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Original Research

Quantifying China's iron and steel industry's CO_2 emissions and environmental health burdens: A pathway to sustainable transformation

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ABSTRACT

Assessing the iron and steel industry's (ISI) impact on climate change and environmental health is vital, particularly in China, where this sector significantly influences air quality and CO_2 emissions. There is a lack of comprehensive analyses that consider the environmental and health burdens of manufacturing processes for ISI enterprises. Here, we present an integrated emission inventory that encompasses air pollutants and CO_2 emissions from 811 ISI enterprises and five key manufacturing processes in 2020. Our analysis shows that sintering is the primary source of air pollution in the ISI. It contributes 71% of SO_2, 73% of NO_x, and 54% of $PM_{2.5}$ emissions. On the other hand, 81% of total CO_2 emissions come from blast furnaces. Significantly, the contributions of ISI have resulted in an increase of 3.6 μg m^{-3} in national population-weighted $PM_{2.5}$ concentration, causing approximately 59,035 premature deaths in 2020. Emissions from Hebei, Jiangsu, Shandong, Shanxi, and Inner Mongolia provinces contributed to 48% of $PM_{2.5}$-related deaths in China. Moreover, the transportation of air pollutants across provincial borders highlights a concerning trend of environmental health inequality. Based on the research findings, it is crucial for ISI manufacturers to prioritize the removal of outdated production capacities and adopt energy-efficient and advanced techniques, along with ultra-low emission technologies. This is particularly important for those manufacturers with substantial environmental footprints. These transformative actions are essential in mitigating the environmental and health impacts in the affected regions.

1. Introduction

China grapples with dual challenges of air quality improvement and climate change mitigation [1–5]. As the largest steel producer globally, China has witnessed an almost tenfold surge in production output over the last 25 years, accounting for more than 56% of global steel production in 2020. The iron and steel industry (ISI) accounted for 16.4%, 22.3%, and 12.1% of sulfur dioxide (SO_2), nitrous oxides (NO_x), and particulate matter (PM) emissions in China in 2020 [6]. Moreover, ISI contributed up to 10% of $PM_{2.5}$ concentrations in some provinces [7] and more than 10% of total domestic CO_2 emissions in China [8,9]. Consequently, fostering a low-carbon and green development of the iron and steel industry is critical for improving air quality and mitigating climate change. Compared with developed countries, China's ISI, with over 90% of its steelmaking involving the blast furnace-converter long process,

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has immense potential for low-carbon transformation [10,11]. Besides, China's iron and steel industry is mainly concentrated in densely inhabited regions, negatively impacting public health. Thus, it is essential to evaluate CO_2 emissions and environmental health impacts of ISI to reduce pollution and carbon emissions collaboratively.

Quantitative evaluation of ISI emissions and environmental health impacts is a key scientific issue. While various studies have delved into this domain [12−18], a majority have predominantly analyzed air pollutants or CO_2 emissions. Notable examples include the investigation by Chen et al. [19] into energy consumption and CO_2 emissions in China's iron and steel industry in 2012 and the comprehensive analysis conducted by Wang et al. [20] on the unit-based emission inventory of SO_2, NO_x, and PM for the iron and steel industry in China between 2010 and 2015. Although Li and Hanaoka [21] pioneered an ISI-integrated emission inventory of air pollutants and CO_2 in 2015, their focus leaned towards mitigation strategies by 2060 in China's iron and steel sector, leaving a gap in fully unraveling the synergy and heterogeneity of ISI between air pollutants and CO_2 emissions. Furthermore, Tang et al. [7] simulated and analyzed the impact of the industry's emissions on air quality but did not evaluate environmental health effects such as $PM_{2.5}$-related premature deaths. Therefore, certain research gaps persist. (1) There is an absence of an integrated unit-based emission inventory for air pollutants and CO_2 in China's iron and steel industry, detailing specific plant locations and manufacturing processes. (2) The imperative need to identify key measures for the collaborative reduction of air pollutants and CO_2 emissions in ISI, with a dearth of synergistic analyses of air pollutants and CO_2 emissions characteristics from the perspective of ISI enterprises, manufacturing processes, and provinces. (3) Considering the long-distance transport of air pollutants, $PM_{2.5}$-related mortality occurring in region A is likely associated with emissions in region B [22,23]. Therefore, it's a key scientific issue to investigate the two-dimensional cross-contributions of ISI manufacturing processes in different provinces to $PM_{2.5}$-related premature deaths, an aspect seldom addressed. (4) Proposals for low-carbon and clean development in China's iron and steel industry currently are absent, lacking consideration for environmental health equity and collaborative reduction of pollution and carbon emissions.

In this study, we established an integrated emission inventory of air pollutants and CO_2 in 2020, derived from unit-based activity data of 811 plants across five major manufacturing processes. Based on the above database, we analyzed ISI's air pollutants and CO_2 emission characteristics. Considering the relatively small emissions from some manufacturing processes, we scrutinized the environmental effects of three key manufacturing processes: sintering and pelletizing, blast furnaces, basic oxygen steelmaking furnaces, and electric arc furnaces. Using the Community Multiscale Air Quality (CMAQ) model with the Integrated Source Apportionment Method (ISAM) module and a health impact model based on the Global Exposure Mortality Model (GEMM), we examined the repercussions of emissions from 93 sources. These comprised the three primary manufacturing processes spread across 31 provinces in China during 2020. Our analysis extended to tracking the influence of these emissions on $PM_{2.5}$ concentration and the consequential mortality. Finally, we propose policy suggestions on low carbon and clean development in the steel industry, considering environmental health equity and coordinated pollution and carbon emission reduction. This study can provide an effective reference for other industries aiming to manage air pollution and CO_2 emissions.

2. Methods and materials

This study explored CO_2 emissions and environmental health effects of China's iron and steel manufacturing processes. First, an integrated emission inventory, including air pollutants and CO_2, was constructed for China's iron and steel industry. Second, the impact on air quality was simulated with the Weather Research and Forecasting (WRF)-CMAQ model. Finally, the population exposure characteristics and health impacts were evaluated based on $PM_{2.5}$ concentrations.

2.1. Air pollutant and CO_2 emission calculation

In this paper, we examined the primary manufacturing processes in the iron and steel industry that are significant sources of air pollutants and CO_2 emissions. These processes encompass sintering, pelletizing, blast furnaces (BF), basic oxygen steelmaking furnaces (BOF), and electric arc furnaces (EAF).

2.1.1. Air pollutant and CO_2 emission calculation method

The emissions of SO_2, NO_x, and $PM_{2.5}$ from China's iron and steel industry were estimated on the unit level using a bottom-up method involving organized and unorganized emissions. The emissions of air pollutants can be calculated according to equation (1):

$$E_k=\sum_i\sum_j EF_{i,k}\times A_{i,j}\times(1-\eta_{i,j,k}) \tag{1}$$

where E_k is the emission of pollutant k from China's iron and steel industry. k represents the air pollutant species; i represents the facility type; j represents the unit of type i facility. $EF_{i,k}$ is the emission factor of pollutant k for type i facility. $A_{i,j}$ is the production output of unit j of type i facility. $\eta_{i,j,k}$ represents the removal efficiency of air pollutant k emitted from unit j of type i facility.

In this study, only direct CO_2 emissions occurring in the iron and steel industry were estimated, including emissions from the combustion of fossil fuels and chemically transformed materials in manufacturing processes. The indirect emissions from the net import of electricity and material transport are not considered. The direct CO_2 emissions from the major manufacturing processes in the iron and steel industry can be calculated using a bottom-up method [11], as detailed in the following equation:

$$E_{CO_2}=\sum_i\sum_j EF_{\mathrm{comb},i,CO_2}\times A_{\mathrm{fuel},i,j}+\sum_i\sum_j EF_{\mathrm{indu},i,CO_2}\times A_{i,j} \tag{2}$$

where E_{CO_2} is the emission of CO_2 from China's iron and steel industry. $EF_{\mathrm{comb},i,CO_2}$ is the emission factor of CO_2 in the fuel combustion process in the type i facility. $EF_{\mathrm{indu},i,CO_2}$ is the emission factor of CO_2 in industrial process in the type i facility. $A_{\mathrm{fuel},i,j}$ is the amount of fuel used in unit j of type i facility. $A_{i,j}$ is the production output of unit j of type i facility.

2.1.2. Activity data

Unit-based activity data of the iron and steel industry in China in 2020 were obtained from a combination of several sources and databases, including Emission Permit Implementation Report (EPIR), Environmental Statistics (ES), National Bureau of Statistics (NBS), city-level yearbooks, and field investigations. The provincial distribution of iron and steel manufacturers' processes is shown in

Supplementary Information, Table S1.

2.1.3. Emission factors

The emission factors of SO_2, NO_x, and PMs in the five major manufacturing processes were obtained or derived from the Calculation Methods and Coefficients of Pollutant Emission Sources Handbook issued by the Ministry of Ecology and Environment (MEE) [24]. The emission factors of $PM_{2.5}$ can be calculated based on equation (3):

$$EF_{i,PM_{2.5}} = EF_{i,TSP} \times f_{i,PM_{2.5}} \quad (3)$$

where $EF_{i,PM_{2.5}}$ and $EF_{i,TSP}$ are emission factors of $PM_{2.5}$ and TSP from type i facility, $f_{i,PM_{2.5}}$ is the proportion of $PM_{2.5}$ in TSP emitted from type i facility.

CO_2 emissions factors for fuel combustion and industrial processes were obtained from the Intergovernmental Panel for Climate Change (IPCC) Guidelines for national greenhouse gas inventories [25] and Guidelines for calculating and reporting greenhouse gas emissions in China's iron and steel enterprises (http://www.gov.cn/zwgk/2013-11/04/content_2520743.htm). The detailed emission factors of SO_2, NO_x, PM, and CO_2 for the iron and steel sector are shown in Supplementary Methods, Table S2, and Table S3.

2.2. WRF-CMAQ model

In this study, we employed the CMAQ model, version 5.3.2, as described by Appel et al. [26], to simulate air quality from China's iron and steel industry. Meteorological data were provided via the Weather Research and Forecasting model (WRF, version 3.6.1). The meteorological conditions were extracted from the global final reanalysis datasets with a 1° × 1° spatial resolution from the National Centers for Environmental Prediction (NCEP-FNL, http://rda.ucar.edu/datasets/ds083.2/). We adopted a Lambert projection for this study, centering at 103° E and 37° N, with standard parallels at 25° N and 40° N. The model domain was structured into a grid of 270 × 216 cells, each spanning 20 km, extending 2690 km in the X direction and 2150 km in the Y direction. The simulation incorporated 30 eta levels, with a pressure of 50 hPa at the top level. The Carbon Bond 06 (CB06) gaseous chemical scheme and the aerosol scheme AERO7 were adopted in the CMAQ model. The ISAM within CMAQ was utilized to track pollutant contributions from varying regions to ambient levels and deposited amounts of pollutants, such as the photochemical substance $PM_{2.5}$ and its precursors [27]. In this study, the contribution of ISI manufacturing processes to $PM_{2.5}$ from different provinces in China was calculated using ISAM in CMAQ version 5.3.2.

The emissions of major air pollutants are necessary inputs for the CMAQ model. The physicochemical reaction of multiple pollutants emitted from China's iron and steel industry and other sectors is fully considered in this study's model simulation. In this study, pollutant emissions from China's iron and steel industry are calculated according to Section 2.1. Emissions from other sectors are retrieved from the 2020 Multi-resolution Emission Inventory for China (MEIC, http://www.meicmodel.org). Biogenic emissions were sourced from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) [28].

We evaluated simulated $PM_{2.5}$ concentrations against ground-based observations across China and three key regions (i.e., "2 + 26" cities, the Fenwei Plain [FWP], and the Yangtze River Delta [YRD]). The observational data were obtained from the national monitoring network operated by the China National Environmental Monitoring Center. The model also showed reasonable performance with normalized mean biases (NMBs) ranging from −19.12% to 11.98% for different regions. Supplementary Information, Fig. S1 and Table 1 compared observed and modeled $PM_{2.5}$ concentrations for each region, using statistical metrics including sample numbers (N), correlation coefficient (r), NMBs, and normalized mean error (NME). Overall, our model simulations closely matched with actual observations, demonstrating the reliability and accuracy of our approach. The detailed introduction of model configuration refers to prior studies [29–32].

Table 1
Statistical indicators for comparison of simulated and monitoring data.

Case	N	r	NMBs (%)	NME (%)
Nation	337	0.82	3.91	33.21
"2 + 26" cities	3444	0.89	−5.00	31.69
FWP	1353	0.88	−19.12	36.22
YRD	5043	0.85	11.98	40.56

2.3. Population exposure characteristics

The population data with a resolution of 1 km was extracted from the Grid dataset of China's population spatial distribution (https://www.resdc.cn/AchievementList1.aspx) [33]. The exposure of the population to $PM_{2.5}$ pollution was evaluated using a population-weighted $PM_{2.5}$ pollution exposure model. The model employs population exposure to varying ambient $PM_{2.5}$ concentrations as a weighting factor, thereby offering a more objective and realistic representation of the actual health impact of $PM_{2.5}$ pollution on population health from ISI. The formula is as follows

$$PPM_{2.5} = \frac{\sum_{i=1}^{n} P_i \times PM_{2.5,i}}{P} \quad (4)$$

where $PPM_{2.5}$ represents the population-weighted $PM_{2.5}$ concentrations for each province. n represents the number of raster image element in each province. P_i represents the number of people in each raster image element. $PM_{2.5,i}$ represents $PM_{2.5}$ mass concentrations in the raster image element. P represents the number of people in each province.

2.4. Evaluating health impacts

Five health endpoints for $PM_{2.5}$-related premature mortality were considered in this study, including chronic obstructive pulmonary disease, ischemic heart disease, lung cancer death, stroke, and lower respiratory infections. In this study, we applied the GEMM model [34] to estimate $PM_{2.5}$-related mortality. The excess mortality associated with ambient $PM_{2.5}$ exposure is calculated as follows:

$$Mort = AF \times Pop \times \gamma_0 \quad (5)$$

$$AF = \frac{RR - 1}{RR} \quad (6)$$

where the excess premature mortality *(Mort)* is calculated by multiplying attributable fraction (*AF*), ground-level gridded population (*Pop*), and the baseline mortality rates (γ_0) from the Global Burden of Disease Study (GBD) [35]. AF is estimated based on the relative risk (*RR*), and RR for $PM_{2.5}$ is calculated using the GEMM model.

We investigated the contribution of ISI emission in 31 provinces and three major manufacturing processes (sources) to $PM_{2.5}$ concentration and related mortality in each 20 km grid (receptors) across China. Based on the grid results, we further calculated the interprovincial contribution matrix (31 provinces × 31 provinces) of $PM_{2.5}$-related deaths.

$$Mort_i = \sum_0^j \sum_0^k Mort_{i,j,k} \quad (7)$$

where $Mort_i$ is national $PM_{2.5}$-related mortality caused by the pollutant's emissions from province i. $Mort_{i,j,k}$ is the $PM_{2.5}$-related mortality in province j caused by the emissions from province i and manufacturing process k, i and j are ranging from 1 to 31, and k is ranging from 1 to 3.

3. Results

3.1. Unit-based integrated air pollutants and CO_2 emissions inventory

3.1.1. Overall emissions

This study compiled a comprehensive database to establish an integrated emission inventory of three air pollutants (SO_2, NO_x, and $PM_{2.5}$) and CO_2 from 811 iron and steel plants in China. The data were collected from 31 provinces in 2020, covering 828 sintering facilities, 397 pelletizing facilities, 1015 blast furnaces, and 1223 steelmaking furnaces. The unit-based inventory revealed that SO_2, NO_x, $PM_{2.5}$, and CO_2 emissions from the ISI in 2020 were estimated to be 0.51, 0.97, 0.42, and 1644 Tg, respectively. Our results were basically in alignment with several previous investigations. MEE [6] reported SO_2, NO_x, and TSP emissions from the ferrous metal smelting and rolling processing industry as 0.41, 0.93, and 0.49 Tg, respectively. Our estimates for SO_2 and NO_x closely mirrored those of MEE. However, our $PM_{2.5}$ estimate was higher, primarily attributed to the underestimation of fugitive emissions in MEE's analysis. Compared our results with the MEIC v1.4 (http://meicmodel.org.cn/), which documented SO_2, NO_x, and $PM_{2.5}$ emissions from the iron and steel industry in 2020 as 0.87, 1.49, and 0.72 Tg, respectively, our results are noticeably lower. This discrepancy can be traced back to the elevated emission factors employed in MEIC v1.4 as compared to our study. Regarding CO_2 emissions, our findings align closely with the data provided by the Carbon Emission Accounts and Datasets for emerging economies (CEADs, https://ceads.net), which estimated emissions at 1853 Tg, and the research by Wang et al. [36], which recorded a direct CO_2 emission of 1657 Tg. The differences between these studies and ours can largely be attributed to variations in the scopes of investigations.

Regarding emission contributions of different manufacturing processes, the sintering process emits the largest proportion of SO_2 and NO_x, accounting for 71% and 73% of the total emissions, respectively. In addition, sintering and BF accounted for a significant proportion of total $PM_{2.5}$ emissions, with sintering contributing 54% and BF contributing 21%. Finally, BF stands out as the primary contributor to CO_2 emissions, contributing 81% to the total emissions.

3.1.2. Spatial distribution

The production output and associated emissions of air pollutants and CO_2 from each manufacturing process in 28 provinces (no steel enterprises in Beijing, Hainan, and Xizang) in 2020 are depicted in Fig. 1. Notably, Hebei (HE), Jiangsu (JS), Liaoning (LN), Shandong (SD), Shanxi (SX), and Nei Mongol (NM) were the main sources of air pollutants and CO_2 emissions due to their high crude steel production. These provinces are responsible for the largest SO_2, NO_x, $PM_{2.5}$, and CO_2 emissions among the top 10, with their contributions over 50% of SO_2, 57% of NO_x, 48.6% of $PM_{2.5}$, and 62.1% of CO_2 emissions from China's iron and steel industry. Due to differences regarding manufacturing processes and control stringency of pollutant emissions, the contributions of ISI to air pollutants and CO_2 emissions varied from province to province. For instance, Hebei (HE) province contributed up to 25% of China's pig iron output, where SO_2, NO_x, and $PM_{2.5}$ emissions accounted for 17%, 17%, and 13% of the totality, respectively. The relatively lower emission levels in Hebei can be primarily attributed to the implementation of ultra-low emission standards in iron and steel manufacturing [37,38]. The spatial distribution of iron and steel manufacturers is shown in Fig. S2.

3.1.3. Identification of manufacturers with high emissions

To identify the primary sources of air pollutants and CO_2 emissions in the ISI, we developed a normalized emission index to rank manufacturers. The normalized emission index for each manufacturer is determined by summing the ratios of the three air pollutants and CO_2 emissions from the manufacturer to the national emissions. Our analysis revealed that a mere 25% of businesses, represented by the top 200 manufacturers, were responsible for a considerable proportion of pollutants and CO_2 emissions. Specifically, these manufacturers accounted for 85.8% of SO_2, 87.1% of NO_x, 84.1% of $PM_{2.5}$, and 82.9% of CO_2 emissions in this industry (Fig. 2). This finding underscores that a small number of plants contribute significantly to emissions. The top 200 manufacturers follow the BF-BOF route, mainly including sintering, pelletizing, BF, and BOF manufacturing processes. These manufacturers are dispersed throughout the country, with at least one major manufacturing site in each of the 28 provinces. Nevertheless, major manufacturing facilities tend to cluster in the Beijing−Tianjin−Hebei and its surroundings, the Yangtze River Delta, and Liaoning province, resulting in pronounced air pollutants and CO_2 emissions in these areas.

3.1.4. Evaluation of the emission control capabilities of top 200 manufacturers

The emission intensities of air pollutants and CO_2 were used to evaluate the emission control capabilities of the top 200 manufacturers. The emission intensity of air pollutants or CO_2 in a manufacturer is defined as the total emissions of the three air pollutants or CO_2 per unit of pig iron production. To further explore the synergy of air pollution and CO_2 emissions control of the top 200 manufacturers, they were classified into four categories: high air pollutant and high CO_2 emission intensities manufacturers (HH), high air pollutant and low CO_2 emission intensities manufacturers (HL), low air pollutant and low CO_2 emission intensities manufacturers (LL), and low air pollutant and high CO_2 emission intensities manufacturers (LH). Manufacturers in the HH group (the first quadrant) exhibited both air pollutant and CO_2 emission intensities that surpassed the national average. HL manufacturers in the second quadrant demonstrated more effective air pollution abatement but lagged in CO_2 emissions control. LL manufacturers in the third quadrant had better control of both air pollutants and CO_2 emissions, while LH manufacturers in the fourth quadrant showed proficiency in CO_2 control but weaker air pollution control (Fig. 3). We also explored the spatial distribution of the four category manufacturers. LL and HL manufacturers are mainly situated in central and eastern China, economy-developed regions that have made rapid progress in ultra-low emission conversion. Conversely, HH and LH manufacturers are mainly located in backward regions, namely northeast, northwest, and southwest China (Fig. S3).

3.2. Contributions to population-weighted $PM_{2.5}$ concentration

$PM_{2.5}$ mass concentrations induced by emission from different manufacturing processes of ISI in 2020 are presented in Fig. S4. The result indicates that the emission from ISI significantly impacts the $PM_{2.5}$ mass concentration in provinces such as Hebei, Liaoning, and Nei Mongol. Among the manufacturing processes, sintering and

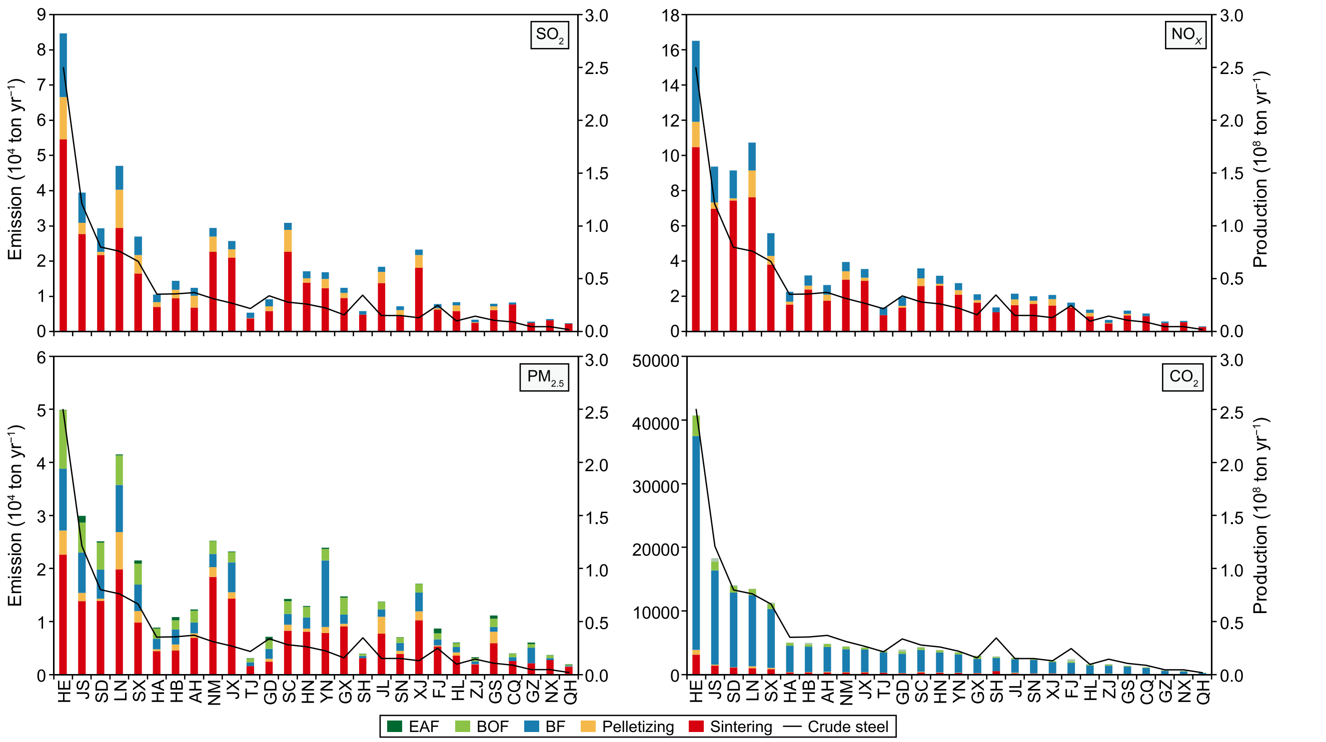

Fig. 1. Provincial production of crude steel and SO_2, NO_x, $PM_{2.5}$, and CO_2 emissions from ISI in 2020. Abbreviation: Beijing (BJ), Tianjin (TJ), Hebei (HE), Shanxi (SX), Nei Mongol (NM), Liaoning (LN), Jilin (JL), Heilongjiang (HL), Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Anhui (AH), Fujian (FJ), Jiangxi (JX), Shandong (SD), Henan (HA), Hubei (HB), Hunan (HN), Guangdong (GD), Guangxi (GX), Hainan (HI), Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN), Xizang (XZ), Shaanxi (SN), Gansu (GS), Qinghai (QH), Ningxia (NX), Xinjiang (XJ).

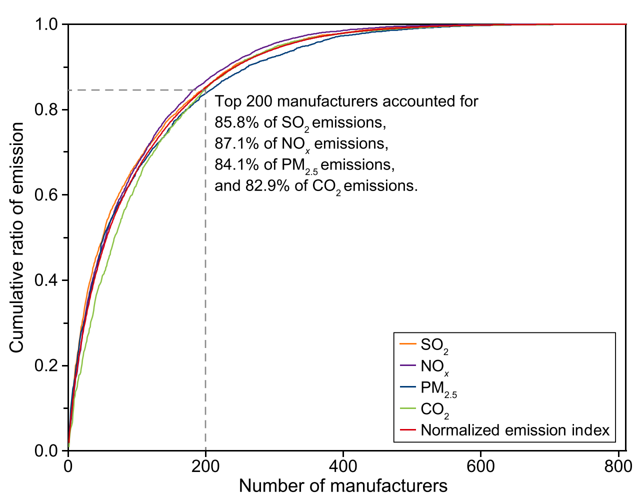

Fig. 2. Cumulative percentage of air pollutants and CO_2 emissions from manufacturers.

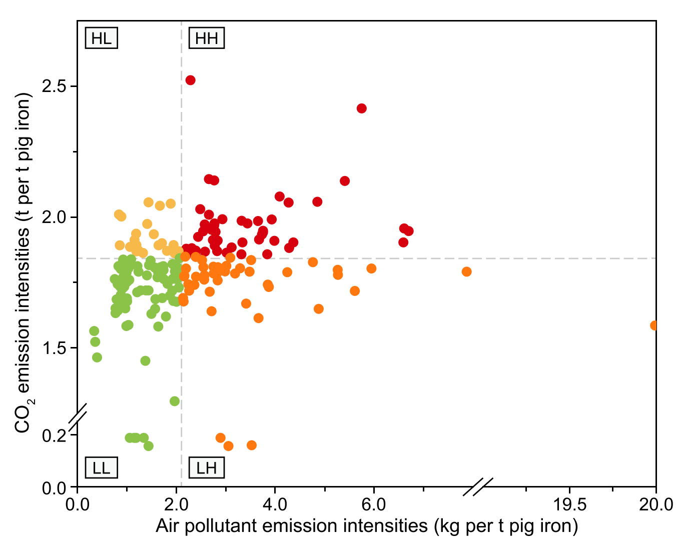

Fig. 3. Analysis of collaborative reduction of CO_2 and air pollutants of top 200 manufacturers. The coordinate origin represents the national average values of air pollutants and CO_2 emissions intensities.

pelleting processes have the greatest impact on $PM_{2.5}$ mass concentrations; BF exhibits a greater influence on $PM_{2.5}$ mass concentration than BOF and EAF processes. Besides, to assess the health exposure level of China's iron and steel industry, we calculated the population-weighted $PM_{2.5}$ concentrations from national emissions and ISI manufacturing processes. Further, to evaluate the contributions of different provinces and manufacturing processes, we established the cross-provincial contribution matrix of population-weighted $PM_{2.5}$ concentrations induced by ISI pollutants emissions in 2020 (Fig. 4).

The national population-weighted annual mean $PM_{2.5}$ concentration caused by ISI emissions was 3.6 μg m^{-3}, contributing ~9% to the total national $PM_{2.5}$ exposure concentration. Among them, sintering and pelletizing processes were the largest contributors with 2.5 μg m^{-3}, followed by BF processes with 0.8 μg m^{-3}, and BOF and EAF processes with 0.3 μg m^{-3}. The provinces with high crude steel production densely inhabited or upwind areas contributed to the highest $PM_{2.5}$ concentration. Specifically, Hebei and Shandong contributed 0.6 and 0.4 μg m^{-3} to

Receptor regions (Unit: μg m^{-3})

Source regions	BJ	TJ	HE	SX	NM	LN	JL	HL	SH	JS	ZJ	AH	FJ	JX	SD	HA	HB	HN	GD	GX	HI	CQ	SC	GZ	YN	XZ	SN	GS	QH	NX	XJ	Nation
BJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TJ	0.2	1.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
HE	1.1	2.0	5.6	0.4	0.1	0.4	0.1	0.1	0.2	0.3	0.2	0.3	0.1	0.2	0.6	0.6	0.3	0.2	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.6
SX	0.1	0.1	0.3	3.5	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.0	0.1	0.1	0.4	0.2	0.2	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.4	0.1	0.0	0.1	0.0	0.2
NM	0.3	0.2	0.2	0.3	4.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.2
LN	0.0	0.0	0.0	0.0	0.0	5.2	0.3	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
JL	0.0	0.0	0.0	0.0	0.0	0.1	1.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
HL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JS	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.8	3.7	0.4	1.0	0.1	0.4	0.3	0.3	0.4	0.3	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.4
ZJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.1	2.4	0.0	0.4	0.0	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
FJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.0	0.3	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
SD	0.1	0.2	0.2	0.1	0.0	0.1	0.0	0.0	0.2	0.4	0.1	0.3	0.1	0.1	2.3	0.3	0.3	0.2	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.3
HA	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.1	1.1	0.2	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
HB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1	2.9	0.3	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
HN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	4.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
GD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
HI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CQ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
SC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
GZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
YN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1
XZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SN	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0
GS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	1.2	0.1	0.1	0.0	0.0
QH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0
NX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.9	0.0	0.0
XJ	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	3.6	0.1
S&P	1.4	2.9	4.5	3.3	3.6	4.9	2.1	0.7	1.9	3.5	1.1	3.5	1.4	3.7	2.6	2.3	3.6	4.7	0.7	1.9	0.3	3.1	1.9	1.1	1.0	0.0	1.1	1.2	1.9	1.3	2.5	2.5
BF	0.5	1.1	1.7	1.2	0.5	1.0	0.3	0.2	0.5	1.3	0.4	1.1	0.3	1.1	1.0	1.0	1.4	1.1	0.2	0.4	0.1	0.9	0.6	0.7	1.2	0.0	0.4	0.2	0.3	0.2	0.8	0.8
B&E	0.1	0.5	0.9	0.6	0.5	0.3	0.1	0.1	0.2	0.6	0.1	0.4	0.2	0.3	0.3	0.2	0.4	0.4	0.1	0.2	0.0	0.3	0.2	0.1	0.1	0.0	0.1	0.2	0.2	0.1	0.2	0.3
ISI	2.1	4.5	7.1	5.0	4.6	6.2	2.6	0.9	2.6	5.4	1.6	5.0	1.9	5.1	3.9	3.5	5.4	6.2	1.1	2.6	0.4	4.2	2.6	1.9	2.4	0.0	1.6	1.6	2.4	1.5	3.6	3.6

Fig. 4. Interprovincial contribution matrix of population-weighted annual mean $PM_{2.5}$ concentration induced by ISI pollutants emissions in 2020. Abbreviation: S&P, Sintering and pelletizing processes; B&E, BOF and EAF processes.

the national population-weighted annual mean $PM_{2.5}$ concentration, respectively.

In most provinces, the predominant source of the population-weighted $PM_{2.5}$ concentration was identified as local ISI emissions. The population-weighted annual mean $PM_{2.5}$ concentrations of Hebei and Liaoning provinces were the highest among all provinces, reaching up to 5.6 and 5.2 μg m^{-3}, respectively, due to local ISI emissions. The sintering and pelleting processes emerged as major contributors to $PM_{2.5}$ concentrations in Hebei and Liaoning, with contributions of 3.5 and 4.2 μg m^{-3}, respectively. The transboundary transport of air pollutants across provincial boundaries markedly impacts air quality, with certain regions experiencing more than 50% of their population-weighted $PM_{2.5}$ concentrations originating from external sources. For instance, in Beijing, a significant portion of the population-weighted $PM_{2.5}$ levels can be attributed to neighboring transport, particularly given the city's lack of iron and steel enterprises. Similarly, in Tianjin, the population-weighted $PM_{2.5}$ concentration was 4.5 μg m^{-3}, with transboundary transport contributing up to 64%.

3.3. $PM_{2.5}$-related premature deaths

The GEMM model was adopted to evaluate the environmental health impacts. Results showed that pollutant emissions from the iron and steel industry led to ~59,035 $PM_{2.5}$-related deaths throughout China in 2020, which accounted for ~6% of total premature deaths induced by $PM_{2.5}$ pollution [22]. Spatially, $PM_{2.5}$-related premature deaths caused by ISI emissions are mainly concentrated in North China, followed by the Yangtze River Delta (Fig. S5).

Among the total deaths, sintering and pelletizing processes contributed the most to mortality burdens nationwide (69%) and dominated mortality burdens, followed by the BF process (23%), while BOF and EAF processes contributed about 8%. From the contribution of provinces, the $PM_{2.5}$-related deaths caused by ISI emissions from different provinces varied greatly. ISI pollutants emissions in Hebei, Jiangsu, Shandong, Shanxi, and Nei Mongol contributed to ~48% of these deaths. For example, ISI emissions from Hebei and Jiangsu provinces contributed to the highest number of national $PM_{2.5}$-related deaths, with 8589 and 7199 cases, respectively, while Qinghai province had only 266 cases. Generally, provinces exhibiting elevated emissions of ISI pollutants and possessing dense populations are more likely to experience increased $PM_{2.5}$-related mortality. Besides, due to long-distance transport, ISI emissions in almost all provinces can cause premature deaths in other provinces. Remarkably, pollutants emitted by Hebei province have significantly impacted both locally and regionally. Locally, they were responsible for 3919 cases of health-related deaths. In addition, they also led to 723 and 655 cases in the adjacent provinces of Shandong and Henan, respectively (Fig. 5 and Fig. S6).

To reduce health effects, identifying the key emission sources is paramount. In this study, we ranked 93 emission sources (three manufacturing processes × 31 provinces) by their contributions to the national deaths. Results revealed that the top five sources accounted for 30% of the total deaths, the following 15 sources contributed 30−70%, and the top 20 of 93 emission sources contributed about 70% of the total mortality (Fig. S7). Among the top 20 emission sources, the sintering and pelletizing processes from Hebei, Jiangsu, Shandong, and Shanxi provinces caused 5,552, 4,605, 3,495, and 2546 cases of national deaths, respectively. The BF process from Hebei and Jiangsu provinces caused 2260 and 1894 cases, respectively. In addition, BOF and EAF processes from Hebei province also have a significant impact, incurring 777 cases of national deaths. The manufacturing processes across these provinces warrant heightened regulatory scrutiny, given the increased mortality burdens attributable to scaling effects, deficient emission controls, and population distribution patterns.

Due to the interacting effects of mortality burdens incurred by

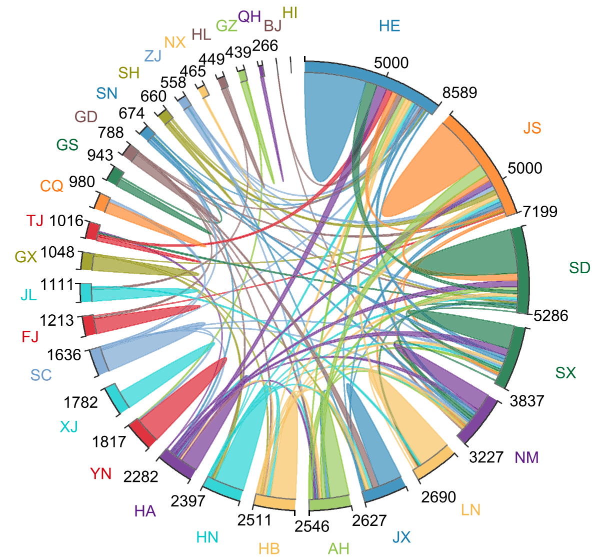

Fig. 5. Interprovincial spatial shift of $PM_{2.5}$-related deaths induced by ISI pollutants emissions.

outside regions and local emissions, net deaths ("all deaths due to local emission" minus "local deaths due to all emissions") from ISI were spatially heterogeneous. The characteristics of interprovincial transport of death revealed in Fig. 6 were significantly different. Provinces such as Hebei, Nei Mongol, Jiangsu, and Shanxi outsourced deaths resulting from ISI emissions being transported to neighboring provinces. For instance, in Hebei province, the national deaths from local ISI emissions were 8589 cases, while local deaths due to national ISI emissions were 5168. This resulted in net death tolls exceeding 3000 cases. In contrast, provinces such as Henan, Hunan, and Guangdong received deaths from adjacent provinces, mainly affected by neighboring provinces with larger emissions. This spillover effect of ISI emissions on the surrounding provinces led to inequality issues in environmental health.

3.4. Synergistic assessment between $PM_{2.5}$-related premature deaths and CO_2 emissions

To identify the provinces that require priority control from the perspective of health impact and carbon emissions, we conducted further analysis on the relationships between $PM_{2.5}$-related premature deaths and CO_2 emissions in 28 provinces (Fig. 7). Based on carbon emission level and health impact mentioned in Sections 3.1 and 3.3, we conducted quadrant analysis and classified 28 provinces into four regions (HH, HL, LL, and LH). Both health impacts and carbon emissions in HH region (the first quadrant, five provinces) are higher than the national average level; HL region (the second quadrant, 0 provinces) has higher health impact but lower carbon emission; LL region (the third quadrant, 17 provinces) has lower carbon emission and health impact level; and LH region (the fourth quadrant, six provinces) has lower health impact but higher carbon emission. Significant discrepancies exist among these four regions, such as the average $PM_{2.5}$-related premature deaths and CO_2 emissions in the HH region, which were 5520 cases and 197 million tons of CO_2 emissions, which were 5.9 and 8.7 times higher than those of the LL region, respectively. Furthermore, the health impact and carbon emission levels of Hebei (HE), Jiangsu (JS), and Shandong (SD) provinces are higher than those of other provinces. Therefore, from the perspective of collaboratively reducing health impact and carbon emissions, stricter control measures should be prioritized in these provinces.

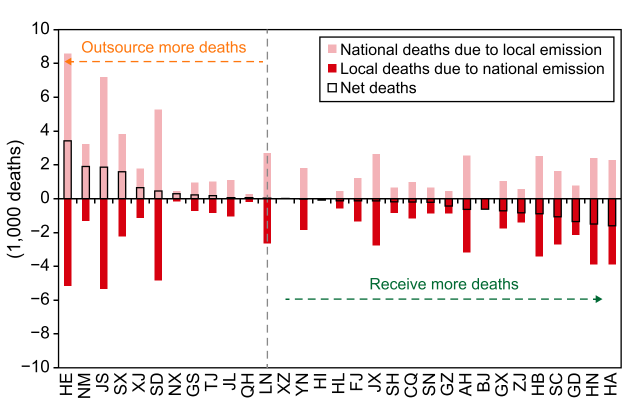

Fig. 6. Provincial $PM_{2.5}$-related deaths incurred by local emissions and transboundary transport of air pollution. Note: local deaths due to all emissions = the deaths in each province due to local emissions and emissions outside the boundary; all deaths due to local emission = the national deaths due to emissions in that province; net deaths = all deaths due to local emission-local deaths due to all emissions.

4. Discussion and conclusion

This study presented an integrated unit-based emission inventory for air pollutants and CO_2 emissions from 811 plants across major manufacturing processes within China's ISI in 2020. We analyzed the emission characteristics and evaluated the cross-contributions of provinces and ISI processes to $PM_{2.5}$ concentrations and related premature deaths. This section advances strategic recommendations to foster low-carbon and environmentally sustainable development within the ISI. These suggestions emphasize a collaborative approach to mitigating both air pollutants and CO_2 emissions, thereby reducing their environmental and public health impacts.

(1) China's steel production is categorized into two routes: the BF-BOF and EAF. Our study revealed that the BF-BOF process, which involves sintering/pelletizing, accounted for 90% of crude steel production in 2020. It contributed almost all SO_2 and NO_x emissions, alongside 98% of $PM_{2.5}$ and CO_2

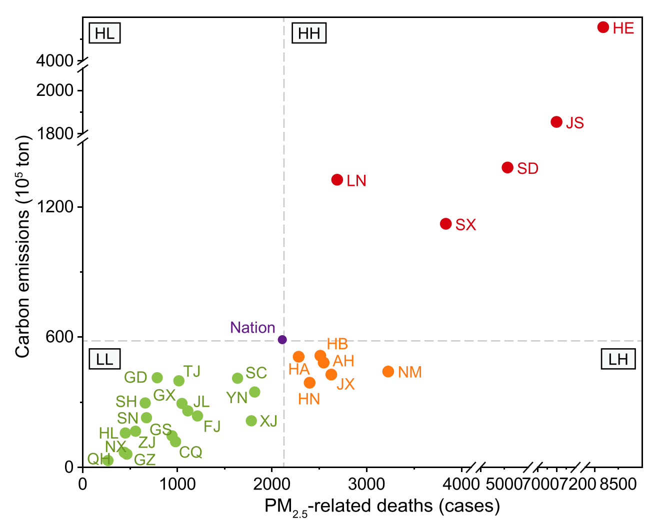

Fig. 7. Four-quadrant distribution of national $PM_{2.5}$-related deaths induced by pollutants emissions in each province and CO_2 emissions of 28 provinces. The coordinate origin represented the national average value (2108, 587) of CO_2 emissions and deaths.

emissions. The top 200 manufacturers follow the BF-BOF route, making the long-term shift towards the EAF route imperative to collaboratively reduce air pollutants and CO_2 emissions. This aligns with findings from recent studies [39,40]. However, the shift towards the EAF route presents significant challenges, such as hefty investment in ISI equipment, a lengthy service life, limited availability of ferrous scrap, high scrap prices, and high industrial electricity prices. Consequently, in the near future, a more practical and economically viable approach may involve the gradual decommissioning of outdated, small-scale BF-BOF facilities. For manufacturers under the HL category that have already completed ultra-low emission retrofits, we recommend pursuing further energy-saving transformations. In contrast, for LH category manufacturers with newer, large-scale, high-efficiency equipment lacking ultra-low emission retrofits, such retrofits could substantially reduce pollution emissions. For HH category manufacturers, we strongly advise replacing or eliminating them with EAF facilities or undertaking both ultra-low emission retrofits and energy-saving transformations, depending on equipment conditions and local pollution and carbon reduction requirements.

(2) From an environmental health perspective, about 48% of $PM_{2.5}$-related deaths due to ISI emissions originated from five provinces: Hebei, Jiangsu, Shandong, Shanxi, and Nei Mongol. Due to transboundary transport of air pollutants, obvious health impacts on the surroundings were observed among these provinces. Notably, ISI emissions in Hebei and Jiangsu outsourced the greatest number of deaths to neighboring provinces, while provinces like Henan received the greatest number of deaths from neighboring regions. This disparity among provinces highlights inequality issues of environmental health. This study shows that the iron and steel industry is mainly in economy-developed, densely inhabited, or upwind areas, such as Hebei, Jiangsu, and Shandong provinces. However, the transformation of ultra-low emissions in the steel industry has almost been completed in these provinces, and the reduction potential of end-of-pipe emission control is limited. Therefore, to mitigate environmental health impacts and manage steel overcapacity, we suggest prohibiting new steel production capacity in these densely inhabited regions and prioritizing eliminating outdated production capacity.

(3) Considering environmental health impacts and collaborative reduction of pollution and carbon emissions, the correlations between $PM_{2.5}$-related premature deaths and carbon emissions varied widely among provinces. As long-lived climate forcers, CO_2 accumulates in the atmosphere over decades to centuries. Thus, CO_2 emissions are directly determined by ISI's total energy consumption, energy efficiency, and process emission. Unlike CO_2, $PM_{2.5}$ concentration and related health burdens can be affected by transboundary transport, uneven population distributions, and air pollutant emissions. Given their higher carbon emissions and health impacts, Hebei, Jiangsu, Shandong, and Shanxi should be prioritized for low-carbon and clean development of ISI.

This study acknowledges certain uncertainties and limitations. Firstly, the scope of our estimation was confined to direct air pollutants and CO_2 emissions from iron and steel production, thereby overlooking indirect emissions from material transport and net import of electricity and heat generation. Secondly, our assessment was limited to premature deaths associated with $PM_{2.5}$ from major manufacturing processes, potentially underestimating the overall mortality burdens from the iron and steel industry. Further research is needed to assess CO_2 emissions and environmental health impacts from the entire iron and steel industry.

CRediT authorship contribution statement

Weiling Wu: Writing - Original Draft, Visualization. **Qian Tang**: Data Curation, Writing - Original Draft. **Wenbo Xue**: Conceptualization, Methodology, Supervision. **Xurong Shi**: Writing - Review & Editing. **Dadi Zhao**: Data Curation. **Zeyuan Liu**: Writing - Review & Editing. **Xin Liu**: Software, Visualization. **Chunlai Jiang**: Writing - Review & Editing. **Gang Yan**: Conceptualization, Methodology, Supervision. **Jinnan Wang**: Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2023.100367.

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