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Substantial Emission Reductions from Chinese Iron- and Steelmaking after the Introduction of Ultralow Emission Standards during the Prepandemic and Midpandemic Periods

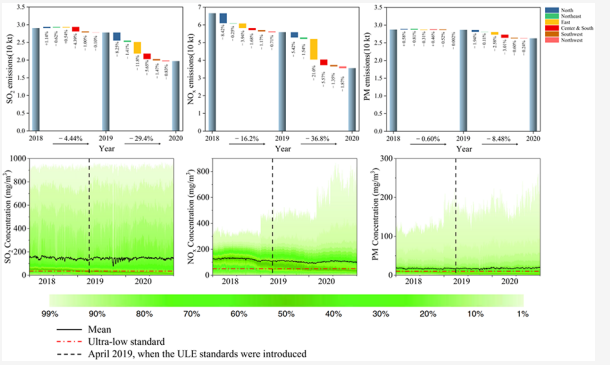
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ABSTRACT: China's iron and steel industry has achieved notable progress in reducing pollution following the implementation of ultralow emission (ULE) standards. However, the extent of pollutant reduction, compliance with ULE standards, and influencing factors, particularly during the prepandemic and midpandemic periods, remain insufficiently explored. In this study, high-resolution, nationwide, process-based, and facility-level emission inventories for China's iron and steel industry for 2018−2020 were developed on the basis of real-time measurements from Continuous Emission Monitoring Systems (CEMS). The emission inventories covered air pollutant emissions from 996 iron and steel enterprises, accounting for 87.98 to 96.43% of China's crude steel production between 2018 and 2020, and encompassed key production processes, including coking, sintering, pelletizing, blast furnaces, basic oxygen furnaces, electric arc furnaces, and steel rolling. Compared to 2018, emissions of SO_2, NO_x, and PM from the iron and steel industry in 2020 decreased by 32.56, 47.02, and 9.05%, respectively, despite a 14.74% increase in production. Furthermore, average hourly concentration compliance rates for SO_2, NO_x, and PM at the sintering machine head, sintering machine tail, and pellet roasting showed significant improvement in 2020. Structural equation modeling identified product output, emission factors, ULE standards, and emission intensity as the key determinants of pollutant emissions. This study highlighted the necessity of strengthening the implementation of ULE standards in regions and fostering regional cooperation for emission reduction.



KEYWORDS: *iron and steel industry, air pollutant emissions, spatiotemporal characteristics, driving factors, ULE standards*

1. INTRODUCTION

China, the world's largest steel producer, has consistently dominated the global market, contributing 45−56% of the global crude steel production from 2010 to 2020.[1,2] As a resource- and energy-intensive industry, the steel sector has been the primary source of key air pollutants, including SO_2, NO_x, and particulate matter (PM), among industrial sectors and 31 manufacturing categories in recent years.[3,4] In 2020, the iron and steel industry was responsible for 16.4, 22.3, and 12.1% of China's total SO_2, NO_x, and PM emissions, respectively.[5] Therefore, examining spatial and temporal variations, driving factors, and policy impacts is essential for formulating more effective environmental management and emission reduction strategies.

In 2012, China's Ministry of Environmental Protection implemented emission standards for major stationary pollution sources, including industrial units, boilers, machinery, and generating facilities, in an effort to reduce air pollutant emissions from the iron and steel industry.[6−10] These standards were revised in 2015, resulting in 60%, 67%, and 40% reductions in the emission limits for PM, SO_2, and NO_x, respectively.[11] In April 2019, the ULE standards further tightened these limits to 35 mg/m^3 for SO_2, 50 mg/m^3 for NO_x, and 10 mg/m^3 for PM.[12] Additionally, CEMS was developed in 2007 to monitor high-emission facilities, covering 63−72% of blast furnaces and 69−91% of steel production facilities in China from 2014 to 2018.[11] Research conducted by Bo et al. demonstrated that, between 2014 and 2018, despite a 14% increase in steel production, PM and SO_2 emissions decreased by 47% and 42%, respectively, whereas NO_x emissions increased by 3%.[11] Since the introduction of the ULE standards in 2019, empirical studies based on real-time measurements from facility-level CEMS remain scarce, limiting insights into emission trends and spatial emission character-

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istics in the iron and steel industry and thereby constraining the development of precise emission reduction strategies. Moreover, the outbreak of the COVID-19 pandemic and the subsequent strict containment measures implemented by the Chinese government—such as city lockdowns and factory shutdowns—have led to substantial declines in energy consumption and pollutant emissions.[13] In response, a growing body of research has quantified the impact of reduced anthropogenic activities during the COVID-19 pandemic on greenhouse gas and air pollutant emissions. Globally, Liu et al.[14] reported an unprecedented 8.8% decline in CO_2 emissions during the first half of 2020, closely linked to national lockdown measures. Focusing on China, Zheng et al.[15] integrated satellite-based NO_2 data with bottom-up data to reveal an 11.5% drop in CO_2 emissions between January and April 2020 compared with the same period in 2019, followed by a rapid rebound to prepandemic levels driven by accelerated industrial recovery in key provinces. Similarly, Liu et al.[16] found a 48% reduction in tropospheric NO_2 concentrations following the 2020 Lunar New Year, which was significantly greater than in previous years, and attributed this to both early outbreak reporting and provincial lockdowns. Wang et al.[17] further estimated an 18.7% year-over-year reduction in China's energy-related CO_2 emissions during the first quarter of 2020, with the transport, industrial, and construction sectors contributing to the decline. However, they cautioned that postpandemic infrastructure stimulus may accelerate future emissions. However, the impact of the COVID-19 pandemic on emissions from the iron and steel industry and the implementation of ULE standards remains insufficiently studied and inadequately characterized. This research gap presents an opportunity to explore the adaptability and effectiveness of these standards under varying environmental and socioeconomic conditions, thereby guiding the development of data-driven emission reduction strategies.

Against this backdrop, efforts have been made to systematically characterize and assess the impacts of emissions from China's iron and steel industry, especially focusing on key production processes and the spatial and temporal dynamics of pollutant emissions. For instance, Wu et al.[2] conducted a comprehensive emission analysis of 811 iron and steel enterprises across China in 2020, highlighting that sintering and blast furnace processes are the dominant sources of air pollutants and CO_2 emissions, respectively, and quantitatively linked these emissions to $PM_{2.5}$ exposure and health burdens, thereby providing critical insights for emission control and structural adjustments in the steel sector. Yang et al.[18] developed a unit-based multipollutant emission inventory for China's iron and steel industry from 2012 to 2021, revealing that ultralow emission retrofits have significantly altered spatiotemporal emission patterns. Additionally, existing evaluations of the ULE standards in the iron and steel industries have primarily focused on specific regions or key processes. Notable examples include Wang et al., who evaluated air pollutant emissions from sintering processes in China's Fenwei Plain based on CEMS data from 2014 to 2017, revealing significant reductions in SO_2 and PM concentrations due to stricter emission control policies. In contrast, persistently high NO_x levels highlighted the urgent need for advanced NO_x abatement technologies.[19] Similarly, Liu et al.[20] conducted a comprehensive assessment of air pollutant emissions from sintering processes in China's iron and steel industry in 2017 using CEMS data, revealing high compliance with standard limits but low adherence to ULE standards and highlighting significant reduction potentials for NO_x, SO_2, and PM. The studies, as mentioned earlier, have several limitations. First, in terms of systematically assessing the emission characteristics and impacts of the iron and steel industry, most studies focus on total emissions and an in-depth analysis of the evolution of the emission factors of key processes is lacking. Second, while research on the effectiveness of ULE standards has focused mainly on specific regions or critical processes, there is a lack of national-level empirical studies using real-time measurements from facility-level CEMS. This gap is particularly noticeable when considering the dynamic changes in emissions under the disruptive impact of the COVID-19 pandemic, highlighting the need for further investigation into the practical effectiveness of ULE standards across China's iron and steel sector. Therefore, assessing the spatial and temporal dynamics of pollutant emissions, tracking changes in emission factors across key production processes, and evaluating the effectiveness of ULE standard implementation during the prepandemic and midpandemic periods in the iron and steel industry are essential for advancing low-carbon, green development, enhancing air quality, and mitigating climate change.

Several studies have extensively investigated mitigation pathways and driving factors for air pollutants in the iron and steel industry. For instance, Li et al.[21] examined strategies for low-carbon transformation in China's iron and steel industry to achieve carbon neutrality, emphasizing adjustments in the energy structure and other critical factors. Zhu et al.[22] developed end-of-pipe technologies, including low-nitrogen combustion, multipollutant synergistic control, selective noncatalytic reduction (SNCR), and ultralow emission bag filters, which efficiently removed pollutants such as SO_2, NO_x, and $PM_{2.5}$, enhancing environmental performance and supporting the green development of the sector. Fan et al.[23] focused on flue gas CO treatment methods in the steel industry, particularly evaluating catalyst modification techniques and their potential in flue gas treatment. In the area of energy-saving technologies, He et al.[24] proposed a list of energy efficiency technologies tailored for the steel sector, leveraging global case studies and cost analyses to improve energy efficiency in steel enterprises. Cheng et al.[25] explored renewable alternative fuels, modifications of solid fuels and reactive gases, and process control technologies, aiming to enhance energy efficiency in the sintering process, minimize environmental impacts, and promote energy-saving practices. Additional studies have combined various emission reduction measures to evaluate the cost-effectiveness and potential of energy-efficient and cobenefit technologies, offering pathways for selecting cost-effective and efficient emission reduction strategies in China's steel industry.[26,27] The literature has focused mainly on the application of specific emission reduction technologies or the resolution of localized issues with limited in-depth analysis of the iron and steel industry as an interconnected system. This narrow focus limits a comprehensive understanding of emission-driving factors and reduction pathways. In particular, there is a notable gap in research regarding the interaction of multiple factors, such as product output, emission factors, national environmental policies, and emission intensity.[28,29] Therefore, this study aims to identify and reveal the key driving factors of emissions in the iron and steel industry through an analysis based on real-time measurements from the CEMS and to explore

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comprehensive and feasible mitigation pathways, thereby addressing this research gap.

In this study, a comprehensive assessment of SO_2, NO_x, and PM emissions from major processes in the iron and steel industry was conducted using real-time measurements from the CEMS spanning 2018−2020. To our knowledge, this is the first comprehensive national-level evaluation of pollutant reduction, compliance with the ULE standards, and emission-driving factors during the prepandemic and mid-pandemic periods, utilizing real-time measurements from the CEMS. This study aimed to (1) analyze the temporal and spatial variation in emissions, (2) evaluate the evolution of emission factors in key processes in mainland China, (3) assess the pandemic's impact on pollutant emissions in the iron and steel industry, (4) identify key factors driving emissions, and (5) propose future recommendations on the basis of research findings.

2. MATERIALS AND METHODS

2.1. Estimation of Pollutant Emission. High-resolution, nationwide, process-based, and facility-level emission inventories for China's iron and steel industry in 2018 based on real-time measurements from the CEMS obtained from our previous research.[11] The emission inventories for China's iron and steel industry in 2019 and 2020 were developed for 996 enterprises, covering 28 provinces, autonomous regions, and municipalities across mainland China (excluding Beijing, Hainan, Tibet, Taiwan, Hong Kong, and Macau). These inventories encompass major production processes, including coking, sintering, pelletizing, blast furnaces, basic oxygen furnaces, electric arc furnaces, and steel rolling, and were compiled by integrating two comprehensive databases of Chinese iron- and steelmaking plants. One database contains source-level measurements of smokestack SO_2, NO_x, and PM concentrations (hourly), which are monitored and recorded by China's CEMS network, with the original data not publicly available. The other data set was constructed using multiple data sources, including Emission Permit Implementation Reports,[30] the National Bureau of Statistics (https://data.stats.gov.cn/), industrial yearbooks,[31,32] and onsite surveys. This database provides detailed information about activity levels (including production, resource inputs, and energy consumption), facility types, emission sources, associated production processes, emission control technologies, and geographic locations. In total, the emission inventories for China's iron and steel industry from 2018 to 2020, which are based on activity data covering 87.98−96.43% of the national crude steel output, can be considered sufficiently representative for national-scale assessments of air pollutant emissions and for evaluating the effectiveness of pollution control policies within the iron and steel sector.

As outlined in our previous research,[11] in this study, the emission factors and emissions of SO_2, NO_x, and PM were estimated via real-time measurements from the CEMS, thereby avoiding reliance on many indirect parameters and associated assumptions.[33,34] To ensure the quality and accuracy of the real-time measurements from the CEMS, comprehensive preprocessing was performed with strict adherence to the official regulations and guidelines. Abnormal values, particularly those that were significantly high and exceeded normal data ranges, were addressed following the *Specifications for Continuous Emissions Monitoring of SO_2, NO_x, and Particulate Matter in the Flue Gas Emitted from Stationary Sources (HJ 75−2017)*, with similar treatment applied to null values.[34] For null or zero values within a 24-h period, missing data were replaced with the valid arithmetic mean of the CEMS data from the time points immediately before and after the occurrence. Moreover, for consecutive nulls or zeros persisting beyond 24 h, which typically oscillate near their historical levels preceding the event, the monthly averages were applied for substitution in accordance with HJ 75−2017. Additionally, the study calculated the air pollutant emission-concentration adjusted to the reference oxygen content,[35] with emission factors estimated based on our prior research.[11]

Based on the quality-assured real-time measurements from CEMS, the pollutant concentrations for different manufacturing processes were obtained (eq 1). By a combination of these concentrations with the corresponding theoretical flue gas volumes for each process, annual average emission factors were calculated at the enterprise level (eq 2) and the regional level (eq 3). By incorporating activity level data and other relevant parameters for each process, a bottom-up approach was applied to estimate pollutant emissions from the iron and steel industry for different enterprises and regions (eq 4). In provinces where CEMS data were unavailable, national average pollutant emission factors were applied as substitutes to ensure consistency and completeness in the emission estimates. The specific calculation formulas are presented below.

$$C_{\mathrm{AVG},s,r,i,n} = \sum_{h} C_{s,r,i,m,h} / \sum_{m} \mathrm{Oph}_{m} \tag{1}$$

$$F_{s,r,i,m} = C_{\mathrm{AVG},s,r,i,m} V_{r,i} \times 10^{-6} \tag{2}$$

$$F_{s,r,i,n} = \sum_{m} F_{s,r,i,m} / N_{s,r,i,n} \tag{3}$$

$$E = \sum_{n} \sum_{p} A_{n,p,i} F_{s,r,i,n} \times 10^{-3} \tag{4}$$

where C_{AVG} represents the average concentration of the pollutant (mg/m^3); *Oph* denotes the number of valid monitoring hours included in the analysis; *F* denotes the emission factor of different pollutants (g/kg of product); *V* denotes the theoretical flue gas volume (m^3/t of product); *N* refers to the number of samples; *E* represents the total annual emissions of the pollutant (t/a); *A* represents the annual product output (t/a); *s* represents different pollutants; *r* denotes different emission sources; *i* refers to different processes; *m* represents different outlets; *h* represents the *h-th* operational hour; *n* denotes different regions; and *p* refers to different iron and steel enterprises.

2.2. Evaluation of Compliance with Emission Standards. As outlined in our previous research,[11] the average hourly concentration compliance rates were used to evaluate adherence to the emission limits from *Opinions on Advancing the Implementation of Ultralow Emissions in the Iron and Steel Industry* (https://www.gov.cn/zhengce/zhengceku/2019−10/10/content_5438149.htm).[12] The average hourly concentration compliance rate is defined as the percentage of observations meeting the emission limits of the emission standards (i.e., smokestack concentrations at or below the specified limits) relative to the total valid observations. A compliance rate of 100% indicates full compliance, whereas rates ranging from 0 to 100% reflect different degrees of noncompliance. The compliance rate was calculated according to eq 5 to assess the compliance status of individual emission

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outlets. The hourly compliance rate for each province was then derived as the weighted average of the hourly compliance rates across all emission outlets within that province.

$$M_j = \frac{\sum t_{i,j}}{\sum T_i} \tag{5}$$

where M_j represents the hourly compliance rate of pollutant j under different emission limits (the standard limits of air pollutants are provided in Supplementary Table 1); $t_{i,j}$ represents the number of compliant hours for pollutant j at outlet i under different emission limits; and T_i represents the total operating hours of outlet i.

2.3. Empirical Models of the Relationship between Pollutant Emissions and Concentration Data. In this study, an empirical model was constructed using SPSS to analyze the correlation between pollutant concentrations from the ChinaHighAirPollutants (CHAP) data set and pollutant emissions from the iron and steel industry during the prepandemic (2018−2019) and midpandemic (2020) periods. Specifically, 2018 was defined as the baseline year before widespread implementation of the ULE standards, while 2019 represented the initial stage of large-scale implementation of the ULE standards. The period from 2018 to 2019 was classified as the prepandemic period. In contrast, 2020, marked by substantial disruptions in industrial activity, energy consumption, and emissions due to the COVID-19 pandemic, was defined as the midpandemic phase, reflecting an "abnormal economic context." To accurately capture variations in pollutant concentrations across these periods, this study employed the CHAP data set to analyze air pollutant concentrations at various iron and steel enterprises.

The CHAP data set integrates multisource satellite remote sensing data with artificial intelligence techniques to characterize the spatiotemporal distribution of air pollution, providing daily, monthly, and yearly estimates of near-surface air pollutant emissions at spatial resolutions of 1 km and 10 km across China.[36] The CHAP data set has demonstrated high accuracy and has been widely applied in various studies.[37,38] In this study, annual concentration data of air pollutants (SO_2, NO_2, and PM) at different iron and steel enterprises with a spatial resolution of 1 km × 1 km from 2018 to 2020 were obtained based on the geographic locations of iron and steel enterprises, using a geographic information system (GIS). The pollutant emissions for each iron and steel enterprise were derived from the high-resolution, nationwide, process-based, and facility-level emission inventories developed in this study for China's iron and steel industry during 2018−2020, based on real-time measurements from the CEMS. The empirical model is expressed in eq 6

$$\ln y = k \ln x + b \tag{6}$$

where x represents the emission level of air pollutants (SO_2, NO_x, and PM) and where y is the concentration of air pollutants obtained from the CHAP data set. The coefficient k is the slope that represents the elasticity or sensitivity of pollutant concentrations to changes in emission levels. The coefficient b is the intercept representing the baseline concentration level when pollutant emissions exert no additional influence on pollutant concentrations.

2.4. Structural Equation Modeling (SEM) Analysis. To identify the factors influencing pollutant emissions in the iron and steel industry, SEM analysis was conducted using R. This model incorporates multiple latent and observed variables to elucidate the direct and indirect impacts of various factors on emissions in the iron and steel industry. In this study, pollutant emissions were defined as the combined total emissions of SO_2, NO_x, and PM across the provinces from 2018 to 2020. From 2018 to 2020, the emission factors of pollutants across different provinces were associated with key processes such as sintering machine heads and tails, pelletizing roasting, coke oven stacks, blast furnace iron tapping areas, hot blast stoves, secondary basic oxygen furnaces, electric arc furnaces, and steel rolling. Product output was quantified on the basis of the total crude steel production in each province from 2018 to 2020. The emission intensity for each province from 2018 to 2020 was calculated as the ratio of total emissions of SO_2, NO_x, and PM to crude steel production. Additionally, the study systematically evaluated the emission reduction effects resulting from the implementation of the ULE standards. Pollution emissions in 2018 were considered to be the baseline scenario. Based on this, the baseline emissions for 2019 and 2020 were estimated by proportionally adjusting the 2018 emissions according to the provincial crude steel production growth rates in those years. This approach assumed that in the absence of ULE standard implementation, the pollutant emission intensity would have remained similar to that of 2018 and would have fluctuated solely in response to changes in crude steel production. The emission reduction effect of the ULE standards was quantified as the difference between actual emissions and baseline emissions for each province and year.

In addition, several model fit indicators were used to assess the goodness of fit of the constructed SEM. Among them, the chi-square/degrees of freedom (χ^2/df) was used as a measure of model parsimony, indicating how well the model fit the data using the fewest possible parameters.[39] The P value was used to test whether the difference between the model and the data was statistically significant, with the null hypothesis being that "the model fits well, meaning there is no significant difference between the sample covariance matrix and the model's estimated covariance matrix." A large P value suggested that the null hypothesis could not be rejected, indicating a good model fit.[40] The goodness-of-fit index (GFI) is an absolute fit index that compares the observed covariance matrix to the model-implied covariance matrix.[41] The comparative fit index (CFI) is an incremental fit index that compares the fit of the hypothesized model to that of an independent model while adjusting for sample size and non-normality.[42] The root-mean-square error of approximation (RMSEA) is an absolute fit index that measures the discrepancy between the model and the population covariance matrix per degree of freedom.[43]

2.5. Uncertainty Analysis. Emission factors and activity levels often exhibit variability during inventory preparation, leading to uncertainties in the emission estimates. The uncertainties for the years 2018−2020 were quantitatively assessed using Monte Carlo simulations performed in R. Probability distributions were established for emission concentrations, flue gas volumes, and operational activity levels based on prior studies.[11] The Monte Carlo simulations, utilizing these probability distributions, were repeated 10,000 times to determine the uncertainty ranges of the estimates. It was assumed that process-specific production outputs at the plant level followed a normal distribution, with the coefficient of variation set at 5%, based on the ratio of the standard deviation to the mean, as reported in previous studies.[11] For the emission inventories spanning 2018−2020, 10,000 Monte

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Carlo simulations were conducted to estimate the 95% confidence intervals for SO_2, NO_x, and PM emissions during this period.[44−46]

3. RESULTS

3.1. Mitigation Effects of ULE Standards. The impact of the ULE standards was evaluated by examining the time-varying emission factors and overall emissions of SO_2, NO_x, and PM from Chinese iron- and steelmaking activities between 2018 and 2020, encompassing the prepandemic period (2018−2019) and the midpandemic period (2020). Although Chinese iron and steel production increased by 14.74% from 2018 to 2020, the positive effects of this increase on emissions were entirely offset by reductions in the emission factors. Consequently, total emissions exhibited a downward trend: SO_2 emissions declined by 32.56% (from 0.29 Mt in 2018 to 0.20 Mt in 2020), NO_x emissions decreased by 47.02% (from 0.67 Mt to 0.35 Mt), and PM emissions decreased by 9.05% (from 0.29 Mt to 0.26 Mt). Compared to estimates from other studies, the values of SO_2, NO_x, and PM based on real-time measurements from CEMS in this study are significantly lower (46.94−77.27%) than those reported earlier, as detailed in Table 1. The main reasons are as follows: Wu et al.'s study involved emission calculations that included both organized and unorganized emissions, whereas this study is based solely on process-based calculations. The differences can be attributed to variations in the scopes of investigations.[2] Compared with our results, the noticeably higher estimates in MEIC v1.4 can be largely attributed to the elevated emission factors employed in that inventory.[47] MEE reported SO_2, NO_x, and TSP emissions from the ferrous metal smelting and rolling processing industry.[48]

In contrast, the PM considered in this study is specifically confined to emissions originating from the primary manufacturing processes of the iron and steel industry, with unorganized emissions excluded from the scope of the assessment.

The spatial distribution analysis of SO_2, NO_x, and PM emissions from China's iron and steel industry revealed significant regional contributions to the nationwide reduction in pollutants from 2018 to 2020, with Figure 1 illustrating the absolute emission reductions across different regions over the years. Across all geographical regions of China (as defined in Supplementary Table 2), emissions from iron- and steelmaking activities have declined substantially, with the eastern region accounting for the largest share of the overall reduction in pollutant emissions: 40.55%, 64.06%, and 9.65% for SO_2, NO_x, and PM, respectively. This region was closely followed by the central-southern region, which accounted for reductions of 48.49%, 42.19%, and 15.89% in the same pollutants, and the southwestern region, which accounted for 32.82%, 36.49%, and 15.67% reductions in the same pollutants. From 2018 to 2020, the eastern region, the central-southern region, and the southwestern region collectively contributed the largest percentages of crude steel production (accounting for an average of 51.09% across the years) and were responsible for 51.09, 54.09, and 52.33% of the national total emissions of SO_2, NO_x, and PM, respectively, over the three years. Furthermore, this study further analyzed the regional differences in pollutant contribution shares, which are likely closely related to the distribution of the steel production capacity and the structure of the production processes. This study compiled the total emissions and shares of major air pollutants across six key regions in China from 2018 to 2020 (Supplementary Table 3). The results revealed that the northern and eastern regions consistently contributed the most to emissions. This spatial distribution pattern was largely influenced by the distribution of the production capacity and the structure of the production processes. Taking the northern region as an example, it is one

Table 1. Comparison of the Variations in the Emissions of Major Pollutants in the Iron and Steel Industry in China from 2018 to 2020 in Different Emission Inventories

	total emission (Mt)			
pollutant	2018	2019	2020	reference
SO_2	0.29	0.28	0.20	this study
			0.51	(Wu et al.)[2]
	0.99	0.90	0.88	(MEIC v 1.4)[47]
	0.73	0.64	0.42	(Ministry of Ecology and Environment)[48]
NO_x	0.67	0.56	0.35	this study
			0.97	(Wu et al.)[2]
	1.83	1.74	1.50	(MEIC v 1.4)[47]
	1.35	1.15	0.93	(Ministry of Ecology and Environment)[48]
PM	0.29	0.29	0.26	this study
				(Wu et al.)[2]
	1.09	1.07	1.05	(MEIC v 1.4)[47]
	1.17	1.00	0.49	(Ministry of Ecology and Environment)[48]

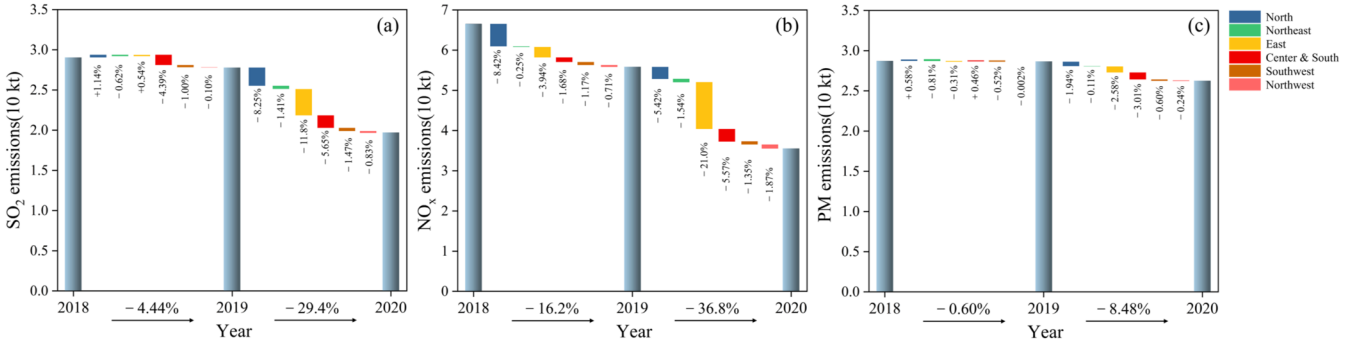


Figure 1. Absolute SO_2, NO_x, and PM emission reductions classified by region from 2018 (a), 2019 (b), and 2020 (c). The blue-gray bars represent the estimated yearly emissions, whereas the bright-colored bars indicate the emission reductions for the corresponding regions. The absolute reductions in emissions over the years are displayed on the *x*-axis.

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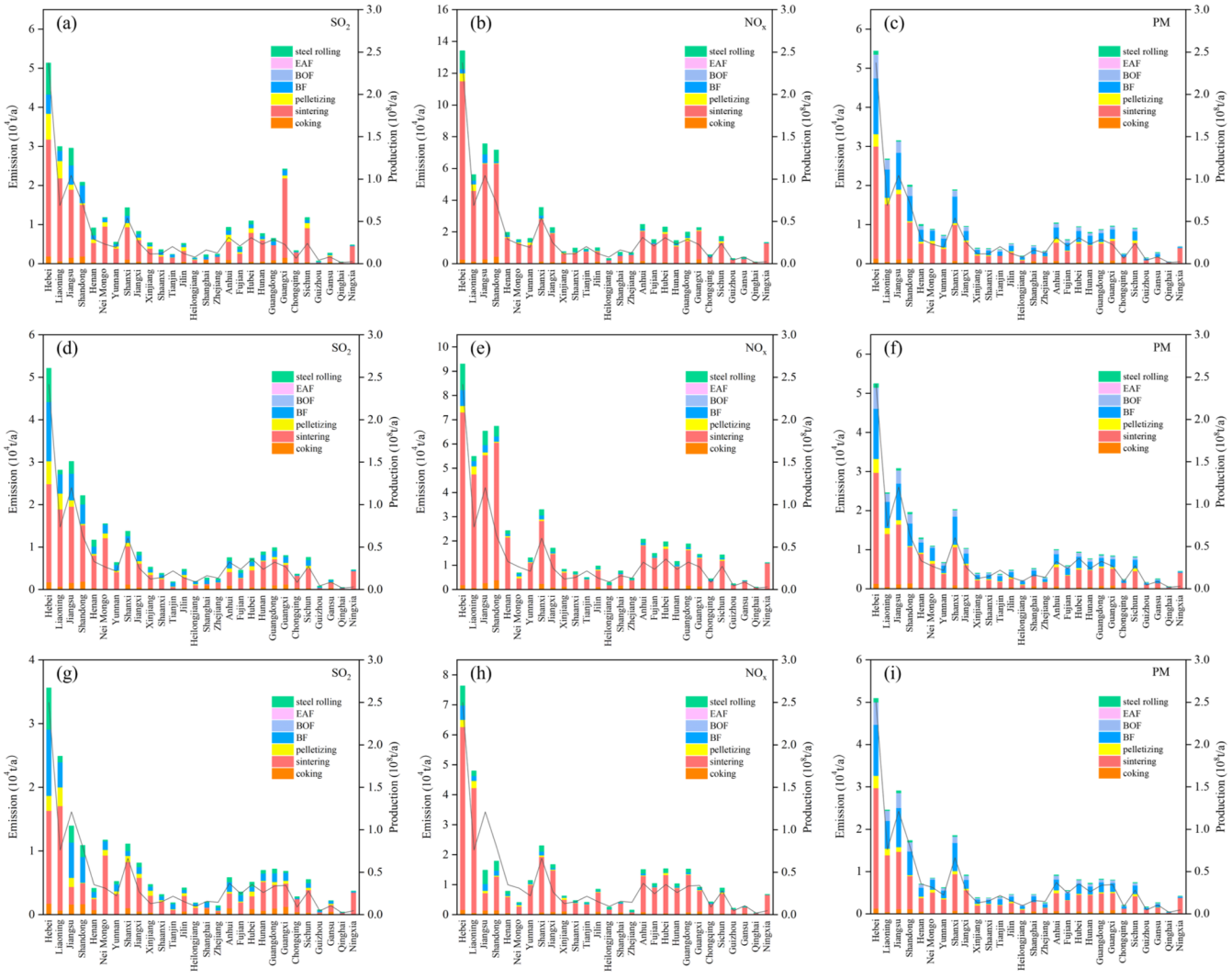


Figure 2. Provincial production of crude steel and emissions of SO_2, NO_x, and PM from the iron and steel industry in 2018 (a–c), 2019 (d–f), and 2020 (g–i).

of the most densely concentrated areas of steel production in China and has the largest production capacity. The region hosts a vast blast furnace-basic oxygen furnace (BF-BOF) long-process steelmaking system, as well as a substantial electric arc furnace (EAF) steelmaking capacity.[49] Its production capacity accounts for more than one-third of the national total (Supplementary Table 4), making it a major contributor to pollutant emissions. In contrast, the northeastern, southwestern, and northwestern regions lagged behind in the development of EAF steelmaking due to constraints such as relatively weak industrial foundations, limited electricity resource guarantees, and underdeveloped scrap steel recycling systems.[50] Furthermore, some of these regions still rely on resource-based production models, where long-process steelmaking supported by local coal and iron ore is more economically feasible, thereby restricting the rapid expansion of the EAF processes. Although the production capacity in these regions was relatively low, the pollutant emission intensity remained high (Supplementary Figure 1). These findings highlighted that the differences in production process structures and capacity distributions across regions played a key role in determining both the contribution shares of pollutants and each region's potential for emission reduction.

At the provincial level, regions with high crude steel outputs, such as Hebei, Jiangsu, Shandong, and Liaoning, consistently contributed significantly to major air pollutant emissions from 2018 to 2020, with their combined crude steel output accounting for about 50% of the national total. Among them, Hebei ranked first in terms of emissions across all major pollutants and years (Supplementary Table 5). For example, the emission of SO_2 in Hebei was 51.40 kt in 2018 (accounting for 17.69% of the national total), and although this value decreased to 35.60 kt by 2020, it remained the highest among all provinces (18.19%). In terms of NO_x, Hebei also led the nation, with emissions declining from 134.00 kt in 2018 (a 20.13% decrease) to 76.34 kt in 2020 (a 21.64% decrease). Similarly, PM emissions in Hebei consistently topped the national rankings, recorded at 54.40 kt (18.94%) in 2018, 52.48 kt (18.38%) in 2019, and 50.89 kt (19.48%) in 2020, reflecting a gradual decline in absolute emissions but a persistently high proportion of the national total. Jiangsu and Shandong also made significant contributions to NO_x and PM emissions, whereas Liaoning ranked among the top emitters for both SO_2 and PM. Despite the overall downward trend in total emissions, the spatial distribution pattern of pollutant contributions remained relatively stable, underscoring the

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long-term influence of regional differences in steel production capacity and process structures on emission levels (Supplementary Figure 2). This was primarily because these regions constitute the core areas of China's steel industry layout, having long borne the majority of the country's steel production. They host many major state-owned and private steel enterprises, which form heavy industrial clusters centered on steel production. The high-density industrial layout resulted in greater energy consumption and raw material input, thereby leading to higher-intensity emissions of air pollutants. In addition, variations in manufacturing processes and the stringency of pollution control measures across provinces further influence the regional contribution of iron and steel to air pollutant emissions. For example, Hebei Province, under substantial pressure, demonstrated the greatest effort in reducing emissions. Despite contributing 23.46% of China's crude steel production in 2020, its SO_2, NO_x, and PM emissions accounted for 18.19%, 21.64%, and 19.48% of the national totals, respectively. These findings align with those of previous studies, such as those by Wu et al.,[2] and can be largely attributed to the implementation of ULE standards and stringent regional policies (Supplementary Table 6).[11,12]

From the perspective of manufacturing processes, long-process enterprises have continued to dominate China's iron and steel industry over the years, with coking, sintering, pelletizing, and blast furnace processes being the major contributors to air pollutant emissions. Similarly, the study by Wu et al.[2] demonstrated that manufacturers with high emissions generally adopt the BF-BOF route, which encompasses sintering, pelletizing, blast furnace, and basic oxygen furnace processes. Among these, the sintering process emerged as the predominant source of emissions, consistently contributing the highest share of SO_2, NO_x, and PM (Figure 2). In 2018, the sintering process accounted for 188.20 kt of SO_2 (64.84%), 524.00 kt of NO_x (78.72%), and 150.00 kt of PM (52.21%), underscoring its critical role in overall emissions. This trend continued in 2019, with the sintering process emitting 162.80 kt of SO_2 (58.70%), 450.00 kt of NO_x (80.64%), and 152.80 kt of PM (53.51%). By 2020, although emissions had decreased, the sintering process remained the dominant contributor, accounting for 102.00 kt of SO_2 (52.13%), 275.60 kt of NO_x (78.14%), and 136.00 kt of PM (52.06%). Over the period from 2018 to 2020, the sintering process consistently contributed more than 50% of the total emissions of all three pollutants, making it the primary source of emissions in the iron and steel industry. To address this, stronger measures are needed to control emissions from iron-making processes. Efforts should focus on accelerating the transition of long-process enterprises to short-process enterprises and promoting the adoption of the EAF route, which can significantly reduce emissions at the source.[51] Compared with the long-process steel production model, which relies on the BF-BOF route, the short-process route primarily depends on the EAF route for scrap-based steelmaking. This approach not only significantly reduced energy intensity and greenhouse gas emissions but also curtailed the release of pollutants such as SO_2, NO_x, and PM at the source.[52−54] By intensifying the promotion and policy support for the EAF route, it was expected that a fundamental transformation in steel production methods could be achieved, thereby facilitating synergistic reductions in pollution and carbon emissions and contributing to the high-quality development of China's iron and steel industry and the realization of its dual carbon goals.[55]

Supplementary Figure 3 illustrates the daily distributions of the stack emission concentrations of SO_2, NO_x, and PM from Chinese iron and steel enterprises. Overall,

the daily average concentrations at major emission outlets across various processes in the iron and steel industry generally decreased from 2018 to 2020. With respect to emission factors across different manufacturing processes, from 2018 to 2020, the emission factors for SO_2, NO_x, and PM across key processes—including sintering machine heads, sintering machine tails, pellet roasting, coke oven stacks, blast furnace iron tapping areas, blast furnace hot blast stoves, secondary basic oxygen furnace off-gas, electric arc furnaces, and steel rolling—declined by −41.02−40.22%, 36.80−57.82%, and 1.59−76.44%, respectively. National average emission factors were used as proxies for provinces without real-time measurements from the CEMS. Processes such as sintering machine heads and tails, pellet roasting, coke oven stacks, and blast furnaces presented the highest emission factors for SO_2, NO_x, and PM, underscoring their substantial contributions to overall emissions (Supplementary Figure 4). Therefore, optimizing production processes, strengthening end-of-pipe control technologies, and adjusting fuel structures are promising approaches to further reduce emissions from these key stages. The spatial heterogeneity in the emission reduction potential across regions was influenced primarily by variations in emission standard enforcement, energy structure composition, and the adoption level of end-of-pipe control technologies.[56] The dual driving forces of fuel structure adjustments and advancements in end-of-pipe control technologies were pivotal in achieving these reductions. Provinces have gradually optimized energy structures by phasing out high-pollution fuels, and promoting clean, low-carbon alternatives, and implementing targeted measures to reduce emissions in the iron and steel industry. For example, in Shandong, high-efficiency desulfurization was applied to blast furnace gas and coke oven gas, whereas low-nitrogen combustion technology was introduced for blast furnace hot stoves and steel rolling heat treatment furnaces. Hebei replaced coal, petroleum coke, residual oil, and heavy oil in heating furnaces, heat treatment furnaces, and drying kilns with cleaner energy sources such as factory waste heat and power plant heat. Jiangsu upgraded its desulfurization systems for blast furnace gas and coke oven gas and replaced coal-fired hot blast stoves and boilers with cleaner options, including waste heat recovery or district heating from power plants (Supplementary Table 7). All three provinces emphasized technological innovation and end-of-pipe control measures to facilitate transformation in the iron and steel industry. Specific actions included adopting advanced dust collection technologies such as wet electrostatic precipitators and baghouse filters, enhancing the efficiency of flue gas desulfurization and denitrification systems, and promoting green and intelligent manufacturing processes (Supplementary Table 8). These strategies contributed to a steady decline in emission factors, leading to significant reductions in overall emissions.

Reductions in pollutant emission factors corresponded with parallel declines in emission intensities within China's iron and steel industry from 2018 to 2020. This study further validated this relationship by analyzing dynamic changes in pollutant emission intensities across provinces, where the emission intensity was defined as the total emissions of SO_2, NO_x, and PM per unit of crude steel production. The analysis revealed an overall reduction in emission intensity across industries,

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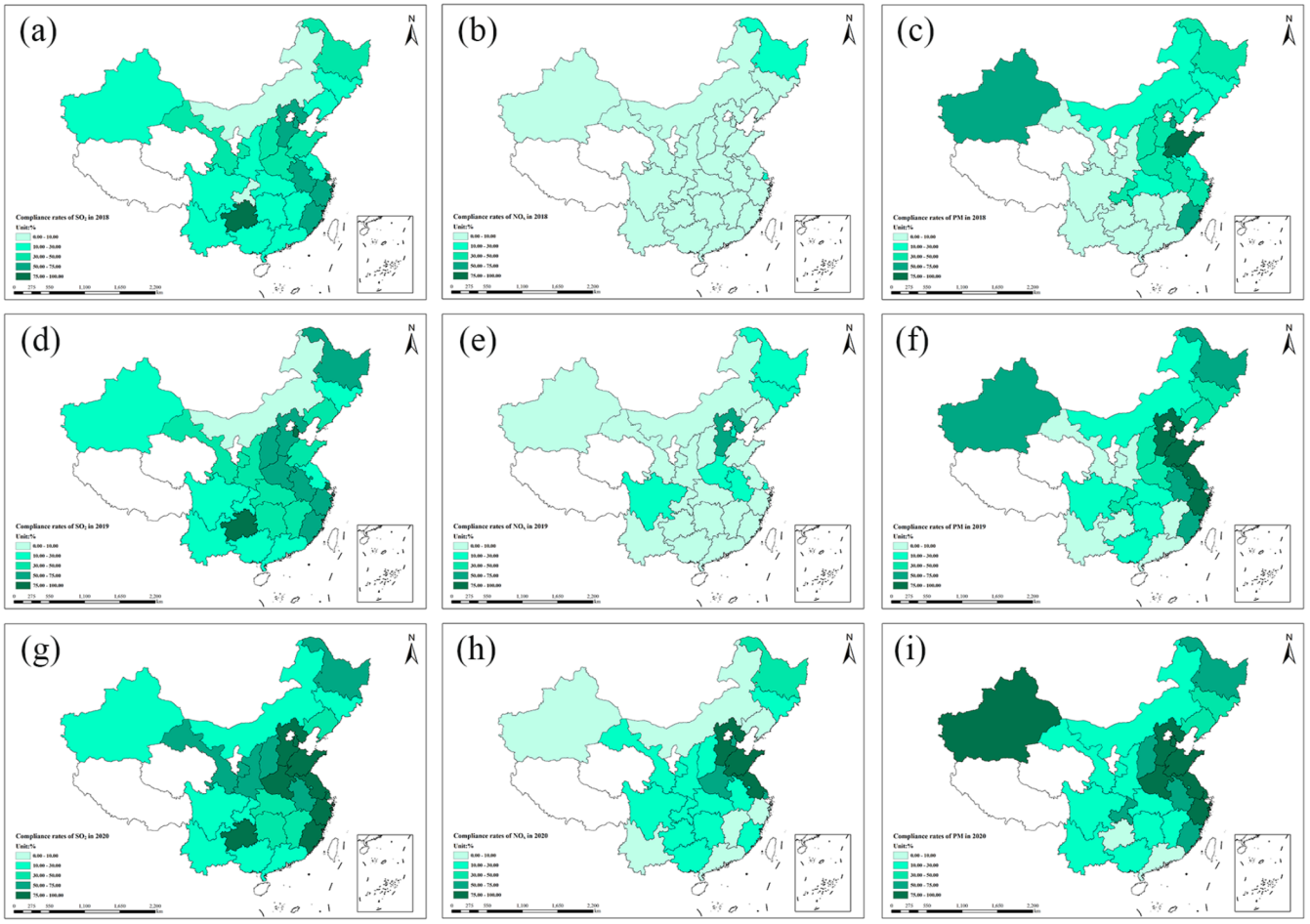


Figure 3. Average hourly concentration compliance rates of SO_2, NO_x, and PM emission concentrations from the sintering machine head in 2018 (a–c), 2019 (d–f), and 2020 (g–i) under the ULE standards.

with significant pressures observed in less developed regions, including northeastern, northwestern, and southwestern provinces such as Ningxia, Liaoning, Guangxi, Jiangxi, Jilin, Chongqing, and Xinjiang (Supplementary Figure 1). A comparison of changes in arc length over time highlighted that strengthened policy enforcement, technological advancements, and energy structure adjustments significantly reduced emission intensities in key provinces, such as Hebei, Jiangsu, and Shandong. These findings offer a robust basis for assessing the impact of current emission reduction policies across provinces, identifying areas with high emission pressures, and optimizing future policy interventions. They also provide valuable insights for targeted resource allocation and the development of tailored strategies to ensure sustainable reductions in pollutant emissions across China's steel industry.

3.2. Compliance Rates under the ULE Standards. In recent years, China has continuously revised and tightened emission-concentration limits for SO_2, NO_x, and PM emissions from the sintering process in the iron and steel industry (Supplementary Table 9). Significant progress was made during the implementation of the *Air Pollution Control Action Plan* (2013–2017) and the *Blue-Sky Battle Action Plan* (2018–2020), which introduced increasingly stringent emission limits. Before 2015, under GB 28662–2012, specific emission limits for key air pollution control regions were initially set at 40 mg/m^3 for PM, 180 mg/m^3 for SO_2, and 300 mg/m^3 for NO_x.[6] These thresholds were further reduced in 2017 to 20 mg/m^3 for PM, 50 mg/m^3 for SO_2, and 100 mg/m^3 for NO_x, following the amendment to GB 28662–2012.[35] The ULE standards further reduced these thresholds to 10 mg/m^3 for PM, 35 mg/m^3 for SO_2, and 50 mg/m^3 for NO_x.[12] Additionally, recognizing the impact of the oxygen content on sintering flue gas emissions, a requirement was introduced in October 2017 to standardize emission concentrations at a reference oxygen level of 16%, mitigating the potential for dilution effects (Amendment to GB 28662–2012). This study evaluated the compliance rates of average hourly pollutant concentrations at sinter plant heads, sinter plant tails, and pelletizing roasting flue gas outlets in the iron and steel industry from 2018 to 2020 under the ULE standards (Figure 3 and Supplementary Figures 5–6), and the color gradient represents the compliance rates of the associated provinces (defined as the proportion of adherence to the corresponding standards) with the ULE standards.

The results revealed significant improvements in compliance rates for average hourly pollutant concentrations in the iron and steel industry under the ULE standards between 2018 and 2020. In 2018, the average hourly concentration compliance rates at the sintering machine head outlet were 39.36% for SO_2, 6.09% for NO_x, and 35.03% for PM, with the PM compliance at the sintering machine tail reaching 70.99%. At the roasting outlet, the average hourly concentration compliance rates were 39.75, 82.10, and 48.48% for SO_2, NO_x, and PM, respectively. By 2019, compliance rates had

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increased to 42.15, 18.56, and 55.70% for SO_2, NO_x, and PM at the sintering machine head; 88.18% for PM at the sintering machine tail; and 44.05, 89.70, and 61.09% for SO_2, NO_x, and PM at the pelletizing roasting outlet, respectively. Further improvements were observed in 2020, with average hourly concentration compliance rates increasing to 62.30, 45.62, and 61.31% for SO_2, NO_x, and PM at the sintering machine head; 89.07% for PM at the sintering machine tail; and 60.51, 92.72, and 62.51% for SO_2, NO_x, and PM at the pelletizing roasting outlet, respectively. These improvements were driven primarily by the adoption of advanced emission-reduction technologies and facilities, spurred by policy initiatives. The 12th Five-Year Plan of the iron and steel industry mandated the installation of desulfurization facilities on all sintering machines by 2015, leading to the widespread deployment of high-efficiency desulfurization systems.[57] By 2017, official reports confirmed that all sintering machines were equipped with systems for both dust control and sulfur removal.[58] Additionally, after the enforcement of the ULE standards, 73% of the 37 newly planned and under-construction steel denitrification projects utilized the selective catalytic reduction (SCR) method.[59] In summary, the combination of policy-driven initiatives and technological advancements significantly enhanced the steel industry's capacity for environmental management, providing a robust foundation for achieving stricter emission standards and advancing sustainable development goals.

From a regional perspective, the northern and eastern regions presented relatively higher average hourly pollutant concentration compliance rates, largely because of their more developed economies and stronger emphasis on environmental policies. These regions strengthened the supervision of pollution sources, enforced stricter emission standards, and actively promoted the green and low-carbon transformation of the iron and steel industry through technological innovation and equipment upgrades, thereby achieving more notable improvements in environmental compliance (Supplementary Tables 6−8). Provinces such as Hebei and Shandong achieved notably high compliance rates, which can be linked to the enforcement of specific standards, such as the *Emission Standard of Air Pollutants for the Iron and Steel Industry in Shandong Province (DB 37/990−2013)* and the *Emission Standard of Air Pollutants for the Iron and Steel Industry (DB 13/2169−2015) in Hebei*.[60,61] Additionally, these regions promoted the reduction of pollutants in the iron and steel industry by optimizing the energy structure and advancing technological innovations.[62,63] Furthermore, the "2 + 26" key cities, prioritized during the revision of GB 28662−2012, were mandated to comply with stricter emission limits than other regions.[35] This special focus resulted in higher compliance rates in the iron and steel industries within these cities, underscoring the strong enforcement of environmental policies and the effectiveness of emission reduction measures. In contrast, the lower compliance rates in the central-southern, northwestern, and southwestern regions were due mainly to insufficient policy enforcement, outdated emission control technologies, and poor raw material quality. These regions exhibited relatively weak enforcement of emission standards, and many iron and steel enterprises continued to use outdated emission control technologies, with inadequate end-of-pipe treatment facilities that failed to effectively control pollutant emissions.[64,65] Additionally, some regions use low-grade iron ore with high impurity contents. For example, steel enterprises in Inner Mongolia use iron ore with a low grade and high impurity content, which leads to substantial SO_2 emissions during high-temperature processes such as sintering and pelletizing.[66] Addressing these gaps requires targeted efforts, including strengthening real-time pollution source monitoring, promoting the construction and upgrading of environmental protection facilities, and strictly enforcing emission standards and regulatory requirements. Furthermore, regional collaboration mechanisms, such as cross-provincial compensation and technology-sharing platforms, should be established to facilitate coordinated emission reductions across regions, improve pollution control effectiveness, enhance air quality, and promote sustainable regional environmental development.

3.3. Effects of the Pandemic on Pollutant Emissions from the Iron and Steel Industry. As mentioned earlier, the reductions in SO_2, NO_x, and PM emissions from 2018 to 2020 during the prepandemic and midpandemic periods ranged from 9.05 to 47.02%, despite the ongoing increase in crude steel production. To assess whether the observed emission reductions effectively translated into improvements in environmental quality, an empirical model was constructed to analyze the correlation between pollutant concentrations from the CHAP data set and emission levels of the iron and steel industry. In this study, segmented regression analysis was employed to evaluate the potential impact of the pandemic on the emission-concentration relationship, with the study period divided into a prepandemic period (covering 2018−2019) and a midpandemic period (covering 2020). Supplementary Table 10 presents the results of the regression coefficients, with t-statistics and F-statistics providing statistical support for this relationship at the 95% confidence level.

Overall, the results of the statistical analyses demonstrated that, compared with those in the prepandemic period, the correlation coefficients of the empirical models for SO_2, NO_x, and PM increased by 24.49%, 9.05%, and 9.35%, respectively, during the midpandemic period (Supplementary Figure 7). Although the increase was limited, this trend suggested that the pandemic did not significantly disrupt the relationship between emissions from the iron and steel industries and their environmental responses. To some extent, these findings also indicate that emission reduction measures have continued to demonstrate favorable environmental effects despite the pandemic context. This stability can be attributed to the continued production activities of the iron and steel industry during the pandemic and the stringent enforcement of emission control policies, which helped maintain the consistency of the emissions-concentration relationship despite economic disruptions and production uncertainties. This provided limited empirical evidence for the effectiveness of policy interventions and the stability of industrial operations, as the analysis did not account for other confounding factors (e.g., economic fluctuations, energy restructuring, and meteorological variations) due to limitations in data availability.

The previous section analyzed the effects of the pandemic on pollutant emissions from the iron and steel industry from two perspectives: the temporal changes in pollutant emissions and the relationships between total emissions and high-resolution near-surface air pollutant concentrations around iron and steel enterprises. Although at the national scale, China's iron and steel industry demonstrated considerable systemic resilience in its overall emission levels during the pandemic, strict lockdown measures implemented in certain regions may have significantly disrupted regional short-term

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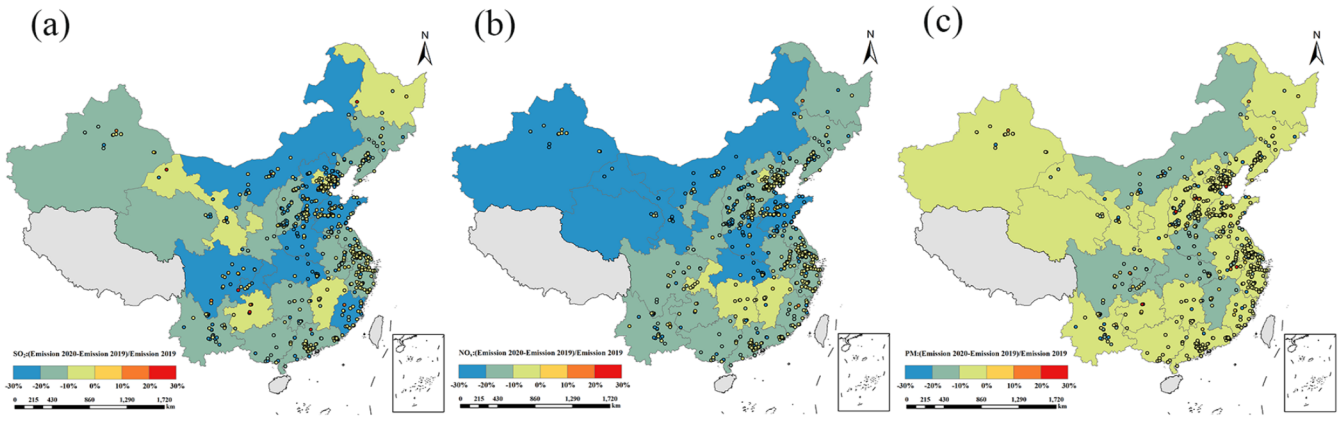


Figure 4. Spatial distributions of the reduction rates of (a) SO_2, (b) NO_x, and (c) PM emissions from the iron and steel industry in 2020 relative to those in 2019 during the Wuhan lockdown period.

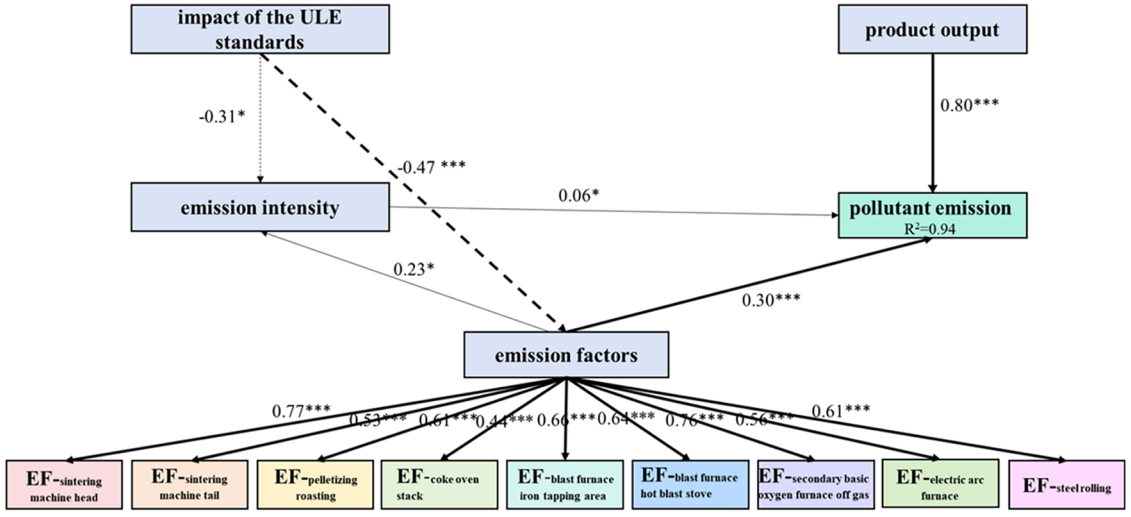


Figure 5. Contribution of driving factors to pollutant emissions in the iron and steel industry estimated by using SEM.

emission patterns. To explore these localized impacts, this study referred to the study by Wu et al.[13] and selected the "Wuhan lockdown" period as a representative case of nationwide emission variation. Furthermore, this study utilized real-time measurements from the CEMS to investigate the spatiotemporal responses of pollutant emissions to lockdown measures, which complemented the macroscale analysis and revealed the dynamic effects of short-term policy interventions on emission patterns. As previously mentioned, to curb the spread of COVID-19, the Chinese government implemented strict control measures including city lockdowns and factory shutdowns. From January 23 to April 8, 2020, Wuhan underwent a 76-day lockdown (the Wuhan lockdown period),[13] during which energy consumption and pollutant emissions decreased significantly. Owing to the differences in the number of days between 2019 and 2020 according to the Western solar calendar, this study presented daily emissions data based on the year with fewer days to enable direct comparisons between the two years. Figure 4 depicts the spatial distribution of the reduction rates in pollutant emissions from the iron and steel industry in 2020 compared with those in 2019 during the Wuhan lockdown period (the color shading in each province represents the relative change in pollutant emissions, while the shaded circles indicate emission changes at individual iron and steel enterprises, and gray shading denotes areas with no valid data). During the lockdown, the emissions of SO_2, NO_x, and PM in Hubei Province decreased by 29.56, 28.16, and 18.60%, respectively, compared with those in the same period in 2019, representing the largest reductions observed nationwide. In contrast, the average reductions in SO_2, NO_x, and PM emissions in other provinces were 14.74, 14.89, and 6.97%, respectively, which was attributed to the earlier recovery of normal activities in the regions outside Hubei. This trend suggested that pollutant emissions from the iron and steel industry across the country generally declined during the pandemic, particularly under the strict implementation of localized lockdown measures, which had a pronounced effect on regional short-term emission levels. In particular, the changes in emissions within Hubei were especially pronounced, reflecting the direct regulatory effect of epidemic control policies on industrial activities and pollutant emissions.

3.4. Factors Driving the Pollutant Emissions of the Iron and Steel Industry. The SEM results demonstrated a strong fit, as indicated by an χ^2/df value of 1.12, a P value of 0.27, a GFI of 0.91, and a CFI of 0.98, all of which exceeded commonly accepted thresholds. Additionally, the RMSEA value of 0.038 indicated minimal fitting error, further confirming the model's excellent overall fit.

Using SEM, this study systematically evaluated the influencing factors and underlying mechanisms of pollutant

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emissions in the steel industry. The results indicated that pollutant emissions are driven by the combined effects of multiple factors, among which product output, emission factors, the impact of ULE standards, and emission intensity were identified as the key drivers (Figure 5). In the SEM diagram, the solid and dashed arrows represent positive and negative associations, respectively. The numbers beside the arrows denote the standardized path coefficients (*P < 0.05, **P < 0.01, ***P < 0.001). The thickness of the arrows indicates the strength of the relationships between variables, with thicker arrows signifying stronger effects in proportion to the magnitude of the path coefficients. Following model interpretation, the impact of the ULE standards was found to indirectly reduce total pollutant emissions by significantly decreasing the emission factors of key processes (−0.47, P < 0.001) and emission intensity (−0.31, P < 0.05). Emission factors had a significant positive effect on emission intensity (0.23, P < 0.05), which in turn significantly contributed to increased pollutant emissions (0.06, P < 0.05), forming a chain-mediated pathway through which the ULE standards influenced pollutant emissions. As the starting point of this pathway, emission factors play a critical mediating role in the effectiveness of the ULE standards in controlling emissions. In the model, emission factors were specified as a latent construct composed of nine key processes, all of which demonstrated highly significant path loadings (P < 0.001). Among these, the sintering machine head (0.77) and secondary basic oxygen furnace off-gas (0.76) contributed most prominently. These results indicate that the latent variable "emission factors" was effectively represented by its observed indicators, thereby supporting its conceptual validity and explanatory strength within the model. In addition, product output had the most substantial direct effect on pollutant emissions (0.80, P < 0.001), identifying it as the primary driver of emission growth. Overall, the model achieved a high coefficient of determination (R^2 = 0.94) for pollutant emissions, suggesting that the structural equation model explained 94% of the variance in emissions. This highlights the model's strong fit and explanatory power, providing robust theoretical support and empirical evidence for pollution control and policy evaluation in the steel industry.

4. DISCUSSION AND IMPLICATIONS FOR POLLUTANT EMISSION CONTROL STRATEGIES

This study systematically examined multiple dimensions of pollutant emissions in China's iron and steel industry, including emission factors, total pollutant emissions, emission intensity, and compliance rates with the ULE standards, based on real-time measurements from the CEMS. This study revealed significant regional and structural disparities in pollutant emissions during both the prepandemic and midpandemic periods. Based on these findings, the study further developed differentiated pollution control strategies tailored to regions with varying levels of emission intensity and provided specific recommendations for regional collaborative governance and more effective implementation of the ULE standards.

The results of this study indicated that the coking, sintering, pelletizing, and blast furnace processes were the major contributors to air pollutant emissions in China's iron and steel industry. Over the period from 2018 to 2020, the sintering process consistently contributed more than 50% of the total emissions of all three pollutants, making it the primary source of emissions in the iron and steel industry. In this context, the transition from the BF-BOF route to the EAF route was driven primarily by the latter's environmental advantages—mainly the recycling of scrap steel, which not only reduced raw material consumption but also significantly decreased pollutant emissions.[67,68] However, the shift to the EAF route faced several critical challenges, including substantial capital investment in existing BF-BOF facilities with long operational lifespans, limited and costly scrap supplies, and high industrial electricity prices. Given these constraints, a more feasible and cost-effective short- to medium-term strategy involves phasing out outdated small-scale BF-BOF units while upgrading existing facilities to improve emission control. Concurrently, to further reduce pollutant emissions from sintering and blast furnace operations, enterprises should adopt cleaner energy sources, such as biomass and hydrogen, in place of conventional fossil fuels. Additionally, targeted technical measures have been proposed based on plant-specific conditions to facilitate the coordinated control of both process and end-of-pipe emissions. For example, in SO_2 emission control, the application of activated carbon adsorption technology and China's original dense phase coherent tower method, both of which have been proven effective in practical applications for removing SO_2, is recommended.[65] With respect to NO_x control, SCR technology and activated carbon adsorption technology for treating NO_x in flue gas are well-established and widely used techniques capable of significantly reducing nitrogen oxide emissions.[69] Furthermore, for dust control, enterprises should close material yards, convey powdery materials pneumatically, and adopt a combination of predust removal (such as gravity dust removal or cyclone dust removal) and deep dust removal (including bag dust removal or electrostatic dust removal).[70]

Compared with total emissions, the emission intensity more accurately reflects the efficiency of pollutant emissions per unit of output. Hence, this study uses emission intensity as the primary criterion, ranks provinces on the basis of average emission intensity from 2018 to 2020, and categorizes regions into different priority levels for targeted pollution control strategies, aiming to implement differentiated policies and precisely advance emission reduction efforts (Supplementary Table 11). In high-emission intensity regions (grades 1−10), implementing stricter emission standards and regulatory measures, while also strengthening cross-regional cooperation to foster technology sharing and the exchange of management experiences, is recommended. This approach is expected to enhance the overall pollution reduction and control capabilities. In medium-emission intensity regions (grades 11−20), intensified efforts in refined management and technological transformation, encouraging steel enterprises to upgrade equipment and optimize production processes to increase energy efficiency and reduce emissions, are recommended. For low-emission intensity regions (grades 21−28), it is essential to consolidate existing ultralow emission achievements while also constructing an integrated "emission-cost-benefit" analysis framework to assist enterprises in optimizing their cost structures while ensuring environmental protection, thereby ensuring long-term sustainable development.

These findings underscore the effectiveness of ULE standards in reducing emissions. In 2020, the emissions of SO_2, NO_x, and PM from the iron and steel industry decreased by 32.56, 47.02, and 9.05%, respectively, compared with those in 2018, despite a 14.74% increase in production. The real-

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time measurements from the CEMS further revealed significant improvements in concentration compliance rates across Chinese iron and steelmaking enterprises after the implementation of ULE standards. Between 2018 and 2020, the hourly concentration compliance rates at the sintering machine head increased by 58.28% for SO_2, 649.10% for NO_x, and 75.02% for PM, whereas the compliance rate for PM at the sintering machine tail improved by 25.47%. Additionally, the compliance rates during the pellet roasting process increased by 52.23% for SO_2, 12.94% for NO_x, and 28.94% for PM. This finding supported the effectiveness of the standard in controlling emissions from iron and steel production by lowering pollutant concentrations and emission factors. Additionally, the results demonstrated that adherence to standards tended to be greater in provinces with higher levels of economic development, and regions prioritized in clean air action plans[71,72] often presented better compliance rates and lower emission intensities. This indicated that, alongside the benefits of the ULE standards, a variety of local standards and policies targeting emissions from iron- and steelmaking (Supplementary Tables 6−8) played a significant role in controlling pollutant emissions. In regions with higher compliance rates, such as Hebei, Shandong, and Jiangsu, most steel enterprises had already completed the upgrades to meet the ULE standards and established relatively mature pollution control technologies and management foundations. By consolidating the existing achievements, efforts should be made to shift emission control levels from "basic compliance" to "high-quality compliance", further enhancing refined management across all processes and improving the stability of pollutant emission control. In contrast, regions with lower compliance rates, such as Sichuan, Yunnan, and Guizhou, still face numerous challenges in advancing ULE standards. It was advised to adhere to the principle of tailored, region-specific policies, explore phased and differentiated pathways to compliance, and introduce a "transition-period performance evaluation mechanism" to improve the feasibility and effectiveness of institutional implementation. On this basis, further efforts are suggested to promote inter-regional emission reduction cooperation, establish cross-provincial emission compensation mechanisms, create platforms for technological collaboration and innovation, and build systems for experience sharing to achieve coordinated governance between high-compliance and low-compliance regions.

This study also revealed a significant spatial disparity in pollutant emissions within China's iron and steel industry. To achieve coordinated emission reductions across the sector, shifting pollution control from territorial management to shared governance was suggested. The specific strategies included the following: (1) Cross-regional environmental compensation mechanism: A system of emission rights trading and fiscal compensation was proposed between high-emission regions and areas with a strong ecological carrying capacity and low emission levels. For example, total pollutant emission control targets for the steel industry could be established, with regional quota adjustments, differentiated tax rates, and fiscal transfer payments used to guide enterprises in meeting local emission constraints while reasonably allocating regional environmental capacity. (2) Coconstruction of technology sharing and collaborative innovation platforms: Efforts are recommended to promote open collaboration and exchange among steel enterprises in key technical areas, such as flue gas treatment, energy efficiency improvement, and short-process alternatives. (3) Coordinated law enforcement and joint prevention and control mechanism: Strengthening regional environmental law enforcement coordination was suggested, especially during high-emission periods or pollution events, with the implementation of cross-provincial emergency emission reduction and industrial regulatory mechanisms. By implementing these mechanisms, China's iron and steel industry could transition from "point-source control" to "systemic collaboration", effectively enhancing regional governance efficiency and pollution control capabilities and thus providing strong support for achieving the goals of peak carbon and carbon neutrality.

Additionally, our analysis assessed the impact of the pandemic on emissions from Chinese iron and steelmaking. As mentioned earlier, despite the ongoing increase in crude steel production, pollutant emissions from the iron and steel industry across the country generally declined during the pandemic, particularly under the strict implementation of localized lockdown measures, which had a pronounced effect on regional short-term emission levels. An empirical model was also developed to assess the correlation between pollutant concentrations and emissions by identifying the corresponding air pollutant concentrations on the basis of the geographic location of each enterprise. Overall, compared with the prepandemic period, the increase in the correlation coefficients of the empirical models for SO_2, NO_x, and PM during the midpandemic period was limited. This trend suggested that the pandemic did not significantly disrupt the relationship between emissions from the iron and steel industries and their environmental responses. To some extent, these findings also indicate that emission reduction measures have continued to demonstrate favorable environmental effects, despite the challenges posed by the pandemic.

Furthermore, the driving factors behind emissions from Chinese iron and steelmaking and the relationships between these factors are important areas for further investigation. Our analysis revealed that key driving factors, such as product output and emission factors, had a significant positive effect on pollutant emissions. Among these factors, emission factors for different manufacturing processes had a notable influence on the overall emission factor (with path coefficients ranging from 0.44−0.77). In addition, the ULE standards indirectly reduce total pollutant emissions by significantly decreasing the emission factors of key processes and the emission intensity. This highlighted the significant role of ULE standards in driving emission reductions in the iron and steel industry, as well as the importance of conducting postimplementation evaluation studies.

Our analysis faced several uncertainties and limitations. From 2018 to 2020, 3.57 to 12.02% of the crude steel production was not included in the analysis due to limitations in data availability. To improve the accuracy of future analysis, future research should focus on collecting emission data from these uncovered enterprises and further investigating whether specific regional or process characteristics influence emission patterns. Furthermore, the complex interference from economic conditions and the impacts of the pandemic on emission changes may also affect the evaluation of the effectiveness of ULE standards. This study was unable to fully eliminate the influence of these factors. Future research should incorporate more comprehensive data on economic, production, and social activities to further analyze the independent contributions of the ULE standards to emission

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changes. The uncertainty ranges we calculated revealed that the uncertainties for SO_2, NO_x, and PM emissions in China's iron and steel industry from 2018 to 2020 were within ± 3.0% (Supplementary Table 12), indicating that the emission inventory calculations for the industry in China are relatively consistent. Despite these limitations, the estimates based on real-time measurements from the CEMS provided a reasonable approximation of compliance with the ULE standards for Chinese iron- and steelmaking enterprises during both the prepandemic and midpandemic periods. The insights derived from this analysis provide valuable guidance for strengthening future mitigation strategies through an in-depth assessment of pollutant emission reductions and compliance rates following the introduction of ULE standards in China. Future studies could extend this work to evaluate the health benefits resulting from these environmental improvements over the study period. This would enable a more comprehensive evaluation of the overall effectiveness of environmental policies and provide essential scientific evidence to support the development of public health policies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestair.5c00197.

Additional details about the ULE standard limits of air pollutants for major steelmaking processes and emission standards of air pollutants in selected provinces; classification of provinces or municipalities; emissions and shares of major pollutants, along with crude steel production across six regions from 2018 to 2020; top three provinces in pollutant emissions at the provincial level and their shares; fuel structure adjustment and technological innovation policies in selected provinces; overview of emission standards for the sintering process; relationships between emissions (SO_2, NO_x, PM) and corresponding concentrations from CHAP data sets; average emission intensity and ranking of different provinces; range of uncertainties in the estimated pollutant emissions; trends in interprovincial emission intensity; geographical distributions of major pollutant emissions and daily distributions of smokestack concentrations; emission factors in various iron and steel processes; compliance rates under ULE standards and empirical models describing the relationships between pollutant concentrations and emissions for pre- and midpandemic periods (PDF)

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Notes

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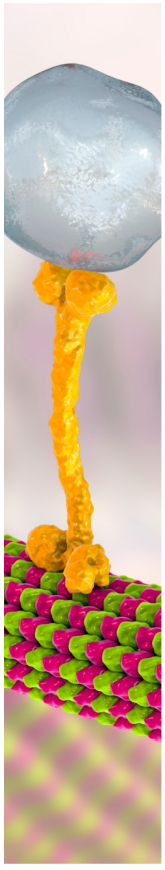
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