting around 25% of China's overall crude steel output, thereby establishing itself as a major steel-producing province in China [2]. As a result, Hebei contributed significantly to air pollutant emissions due to its developed ISI

enterprise [3]. Moreover, Tangshan, a representative industrial city in Hebei, accounted for 50.8% and 12.3% of the province's and the nation's crude steel production, respectively [4]. However, Tangshan's thriving iron and steel industries (ISIs) have led to deteriorating air quality and escalating carbon dioxide (CO_2) emissions.

Tangshan ranked first among all prefecture-level cities in China in terms of SO_2, NO_x, and CO emissions in 2018 [5]. Industrial sources constitute a predominant contributor to Tangshan's pollutants, accounting for 37.6%, with iron and steel, cement, and coking accounting for 31.0%, 3.4%, and 3.1%, respectively [6]. Positive Matrix Factorization (PMF) analysis revealed that metal smelting contributed 24% to $PM_{2.5}$ concentration in Tangshan in 2017 [7]. The ISIs were responsible for 16.92% of summer NO_x concentrations in Tangshan in 2018 [8]. Direct emissions from Tangshan's ISI enterprises led to monthly average concentrations of $PM_{2.5}$ and SO_2 reaching 90 $\mu g/m^3$ in 2012 [9]. Moreover, the annual average concentrations of NO_2, PM_{10}, and $PM_{2.5}$ in Tangshan still exceed the national standards, and the traditional air pollution problem has not been completely solved. It was reported that the control of air pollutant emissions can improve local air quality [10]. However, Tangshan's air quality ranking among China's 169 key cities has been consistently low; it was fourth from the bottom in 2018 and 2020, and sixth from the bottom in 2019 [11]. This poor ranking may be attributed to intensive air pollutant emissions and adverse meteorological conditions [12]. In 2005, Tangshan's CO_2 emissions were the second highest among all prefecture-level cities in China. By 2018, these emissions had increased, ranking first among such cities [5]. In comparison, carbon emissions in Tangshan were double those in Shijiazhuang, another typical industrial city in Hebei Province. Tangshan's carbon emissions were approximately 3×10^9 tons, compared to 1.3×10^9 tons emitted by Handan, another industrial city in the province. Tangshan's carbon emissions were also higher than those of Jilin City in both 2005 and 2018. From 2010 to 2016, CO_2 emissions from the ISIs in Tangshan ranged from 0.55 to 1.1×10^9 tons [13,14]. In 2017, the amount of CO_2 emitted by Tangshan's ISIs accounted for approximately 50% of the total local CO_2 emissions [6]. Therefore, an optimized combination of air pollutants and CO_2 emission reduction measures in Tangshan's ISI enterprises is a crucial approach to improving environmental quality. Specifically, the local government should employ a scientific model to identify enterprises with the characteristics of high air pollutant emissions, high carbon dioxide emissions, and significant contributions to air pollutant concentrations. The focus should then be on transforming these enterprises.

Scholars have developed air pollutant emission inventories at various scales, including global, national [5], and regional [15,16]. The results of these studies indicated that air pollutant emissions from industrial sectors were larger than emissions from other sources. Tang et al. [17] developed an ISI emission inventory and assessed its contribution to air pollutant concentrations using the Comprehensive Air Quality Model with Extensions (CAMx) in China for the year 2012. This assessment reflected historical characteristics of air pollutant emissions and highlighted more potential for emission reductions. The CAMx model was also deployed to gauge Chinese ISIs' contributions to annual SO_2, NO_x, and $PM_{2.5}$ concentrations in 2018 and beyond [8]. Zhu et al. [18] predicted a reduction in SO_2 concentrations attributable to the ISIs in China by 2025 using the Community Multiscale Air Quality model. CALPUFF has also been widely applied to assess the effects of air pollutant emissions from individual industrial sources on air quality at small scales. The CALPUFF model indicated that the air pollutant concentrations contributed by Waste Incineration enterprises in Shandong Province (China) would decrease by more than 20% [19]. Applying CALPUFF, a study on Muscat's (Oman) ISIs revealed winter NO_x concentrations surpassing the guidelines set by the United States Environmental Protection Agency (U.S. EPA) [20]. Similarly, in the case of Baosteel Group, a typical steel enterprise in Urumqi, Xinjiang Province, China, CALPUFF identified the highest contribution to the Saybagh high concentration area (SO_2 at 37 $\mu g/m^3/a$) [21]. While these scholars evaluated and ranked air pollutant contributions from ISIs, their assessments often omitted corresponding carbon emissions.

Given the imperative of achieving carbon neutrality, China's ISI sector urgently requires low-carbon development. ISIs' CO_2 emissions constitute approximately 14% of China's anthropogenic CO_2 emissions [22,23], with ISIs' carbon emissions accounting for 30% of total industrial carbon emissions in 2018 [5]. These scholars identified that carbon emissions from ISIs were a significant carbon emission source; however, they did not offer a method to regulate carbon emissions by categorizing ISIs with grades. Furthermore, the complex interplay between air pollution emissions, carbon emissions, and their combined impact on air quality, as well as the identification of specific categories of iron and steel enterprises necessitating targeted regulation, remains underexplored.

Therefore, this study introduces the Air Pollutant and Carbon Emission and Air Quality (ACEA) model to pinpoint enterprises with notable air pollution and carbon emissions, and significant contributions to air pollutant concentrations. We initially compiled an emission inventory for air pollutants and carbon from Tangshan's ISIs in 2019. Subsequently, we employed the CALPUFF model to assess the contributions of air pollutants emitted by iron and steel enterprises to air pollutant concentrations. Guided by references and guidelines, we evaluated the grades of air pollution emissions and carbon emissions. This led to the establishment of the ACEA model, which aimed to identify enterprises characterized by high air pollutant emissions, elevated carbon dioxide emissions, and significant contributions to air pollutant concentrations. Based on the ACEA model's results, this study offers novel insights to enhance local air quality and reduce carbon emissions within Chinese industrial cities.

2. Methodology

Tangshan is situated in the eastern part of Hebei Province, China (117°31′–119°19′ E, 38°55′–40°28′ N), covering an area of 13,472 km^2 (shown in Figure 1). It holds a vital role in the Beijing–Tianjin–Hebei economic circle as a significant industrial city. Tangshan offers abundant energy and mineral resources, fostering a robust industrial foundation. In 2019, the city achieved a GDP of CNY 689 billion, with a per capita GDP of CNY 86,500, significantly surpassing the second-ranked city of Shijiazhuang, which had a per capita GDP of CNY 52,700 [4].

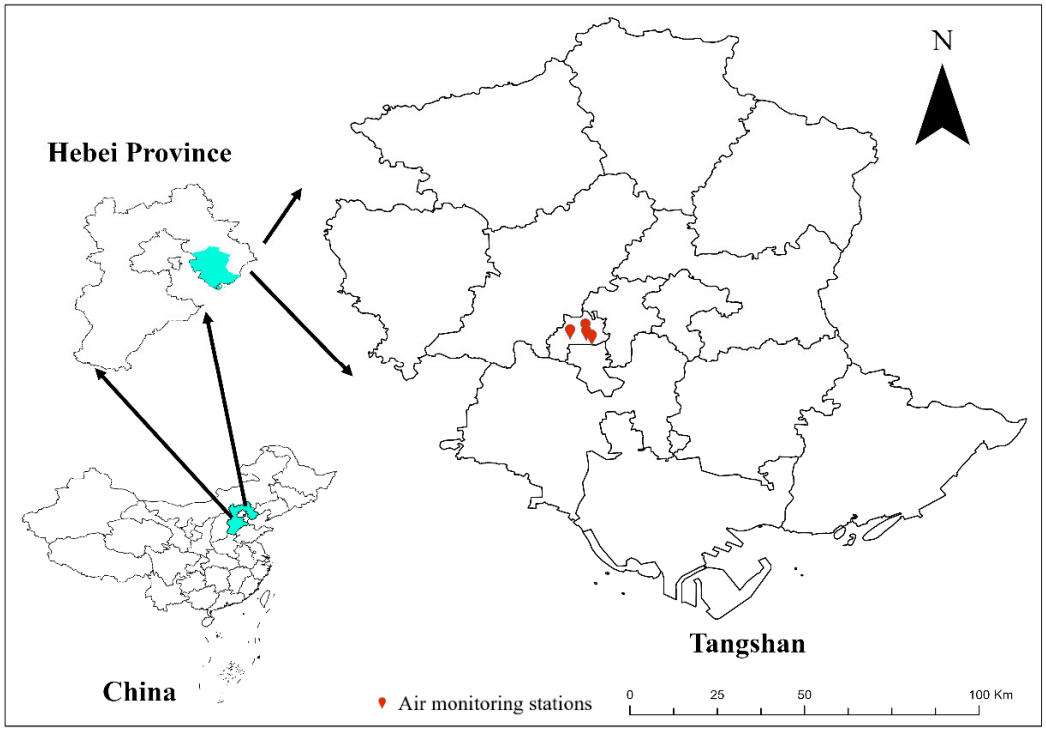


Figure 1. Map showing the study domain (Tangshan City) and its localization within China.

2.1. The Technical Route of the Air Pollutant and Carbon Emission and Air Quality (ACEA) Model

We formulated a model to appraise enterprises' air pollutant and CO_2 emissions, as well as their contributions to air pollutant concentrations. The process involved developing an emission inventory for air pollutants and CO_2 from each enterprise within Tangshan's ISIs. Subsequently, we input this inventory into the CALPUFF model for simulation, which yielded the enterprises' pollution contribution to air monitoring stations (shown in Figure 2). Drawing on references and guidelines, we employed diverse classification methods to evaluate each enterprise's pollutant and CO_2 emissions and their contributions to national control sites. This analysis facilitated the categorization and discussion of enterprises at varying levels.

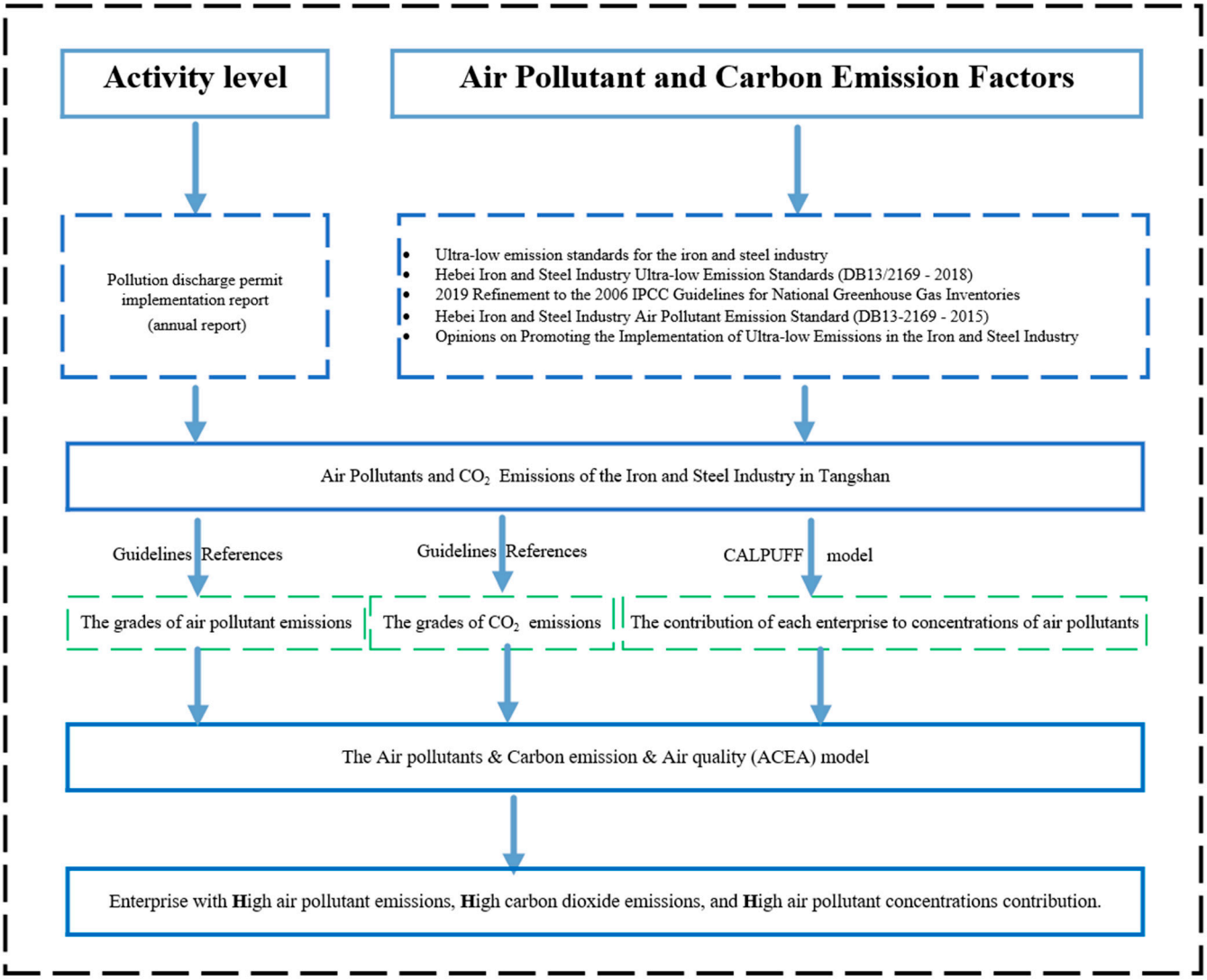


Figure 2. The technical route of the Air pollutant and Carbon emission and Air quality (ACEA) model.

2.2. The Establishment of Air Pollutant and Carbon Emission Inventories

We employed a unit-based bottom-up approach, utilizing production data for processes in each Tangshan ISI enterprise for the year 2019. Emission factors were used to calculate air pollutant and CO_2 emissions. The fundamental emission calculation formula is as follows [24–26]:

$$E_f = \sum_i \sum_p \left(AC_{i,p} \times EF_{f,s,p} \right) \quad (1)$$

where E denotes pollutant emissions (g); AC represents production quantity for each process of ISI enterprises (kg); EF signifies the emission factor (g/kg); f represents different

pollutants and CO_2; *s* denotes diverse emission sources; *p* signifies different production processes; and *i* signifies distinct enterprises.

The activity level of ISI enterprises quantifies activities leading to air pollutant and CO_2 emissions. For medium and long process iron and steel production enterprises, activity levels primarily include sintering, blast furnace, converter, electric furnace, and steel rolling processes. Data on Tangshan's iron and steel enterprises' activity levels in 2019 were obtained from the product output statistics of the pollution discharge permit implementation report (annual report) (http://permit.mee.gov.cn/permitExt/defaults/default-index!getInformation.action, accessed on 25 September 2023).

2.3. The Determination of Emission Factors and the Grades of Emission Performance

2.3.1. The Emission Factors of Air Pollutants and the Corresponding Grades of Emission Performance

Since 2019, the Metallurgical Industry Planning and Research Institute has conducted emergency emission reduction performance assessments for Tangshan Mayor Process United Iron and Steel Enterprises [27]. Aligned with the "Technical Guidelines for Formulating Emergency Emission Reduction Measures for Heavy Pollution Weather [28]", these assessments include pollution control technologies, fugitive emissions, monitoring levels, emission limits, and transportation methods. The 29 long-process ISI enterprises and 3 short-process ISI enterprises in Tangshan were classified into five grades: A, B, B-, C, and D.

This study particularly emphasizes organized emissions indicators. Both grade A and grade B standards are anchored in ultra-low emission standards for ISIs. The divergence lies in the environmental impact of the transportation link, which is lesser than that of the production link. Consequently, the "Opinions on Promoting the Implementation of Ultra-low Emissions in the Iron and Steel Industry [28]" constitutes the emission standard for grade B enterprises. Given that Tangshan has only two grade A enterprises, a smaller number, and their emission standard is more stringent than that of grade B enterprises, the more rigorous local ultra-low emission standard of Hebei Province, "Hebei Iron and Steel Industry Ultra-low Emission Standards (DB13/2169)—2018" [29], serves as the emission standard for grade A enterprises. Grades B- and C adhere to the classification standards outlined in the "Technical Guidelines [28]". Grade D enterprises fail to meet grade C requirements; hence, this paper uses the Hebei Iron and Steel Industry Air Pollutant Emission Standard (DB13/2196-2015) [30] as the emission basis. Specific classification standards are presented in Table S1 [28–32].

Considering air pollutant emission concentration standards for distinct performance grades and combining them with activity grade data from the pollutant discharge permit implementation reports of various Tangshan ISI enterprises in 2019, we calculated SO_2, NO_x, and particulate matter emission factors of ISI enterprises by grade, which are shown in Table S2. The calculation methodology is as follows [26]:

$$EF_{f,s,p} = C_{std,f,s,p} \times V_{s,p} \quad (2)$$

where C_{std} denotes the emission concentration limit of each grade (mg/m^3) and V denotes the volume of theoretical flue gas emitted by producing per ton of product.

Emission factors for $PM_{2.5}$ and CO were derived from the literature research, as indicated in Tables S3 and S4 [33,34].

2.3.2. Emission Factors of CO_2 and Grades of Emission Performance

Within this study, emission factors for the coking, sintering, pelletizing, blast furnace, converter, and electric furnace processes were obtained from IPCC sources [35]. Table S5 shows the CO_2 emission factors for each process.

For this study, the carbon emission performances of ISIs was gauged as the ratio of a company's total CO_2 emissions to its crude steel production. CO_2 emission performance grades were established primarily by consulting experts and referencing air pollutant emission performance levels (Section 2.4.1). As illustrated in Table S6, carbon emission perfor-

mance within the ranges of 0.77–1.20, 1.20–1.67, 1.67–1.89, 1.90–2.02, and 2.02–2.20 tCO_2/t crude steel were designated as Grade A, B, B-, C, and D, respectively.

2.3.3. Analysis of Uncertainty

The Monte Carlo simulation was broadly employed to validate the accuracy of the emission inventory. Generally, it was assumed that production probabilities followed normal distributions with coefficients of variations of 5% [36]. For emission factor probabilities, a normal distribution with a coefficient of variation (CV) of 20% was assumed [36]. Subsequently, random values were generated for both activity data and emission factors for each unit. A total of 10,000 simulations were conducted to determine the range of uncertainties within our estimations.

2.4. The Settings of the CALPUFF Model

CALPUFF, a three-dimensional unsteady Lagrangian diffusion model, is a widely employed tool for studying pollutant diffusion on urban and regional scales [37–42]. The CALPUFF model system includes the CALMET meteorological model, CALPUFF diffusion model, and a series of pre-/post-processing procedures. CALMET utilizes terrain, land type, meteorological observation data, and mesoscale meteorological model data to generate the requisite three-dimensional meteorological field for CALPUFF, including wind and temperature fields. Widely used mesoscale meteorological models, such as MM5 and WRF, were employed. WRF, a next-generation meteorological model, offers higher spatial-temporal resolution and utilizes terrain, land type, meteorological observation data, and global meteorological initial field data to predict meteorological fields. The CALPUFF model employed the meteorological field produced by CALMET to simulate the movement, dispersion, settling, and other pathways of pollutants emitted from pollution sources. The Weather Research and Forecasting model (WRF3.6) provided simulated three-dimensional meteorological field data for this study. Surface meteorological data, upper air detection data, and precipitation data were all derived from the WRF meteorological model. The output results of the WRF model were then processed through the CALWRF conversion program, which was utilized to generate a three-dimensional hourly meteorological field by executing the CALMET model. The vertical direction of the CALMET model comprised ten layers, with ascending heights of 20, 40, 80, 160, 320, 640, 1200, 2000, 3000, and 4000 m. Terrain data precision was 90 m from the US Geological Survey, while land-use type data precision was 30 m, sourced from previous team research [42]. Information like the latitude and longitude of the 743 discharge outlets of each steel plant, chimney height, outlet temperature, flue gas flow rate, and pollutant emission amount were considered. For grid setup, this study utilized the Lambert conformal conic (LCC) projection, including the entirety of Tangshan City, with a false easting value of 500.00 km and a false north value of 4261.294 km. The grid resolution was set at 3 km, featuring 83 grid points east–west and 93 grid points north–south. Employing the MESOPUFF II chemical mechanism, the CALPUFF model simulated SO_2, NO_x, SO_4^{2-}, NO_3^-, and HNO_3 pollutants.

2.4.1. The Grade of Contributions to the Concentration of Air Pollutants

Typically, researchers utilize average air pollutant concentrations to describe the impact of air pollutant emissions from ISIs on the atmospheric environment [8,17]. Data on air quality across China are based on observation data of air pollutant concentrations from air monitoring stations. Simulated concentrations of air pollutants (SO_2, NO_x, PM_{10}, and $PM_{2.5}$) were averaged. Consequently, in this section, we defined the ratio of the simulated average concentration in the region to the observed value at air monitoring stations as contributions of pollutants emissions from ISI enterprises to concentrations of pollutants in the air (air monitoring stations shown in Figure 1). Contributions exceeding or falling below the average were classified as high or low pollutant concentration contribution enterprises.

2.4.2. Model Verification

The parameter setting of WRF model in this study has been applied in a number of air quality simulation studies in the Beijing-Tianjin-Hebei region, and three-dimensional meteorological field data provided have achieved good simulation results [17,26,38,43]. Therefore, the results of WRF simulations are reliable.

Surface air pollutant data for Tangshan were sourced from the China National Environmental Monitoring Center [11] network, accessible at http://www.cnemc.cn/jcbg/kqzlzkbg/index_2.shtml (accessed on 25 September 2023). Subsequently, the air pollutant concentrations derived from the CALPUFF model were compared with observed values, with analysis conducted through statistical means. The verification results for the CALPUFF model, as presented in Table S7, demonstrate Pearson's correlation coefficients (R) between the modeled and observed values of air pollutants: 0.65 for SO_2, 0.99 for NO_x, and 0.63 for PM. These R values meet the verification criteria for air quality models outlined in reference [44], thereby ensuring the reliability of our research findings.

3. Results

3.1. Emission Characteristics of Air Pollutant and CO_2 in 2019 Tangshan

As depicted in Figure 3, Tangshan housed 133 iron and steel smelting and rolling enterprises in 2019. Based on data from the Pollution Discharge Permit Implementation Reports (2019) (http://permit.mee.gov.cn/permitExt/defaults/default-index!getInformation.action, accessed on 25 September 2023), pig iron, crude steel, and steel product production in Tangshan amounted to 122.77, 137.11, and 150.87 Mt, respectively. Notably, 10 small-sized ISI enterprises with crude steel outputs below 1 Mt collectively produced 11.9279 Mt, comprising 2.43% of the total output. Meanwhile, 24 medium-sized enterprises with crude steel outputs ranging from 1 to 10 Mt collectively contributed 98.91 Mt, accounting for 81.24% of the total output. Lastly, two large-sized enterprises, each generating over 10 Mt of crude steel, produced 26.27 Mt, representing 16.33% of the total output. This analysis underscores that medium- and large-sized enterprises are the primary contributors to Tangshan's iron and steel production. Specifically, production quantities for sinter ore, pellets, coke, converter furnaces, and electric furnaces in Tangshan were 155.50, 27.74, 2.70, 119.69, and 17.13 Mt, respectively.

Ayres and Walter first proposed the concept of 'accompanying benefits' to describe how practices aimed at reducing greenhouse gas emissions can simultaneously mitigate damage caused by other pollutants [11]. In its third evaluation report, the IPCC explicitly introduced the concept of 'co-benefits', referring to the non-climate advantages of policies aimed at reducing greenhouse gas emissions [45]. Therefore, understanding the emission characteristics of both CO_2 and air pollutant emissions in ISIs, and in particular that of their mutual sources, is crucial for assessing the feasibility of achieving their concomitant emission control.

Air pollutant emissions included 5.75×10^4 t of SO_2, 13.47×10^4 t of NO_x, 3.55×10^4 t of PM_{10}, 1.80×10^4 t of $PM_{2.5}$, 5.79×10^6 t of CO and 219.62 Mt of CO_2 (Figure 4). As depicted in Figure 5, medium-sized, large-sized, and small-sized enterprises contributed 73.2%, 20.14%, and 6.67%, respectively, to the total average air pollutant emissions. Medium-sized enterprises were the primary contributors, representing 72.14% of regional crude steel output.

Among all of Tangshan's ISI production processes, sintering emerged as the largest emitter. It contributed 40.06% (2.32×10^4 t), 28.00% (3.77×10^4 t), 38.37% (1.36×10^4 t), 36.57% (0.65×10^4 t), and 42.6% (24.32×10^4 t) of SO_2, NO_x, PM_{10}, $PM_{2.5}$, and CO emissions, respectively (Figure 6). The high sulfur content in fuel and iron ore feedstock was the reason behind sintering's significant contribution to SO_2. Additionally, the pre-ironmaking processes (coking, sintering, pelletizing) were the primary culprits for ISIs' air pollutant emissions. These processes accounted for 47.07%, 32.69%, 42.80%, 40.34% and 42.70% of SO_2, NO_x, PM_{10}, $PM_{2.5}$ SO_2, NO_x, PM_{10}, $PM_{2.5}$ and CO emissions, respectively.

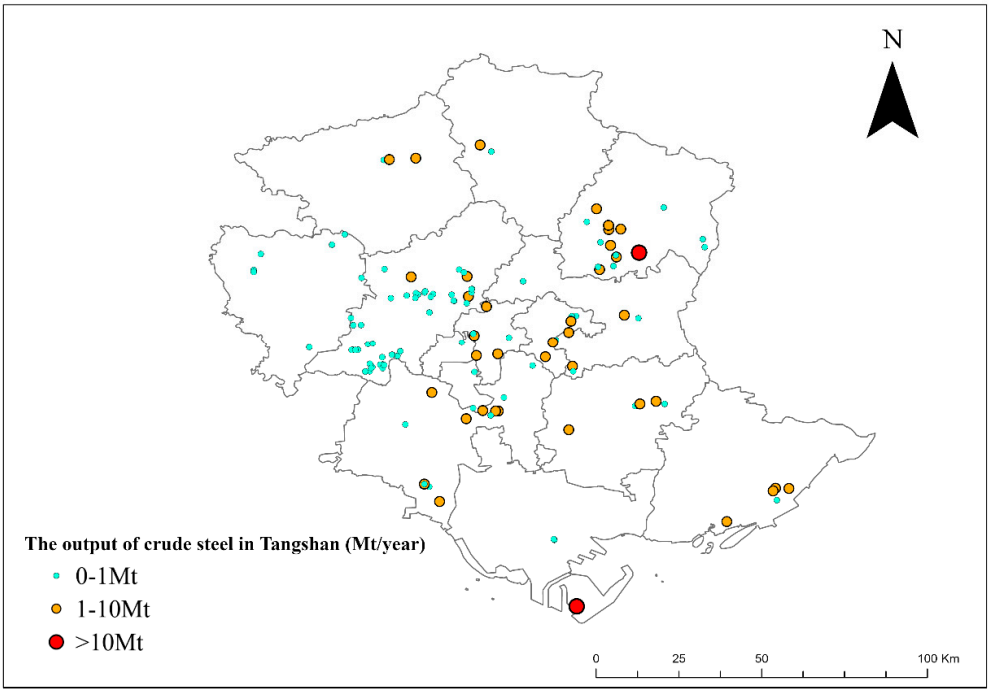


Figure 3. The distribution and output of iron and steel smelting and rolling enterprises in Tangshan for 2019.

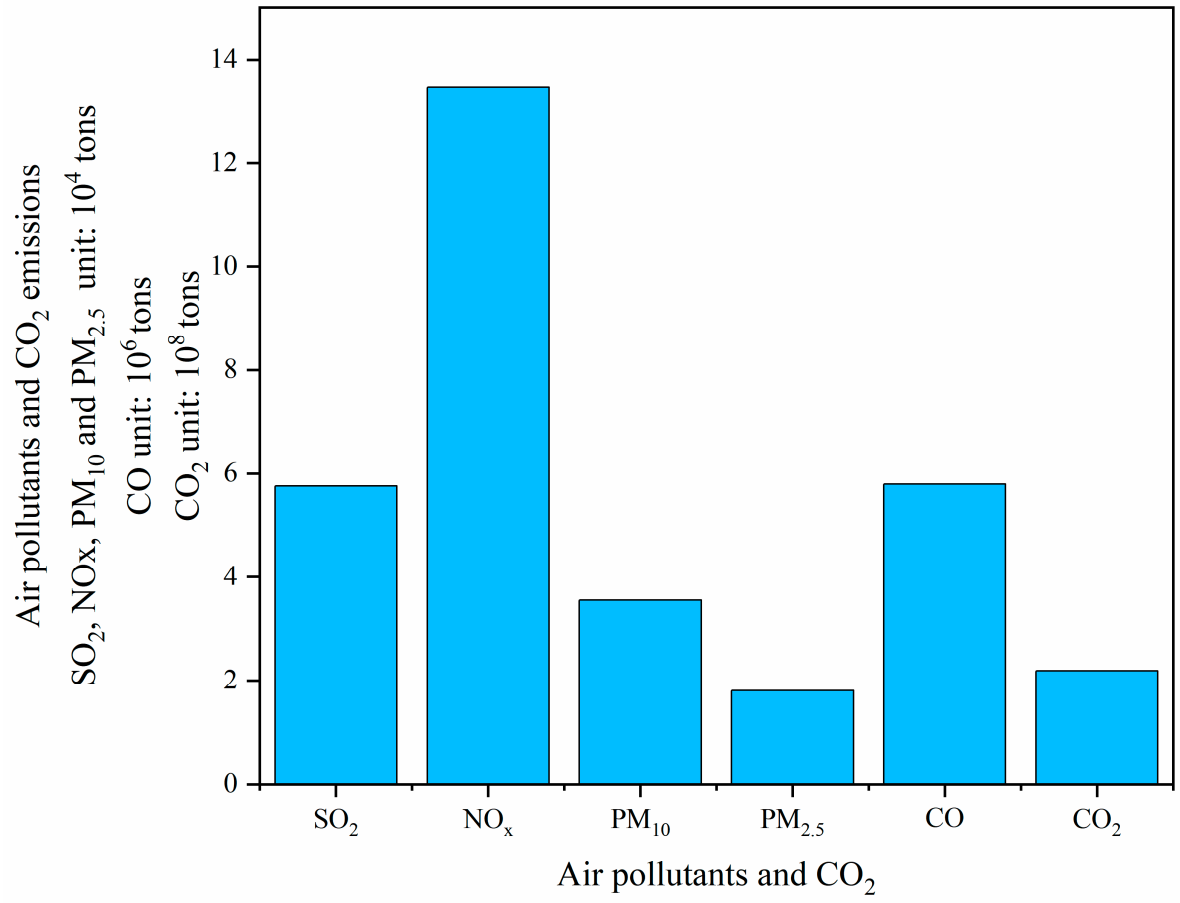


Figure 4. The emission of air pollutants and CO_2 in ISI enterprises in Tangshan for 2019.

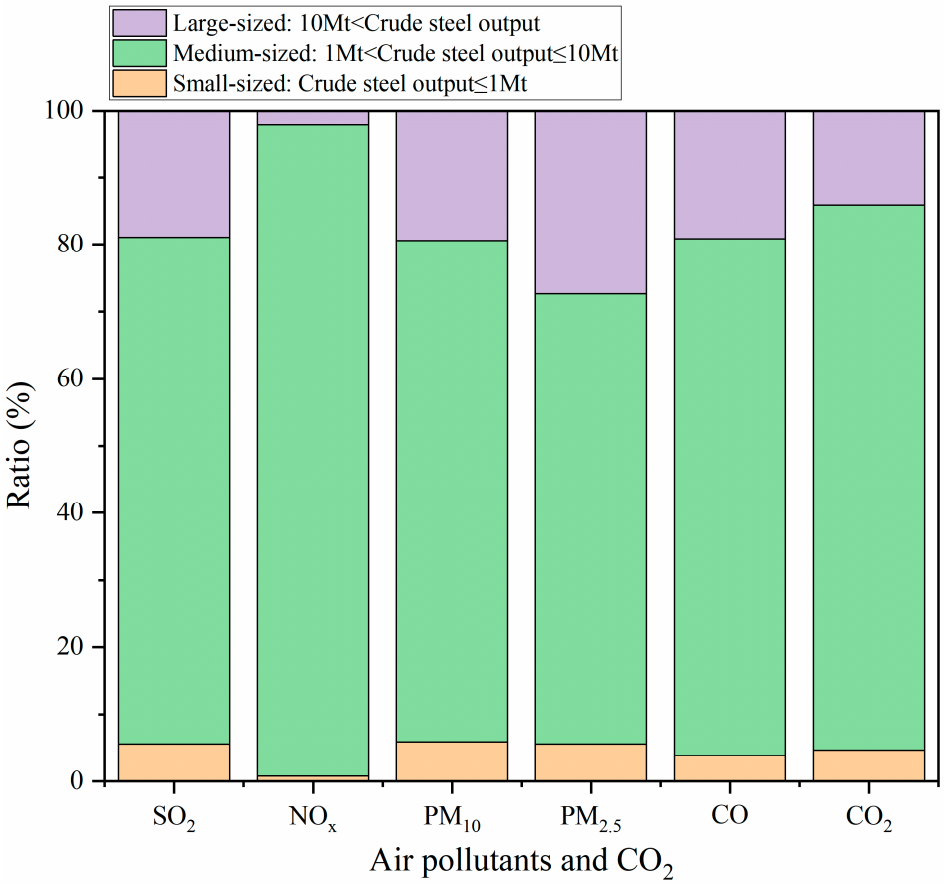


Figure 5. Pollutant emission ratios of ISI enterprises with different sizes in Tangshan in 2019.

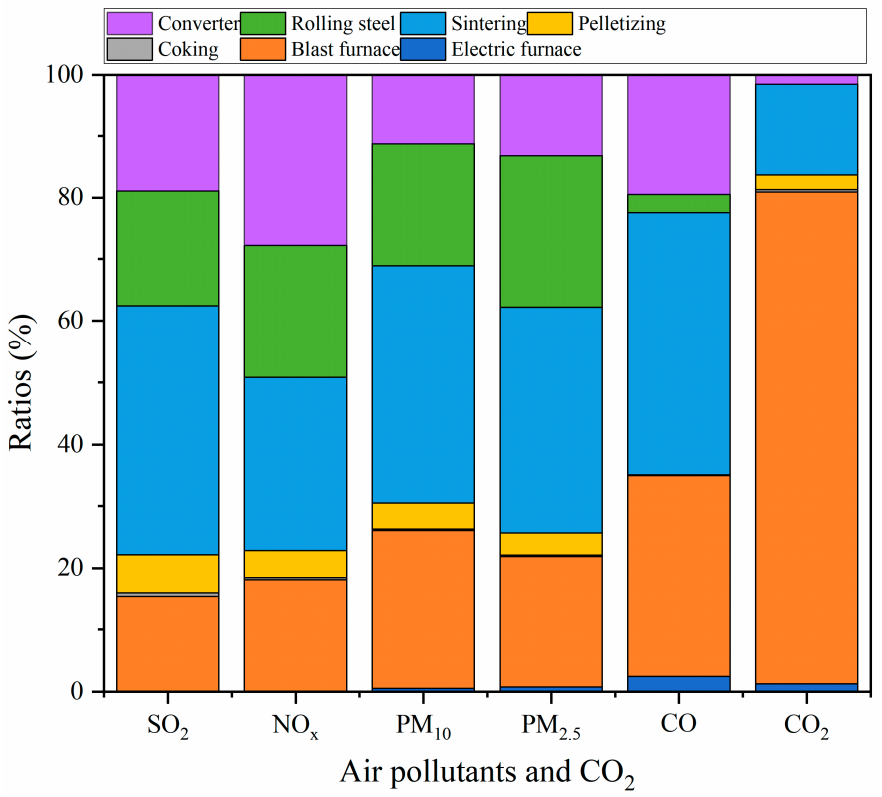


Figure 6. The ratios of pollutant emissions in ISI enterprises in Tangshan in 2019.

The blast furnace process was responsible for 79.63% (174.89 Mt) of the total CO_2 emissions. Blast furnace ironmaking, consuming over 70% of steel production energy, emerged as the most energy-intensive process. Conversely, the electric furnace process contributed only 1.28% of the total CO_2 emissions. Generally, the long processes in iron and steel production, including coking, sintering, pelletizing, and blast furnace, remained the predominant CO_2 emission sources.

To ensure the reliability of the emissions estimates for Tangshan presented in this paper, we compared our results with those from other studies in the same region (Table 1). It can be concluded that prior to the completion of Tangshan's ultra-low emission transformation plan for ISI enterprises at the end of 2018, the air pollutant emissions from Tangshan's ISI enterprises remained high. For instance, Chinese ISI emissions in 2012 were higher, as ultra-low emission standards had not been implemented yet, according to the results from Bo et al. [43] Furthermore, the air pollutant emissions estimated in Tangshan for 2016 were still higher than those in 2019, as reported in this study. This underscores the crucial role of ultra-low emission standards in reducing air pollutant emissions. In contrast to the significant reduction in air pollutant emissions from 2012 to 2019, the carbon emissions from ISI enterprises in Tangshan were similar in 2018 and 2019. Specifically, Yang et al. reported that carbon emissions from Tangshan's ISI were 1.80×10^8 tons, while another study estimated them at 1.90×10^8 tons. The carbon emissions in this study were 2.19×10^8 tons. Based on these comparisons, we conclude that our estimates of both air pollutant and carbon emissions are reliable.

Table 1. The comparison of this paper with other studies in Tangshan (unit: ton).

Reference	Year	SO_2	NO_x	CO	PM_{10}	$PM_{2.5}$	CO_2
Bo et al. [43]	2012	186,892.1	228,576.9			59,986.4	
Yang et al. [9]	2016	223,373.9	254,707.2				
Yang et al. [13]	2018						1.8×10^8
Yang et al. [46]	2018	1.2×10^8	2.5×10^8			0.45×10^8	1.9×10^8
This study	2019	57,500	134,700	5,790,400	35,500	18,000	2.2×10^8

3.2. Air Quality Impacts

Based on the simulated air pollutant emissions (NO_x, SO_2, $PM_{2.5}$, and PM_{10}) in 2019, Figure 7 displays the annual average mass concentration distribution of these four air pollutants emitted by Tangshan's ISI enterprises. Overall, the pollutant concentrations exhibited a "fried egg" pattern: concentrations were higher closer to the emission outlets. Concentrations in the northeast of the city surpassed those in the southwest. The highest pollutant concentrations emitted by Tangshan's ISI enterprises were: NO_x (25.3 $\mu g/m^3$), SO_2 (12.5 $\mu g/m^3$), $PM_{2.5}$ (8.0 $\mu g/m^3$), and PM_{10} (15.0 $\mu g/m^3$). Among these pollutants, NO_x concentrations were the highest due to substantial air pollutant emissions from ISI enterprises. Notably, elevated NO_x concentrations were found in the city center, highlighting the need for enhanced NO_x emission control strategies. Thanks to the success of ultra-low emission transformations in Tangshan's ISI enterprises, $PM_{2.5}$ and PM_{10} concentrations were significantly lower than those of NO_x. A further reduction in PM emissions would contribute to an improved local air quality. The distribution of SO_2 concentration was similar to that of PM and NO_x.

Regarding the contribution of average annual pollutant concentration from ISI enterprise emissions to air monitoring station values in Tangshan, SO_2, NO_x, PM_{10}, and $PM_{2.5}$ contributed 17.43%, 17.05%, 4.94%, and 6.01%, respectively. Additionally, Table 2 presents the average contributions of 32 ISI enterprises to air quality across the country. Generally, the overall average pollutant contribution from each enterprise ranged from 0% to 1.195%. Notably, Enterprise 6 (Hebei Tangyin Iron and Steel Co., Ltd., Tangshan, China) exhibited the highest contributions, with averages of 2.137% for NO_x, 1.633% for SO_2, 0.459% for

PM_{10}, and 0.553% for $PM_{2.5}$. This company's lack of stringent pollution control measures, high output, and proximity to air monitoring stations contributed to its significant impact on air quality. Enterprises 14, 21, 13, 19, and 10 also showed substantial contributions to air quality. These enterprises' emissions disproportionately influenced the air quality of national control sites, emphasizing the need for enhanced control measures to mitigate their impact, including limiting production growth and reducing effects on sensitive areas.

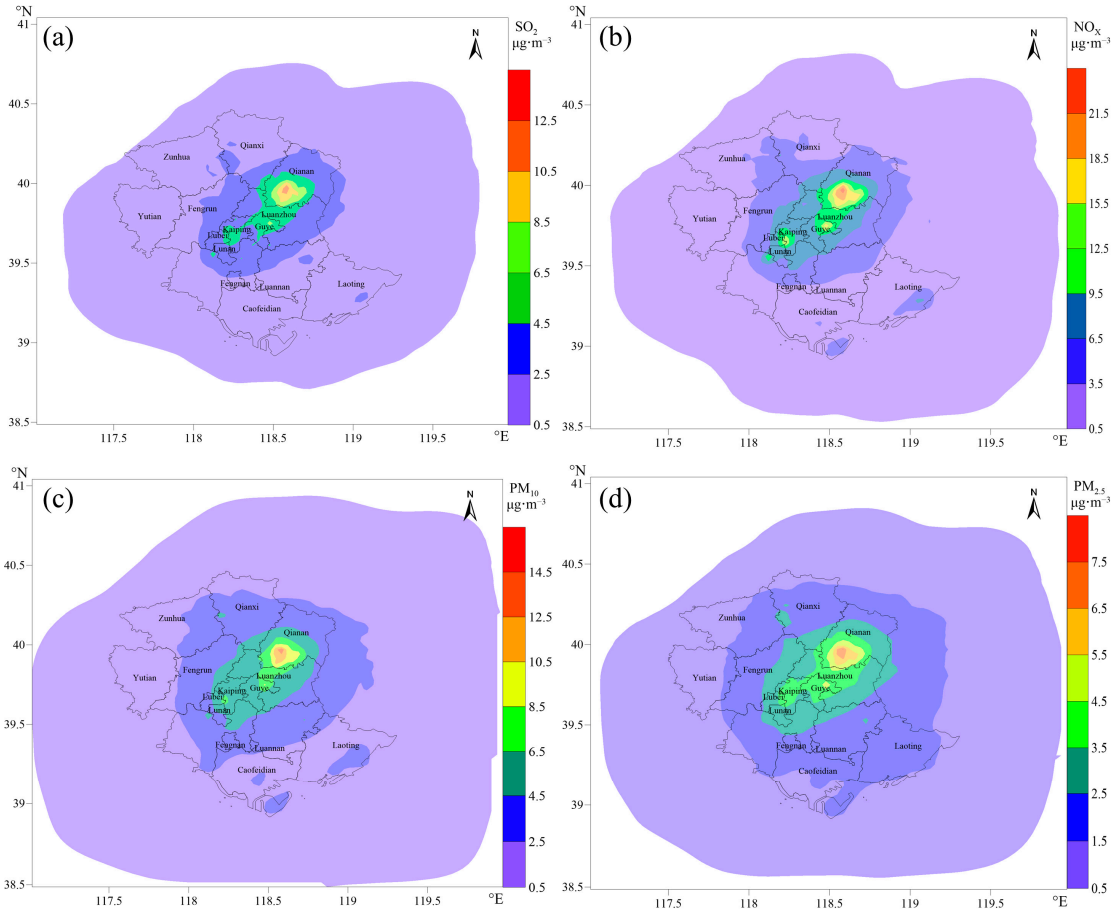


Figure 7. The annual average concentration distribution of SO_2 (**a**), NO_x (**b**), PM_{10} (**c**) and $PM_{2.5}$ (**d**) in Tangshan's ISIs.

Table 2. Contributions to air pollutant concentrations.

Enterprise Number	SO_2 (%)	NO_x (%)	PM_{10} (%)	$PM_{2.5}$ (%)	Average (%)
6	1.632	2.137	0.459	0.552	1.195
14	1.096	0.73	0.282	0.326	0.609
21	0.742	0.645	0.236	0.289	0.478
13	0.531	0.493	0.148	0.205	0.344
19	0.635	0.321	0.177	0.225	0.34
10	0.522	0.352	0.139	0.185	0.3
26	0.377	0.297	0.107	0.129	0.228
1	0.402	0.253	0.104	0.118	0.219
7	0.303	0.225	0.084	0.095	0.177
8	0.253	0.168	0.1	0.113	0.159
15	0.216	0.176	0.063	0.08	0.134
22	0.186	0.154	0.072	0.094	0.127
17	0.188	0.155	0.056	0.072	0.118
12	0.185	0.13	0.067	0.084	0.117
27	0.182	0.1	0.069	0.087	0.11

Table 2. *Cont.*

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3.3. Identification Results of the ACEA Model for ISIs in Tangshan

Based on air pollutant emission and carbon performance grades, as well as contributions to pollutant concentrations, the ACEA model categorized Tangshan's ISI enterprises into 8 categories. These included low carbon (A/B) and low air pollutant emissions (A/B) with low contributions to pollutant concentrations (L-L-L); low carbon (A/B) and high air pollutant (B-/C/D) emission with low contributions to pollutant concentrations (L-H-L); low carbon and high air pollutant emission with high contributions to pollutant concentrations (L-H-H); high carbon (B-/C/D) and high air pollutant (B-/C/D) emission with high contributions to pollutant concentrations (H-H-H), among others. Notably, Grade B- reflected an inadequate SO_2 control in blast furnaces and rolling processes in non-ultra-low emission standard steel companies, leading to lower grades. The differences between grades C and B- mainly centered on NO_x emissions control in blast furnaces and rolling processes. The gap between grades D and C was evident in multiple production processes and pollutants.

There were 8, 4, 3, 6, 5, 1, 3, and 2 ISI enterprises categorized as H-H-H, H-H-L, H-L-H, H-L-L, L-L-L, L-L-H, L-H-H, and L-H-L respectively. Notably, enterprises close to air monitoring stations had at least one grade of H. As the distance from monitoring stations increased, the occurrence of "H" grades decreased in enterprise categories. ISI enterprises labeled as H-H-H constituted 25% of total enterprises, indicating a need for Tangshan's government to focus on air pollutant and carbon emission reduction measures, as well as pollutant-control technologies. For instance, An et al. [47] summarized and compared four main pollution and carbon reduction strategies for the future. The Clean Fuels option integrates these strategies; however, it is not necessarily the optimal choice due to its associated costs. Consequently, this presents a decision-making challenge in identifying diverse technology combinations. The comparison highlights low-carbon technology (LT) as a vital catalyst for future pollution and carbon reduction, substantially reducing carbon dioxide emission costs. Moreover, considering that the air pollutant and carbon emissions were mainly from the processes of fossil fuel combustion (sintering, pelletizing, coking and blast furnace), the relationship between air pollutants and carbon emissions should be emphasized. It was reported that CO_2, used as the fluidizing gas, contributes high amounts of CO_2 and CO, and that a decrease in CO and unburned carbon content corresponds to an increase in NO_x emissions [48,49]. In other words, CO oxidation was inhibited under SO_2, which may have reduced NO emissions. Therefore, Tangshan's ISI enterprises should pay more attention to the chemical reactions associated with fossil fuel combustion to further reduce air pollutant and carbon emissions. For example, the application of more advanced combustion technologies in steel production processes could be beneficial [48]. ISI enterprises labeled as H-H-L accounted for 12.5% of the total, primarily attributed to

their distant proximity from air monitoring stations. These enterprises should prioritize carbon emission reduction through carbon CCUS and emission reduction technologies to further diminish their contribution to air pollutant concentrations. In cases of H-L-H labeling, future efforts should center on enhancing emission reduction strategies to lessen their corresponding impact on air quality. Similarly, H-L-L-labeled ISI enterprises should strengthen their emission reduction technologies to further decrease their contribution to air pollutant concentrations.

L-L-L-labeled ISI enterprises constituted 18.75% of the total, exemplifying Tangshan's effective air pollution and carbon reduction endeavors. Among L-L-L-labeled enterprises, 60% employed short-process techniques, suggesting the significant potential for air quality improvement. Additionally, other L-L-L enterprises situated far from air monitoring stations indicated that relocating ISI operations might enhance local environmental quality. To optimize the role of L-L-L-labeled ISI enterprises in leading air pollution and carbon reduction, the government support should facilitate the establishment of regional integrated demonstration zones. These zones would significantly advance air pollutant and carbon emission reduction and contribute to air quality improvement. Such initiatives position Tangshan as a trailblazer, providing valuable experiences that can be scaled and replicated. In the cases of L-L-H- and L-H-H-labeled ISI enterprises, despite their low air pollutant emissions, their substantial contributions to air pollutant concentrations warrant a comparison of carbon emission control measures. The remaining category, L-H-L, should implement improvements in carbon emission practices, as demonstrated by L-H-H-labeled ISI enterprises.

3.4. Uncertainty Analysis of the ACEA Model

Considering the ACEA model's technical approach, uncertainties mainly resided in pollutant emission inventories and the CALPUFF model. To evaluate the accuracy of the established air pollutant emission inventory for Tangshan's ISI in 2019, we conducted Monte Carlo simulations. These simulations revealed uncertainties in pollutants, as detailed in Table 3. SO_2, NO_x, PM_{10}, $PM_{2.5}$, CO and CO_2 exhibited uncertainties ranging from −4.7% to 4.9%, −4.5% to 4.5%, −3.1% to 3.0%, −4.5% to 4.6%, −4.9% to 4.9% and −5% to 5%, respectively. The uncertainties of CO_2 were larger than those of other air pollutants, which may be attributed to the emission factors of CO_2 in this paper being from IPCC. Generally, the carbon emission factors from IPCC were larger than those reported by other researches. The uncertainties of other air pollutants were lower than those found in previous studies [17,50], indicating the reliability of this emission inventory's results. The model verification indicated that the simulation results were reliable (Section 2.4.2).

Table 3. The results of Monte Carlo simulations.

Pollutant	SO_2	NO_x	PM_{10}	$PM_{2.5}$	CO	CO_2
Uncertainty	−4.7–4.9%	−4.5–4.5%	−3.1–3.0%	−4.5–4.6%	−4.9–4.9%	−5–5%

4. Conclusions

Given the insufficiency of prior research regarding the management of air pollutant emissions, carbon emissions, and their contributions to air pollutant concentrations within the ISI, this study has developed the ACEA model. This model establishes connections between emission performance grades for air pollutants and carbon emissions, alongside grades for contributions to air pollutant concentrations. In Tangshan during 2019, the emissions of SO_2, NO_x, PM_{10}, $PM_{2.5}$, CO and CO_2 amounted to 5.75×10^4 t, 13.47×10^4 t, 3.55×10^4 t, 1.80×10^4 t, 5.79×10^6 t and 219.62 Mt, respectively. The ACEA model's outcomes reveal that the pre-iron making process contributed 47.07%, 32.69%, 42.80%, and 40.34% to the emissions of SO_2, NO_x, PM_{10}, and $PM_{2.5}$. Furthermore, CALPUFF model simulations highlight a distinct "fried egg" distribution in air pollutant concentrations: concentrations were higher closer to the emission outlets. The ACEA model outcomes also

indicate that 25% of ISI enterprises emitted significant air pollutant and carbon emissions, exerting substantial influence on air pollutant concentrations. This model offers concise guidance to enterprises and decision makers to address corresponding air pollutant emission challenges. For the Tangshan case in 2019, our developed ACEA model bridges gaps among air pollutant emissions, carbon emissions, and their contributions to air pollutant concentrations within the ISI. It furnishes decision makers with a scientifically grounded management tool in the realm of air pollution and carbon control. Additionally, the successful implementation in Tangshan stands to enhance environmental management in analogous cities and industries, both domestically and internationally.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14121747/s1, Table S1: Autumn and winter emergency emission reduction performance rating standards of major steel enterprises in Tangshan ($m^3 \cdot t^{-1}$ product;$mg \cdot m^{-3}$); Table S2: Classification emission factors of air pollutants in each process of Tangshan iron and steel enterprises ($g \cdot kg^{-1}$ product); Table S3: Mass percentage of $PM_{2.5}$ in PM_{10} (%); Table S4: CO emission factors for different processes ($kg \cdot t^{-1}$ product); Table S5: CO_2 emission factors for different processes ($t\ CO_2 \cdot t^{-1}$ product); Table S6: CO_2 emission performance grades ($t\ CO_2 \cdot t^{-1}$); Table S7: The results of CALPUFF model verification.

Author Contributions: Conceptualization, J.L., X.B. and R.Z.; Methodology, S.C., Q.Y., W.S., X.B. and R.Z.; Investigation, S.C., J.L., Q.Y. and Z.W.; Writing—original draft, S.C. and J.L.; Writing—review & editing, X.B. and R.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by grants from the National Natural Science Foundation of China (No. 72174125), Fundamental Research Funds for the Central Universities (buctrc202133).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article and supplementary material.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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