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Relocating Industrial Plants Delivers Win–Win Emission Reduction Benefits to Origin and Destination Regions

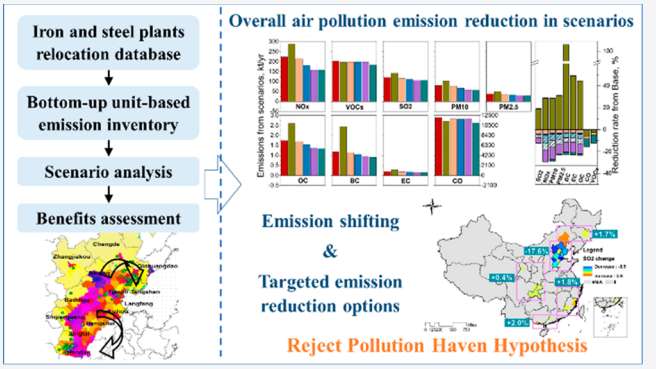
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ABSTRACT: Relocating pollution-intensive factories is one of the most effective measures to meet mandatory environmental regulations in developed cities while simultaneously imposing environmental pressure on the receiving cities. Existing studies often assume that relocated plants produce the same or higher emissions when relocated. However, the current pollution mitigation policies enforce even higher emission standards in the destination after plant relocation. We employ a bottom-up pollution accounting approach to assess the impact of intraregional or interregional relocation of iron and steel plants in China's Beijing–Tianjin–Hebei (BTH) area on various air pollutants; specifically, seven policy scenarios are modeled, based on stringency, implementation scope, and production technologies. We find that relocation combined with emission standards enforcement and shifts from BOF (basic oxygen furnace) to EAF (electric arc furnace) production technology may significantly reduce emissions within and outside BTH areas by as much as 28.8% compared to business as usual. The observed reduction is mainly due to the requirement of meeting ultralow emission standards directly or indirectly after relocation. Both origin and destination cities benefit from the relocation, with limited emission spillovers (+9.1%) for destinations outside BTH and even a net reduction (9.4%) in Tangshan. We conclude that combining factory relocation with stricter emission standards and production technological innovation could circumvent the Pollution Haven Hypothesis and deliver win–win air pollution reduction benefits for both origins and destinations.



KEYWORDS: *Industrial relocation, air pollution mitigation, process units-based bottom-up model, Pollution Haven Hypothesis*

1. INTRODUCTION

Megacities in fast-growing emerging economies such as China are home to heavy industries like the iron and steel industry (ISI), which emits more than 40% of national air pollutants, seriously threatening citizens' health.[1−3] To address these challenges, the State Council of China established the most stringent air pollution policy ever, the Air Pollution Prevention and Control Action Plan (APPCAP), in 2013.[4] The APPCAP set the goal for megacities like Beijing–Tianjin–Hebei (BTH) to cut the level of $PM_{2.5}$ by 25% in five years. Moreover, local governments have incorporated the air quality targets in their performance appraisal systems. Incentivized by the new performance criteria, local governments launched various urgent and effective pollution control measures. One such measure is the outward relocation of pollution-intensive factories, which is considered an effective approach to reduce local air pollution in some well-developed but severely polluted cities. As a result, factory relocation has been incorporated into the APPCAP agenda.[5] For example, in the largest ISI relocation project ever in China, Shougang Group (~8 million tonnes production capacity of steel, equivalent to the national scale of the entire UK in 2018) was relocated from Beijing to Tangshan in 2010 in a bid to alleviate air pollution in Beijing.

Scholars have investigated the impacts of industrial relocation on air pollution emissions and human health from the perspective of assessing the outsourcing impacts derived from trade activities.[6−8] The resulting shift of emissions has been widely examined in the context of the Pollution Haven Hypothesis (PHH),[9−13] a theory that is supported by studies focusing on interregional relocation, in particular.[14−20] However, existing studies present mixed conclusions regarding the existence of the Pollution Haven Hypothesis.[21] In fact, the effects of relocation are reflected in not only the spatial

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movement of plants but also their production factors, such as production capacity replacement and upgraded technology. Most existing studies focus on particular industry sectors, generally taking the industrial plants in a specific industry sector as a whole, thus neglecting the significant heterogeneity across individual plants in terms of emissions.[22−25] In addition, overlooking the policy-driven innovations and higher emission standards associated with industry relocation may also result in underestimations of the emission mitigation from the relocation. Indeed, the heterogeneity among industrial plants should be considered by compiling high-resolution inventories to improve the measurement accuracy.[26−28] Meanwhile, pollution control policies[29] including ISI plants are crucial to understanding the actual effects of relocation on air pollution.

To uncover a fuller picture of the industrial plants' relocations and associated impacts on air pollution, we carry out a comprehensive assessment of the environmental impacts of relocation at the unit level (at each individual factory). This assessment is based on our newly constructed unit-level emission inventory and ISI relocation data for the BTH area, one of the world's largest megalopolises. A heavily polluted region with seven out of 50 global cities with the worst air pollution in 2019,[30] BTH is home to 14.2% of the global crude steel production. BTH is also the biggest victim of ISI pollutant emissions, with 10%−20% of the $PM_{2.5}$ pollutants emissions from the ISI in a large number of cities.[28,31] Since APPCAP was implemented in 2013, BTH planned to transfer around 32% of ISI production capacity to less-developed and less-populous locations such as Tangshan (inside BTH) or cities in nine other provinces (outside BTH) within five years (Figure S1). Meanwhile, the government set stringent environmental protection policies such as larger equipment and ultralow emission (ULE) standard to target the negative emission displacement, which aims to reduce the emission displacement to the move-in regions, thus reducing the national air pollution emissions during the industrial relocation. As a result, ISI relocation reshapes the production distribution, air pollution profiles, and related health impacts for both origin and destination cities.

In this paper, we assess the air pollution effects of ISI relocation within and outside the BTH area using multiple air pollution indicators. Seven policy scenarios were distinguished by considering the stringency and implementation scope of emission standards as well as production technology by 2025. We develop a bottom-up unit-level air pollution estimation model to compile high-resolution emission inventories before and after relocation. This will allow us to better understand the variations in emissions from ISI plants according to the parameters of each relocation project (location, units type, and size) since 2013. In addition, we present a high-resolution map of emission reduction benefits derived from the industrial relocations and compare the benefits across different policy measures. We find that both origin and destination cities benefit significantly in terms of emission reductions in the most stringent scenario when plant relocation combined with ULE implementation and production technology shifts, which reject the Pollution Haven Hypothesis. The heavy industry relocation across regions presents a feasible approach to alleviate air pollution within a region rather than outsourcing via interregional trading. This study showcases a novel methodology and data inventory to assess various impacts for the relocation of heavy industry across regions. Results provide practical solutions for relocating heavy industry within emerging economies while delivering win−win air pollution mitigation benefits for both origins and destinations.

2. MATERIALS AND METHODS

2.1. System Boundary. According to the Air Pollution Prevention and Control Action Plan, one air pollution mitigation measure is to transfer industry capacity out, leading to "production relocation". We focus on the iron and steel industry (ISI) relocation in the heavily polluted Beijing−Tianjin−Hebei (BTH) area in China. This relocation policy reshaped the environmental quality in the BTH area and beyond. The measures associated with production relocation include plant relocation, combining small plants in new locations, and capacity replacement among plants. We collected data on 55 projects relevant to BTH, including completed projects and those planned since 2013, retrieved primarily from government websites.

Nine typical air pollutants were taken into account: sulfur dioxide (SO_2), nitrogen oxides (NO_X), PM_{10} (particulate matter with diameter less than or equal to 10 μm), $PM_{2.5}$, black carbon (BC), carbon monoxide (CO), elemental carbon (EC), organic carbon (OC), and volatile organic carbons (VOCs). These carbonaceous species (BC, CO, EC, OC, and VOCs) are major components or precursors of $PM_{2.5}$ pollution as well as crucial climate forcers, threatening air quality, human health, climate system, and ecosystems.[32,33] Our study covers both direct air pollutant emissions (e.g., fuel combustion in the ISI process) and indirect air pollutant emissions (e.g., the electricity generation) following the GHG Protocol Scope 2 Guidance.[34] In contrast, fugitive emissions and the relatively lower Scope 3 emissions (e.g., mining or transportation of raw materials and infrastructure-related emissions) are beyond the scope of our study, given the higher uncertainties and extra challenges in the development of inventory or complex modeling[35−37] and thus are not taken into consideration.

2.2. Unit-Level Emission Inventory. Our study developed a unit-based bottom-up model to estimate the impacts of "production relocation" on air pollutants mitigation in the BTH area. We examined the overall benefits holistically by considering the effects on destination areas outside BTH. Unlike other studies of the "spillover effects" of public policies that focus on free riders, we internalize these spillovers into a single analysis, reflecting the relocation focus of the policy being analyzed.

2.2.1. ISI Relocation Database. The ISI relocation database consists of detailed unit-specific relocation information, which facilities the estimation of the unit-specific emissions shifting across cities along with the ISI relocation from BTH.

To compile the relocation database, we referred to the original database of iron and steel works in 2018, which was obtained from the Appraisal Center for Environment and Engineering, Ministry of Ecology and Environment. It contained numerous plant-level data (233 steel-works plants and 1484 units) with detailed information such as the process activity level, unit air pollutant emissions, flus gas rate, and geographic location. In addition, we updated the original database with the information on unit size from the relevant authorities.

The relocation database was then compiled by coupling the original database with the relocation information, such as name, type, size, and location of relocated units before and after relocation. The relocation database encompasses the original units and newly built units related to 55 relocation

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

projects in BTH and nine provinces outside BTH. In total, 148 blast furnaces, 126 basic oxygen furnaces, and four EAFs were involved in the relocation database. Combined with the unit-specific continuous emission monitoring system (CEMS) data, we can detail the coverage that would be required to comply with ULE standards after relocation in our scenarios. Details can be found in Supporting Information, Sections 1 and 2.

2.2.2. Air Pollutants Emission Estimations with CEMS Data. The absolute air pollutant emissions of each steel-works plant unit were estimated by the process unit-based bottom-up model, i.e., multiplying the activity level by the emission factors, expressed as[38]

$$E_{i,n,t} = \sum_j E_{i,j,n,t} = \sum_j A_{j,n,t} \times EF_{i,j,n,t} \quad (1)$$

where the subscripts i, j, n, and t represent the pollutant species, process, city, and year. $E_{i,n,t}$ is the pollutant i emission in city n in calendar year t. $E_{i,j,n,t}$ is the pollutant i emission from process j in city n in calendar year t. $A_{j,n,t}$ is the activity level, represented by the products output of process j in city n in year t (tons/y). $EF_{i,j,n,t}$ is the emission factor of pollutant i from process j in city n in year t (kg/tons).

Activity Level. The activity levels of both the unrelocated and relocated plants in 2018 and 2025 were obtained from our refined database.

Emission Factors. The CEMS was used to track real-time concentrations of selected air pollutants in the flue gas in plants, including coal power plants and steel-works plants. The CEMS data provides direct, actual measurements and avoids the indirect parameters and associated assumptions used in previous studies.[39] On the basis of the stack concentration covered in CEMS data, the unit-level emission factors can be estimated as follows

$$EF_{i,j,n,t} = C_{i,j,n,t} \times V_{i,j,n,t} \quad (2)$$

where $C_{i,j,n,t}$ is the stack concentration in flus gas of air pollutant i of process j in city n in year t (kg/m^3). $V_{i,j,n,t}$ is the flus gas volume, that is, the flue gas volume per unit of fuel consumption (m^3/kg for solid fuel or m^3/m^3 for gas-based units). It is worth noting that the CEMS concentration data were monitored after the pollution control devices (if available); thus, the abated emission factor was estimated without using parameters such as removal efficiency.

2.2.3. Indirect Air Pollutants Emission Estimation. In terms of air pollutant emissions from electricity generation, we applied the process unit-based bottom-up model with process electricity consumption and air pollutant emission factors of electricity generation, expressed as

$$IE_{i,n,t} = \sum_j IE_{i,j,n,t} = \sum_j A_{j,n,t} \times EF_{ele,i,j,n,t} = \sum_j A_{j,n,t} \times EI_{j,n,t} \times EF_{ele,i,n,t} \quad (3)$$

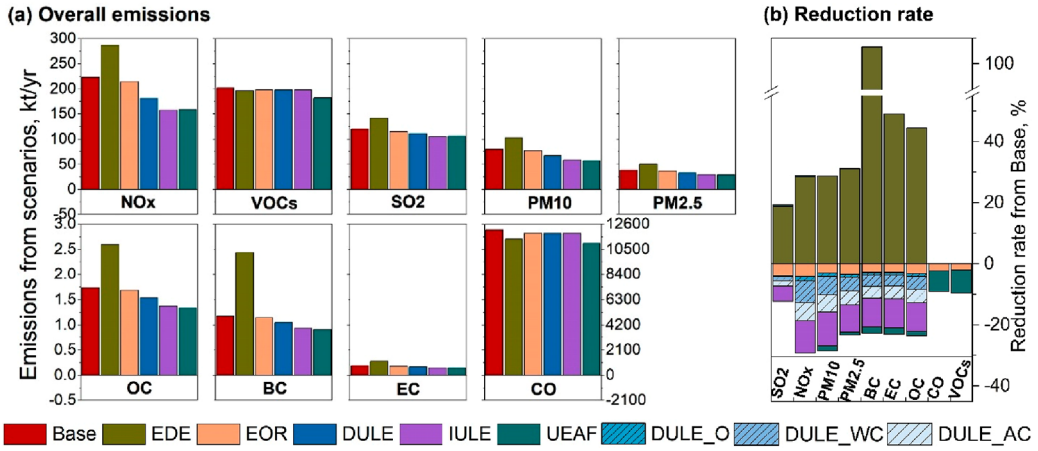
where $EF_{ele,i,j,n,t}$ is the emission factor of pollutant i from electricity consumption in process j in city n in year t (kg/tons). $EI_{j,n,t}$ is the electricity intensity in process j in city n in year t (kWh/tons). $EF_{ele,i,n,t}$ represents the emission factor of pollutant i from electricity generation in city n in year t (kg/tons). The total air pollutant emission is obtained by summing the direct and indirect emissions.

2.3. Scenario Analysis. Our study aimed to explore the impacts of steel-works production relocation on air pollution emissions in cities within and beyond the boundary of the BTH area. Since most production relocation projects have not been completed yet, we set 2025 as the target year because there is sufficient time to complete the demolition, rebuild, and commission the plants. Thus, a refined relocation database before and after production relocation for 2025 is established in the scenario analysis. Given the huge uncertainties of accurate time of relocation units commission and the lifespan, we did not examine the cumulative air pollution benefits and focus on the single year 2025 in the analysis. The framework is shown in Figure S2.

To identify the future emission reduction potential in BTH under various scenarios in 2025, we considered a series of factors such as emission standards and production technology changes. In all scenarios, no additional ISI production capacity will be invested in BTH referring to the "Three-year Action Plan to Win the Blue Sky Defense War" (the Blue Sky Defense War) issued by State Council of China in 2018.[40] The *Base* scenario assumed exactly the same capacity with the same size and geographic distribution as 2018 but with production scaled to 2025 based on the change ratio of crude steel production level. The *OD* (*Outdated*) scenario considered the retirement of small, outdated, and low-efficiency plants based on the "Plan for Elimination Overcapacity in Iron and Steel Industry (2018−2020) in Hebei province." The *EDE* (*Relocation as emission standards of destination sites*) and *EOR* (*Relocation as emission standards of original sites*) scenarios reshaped the production portfolio with equipment renovations and pollutant emission intensities in compliance with those of the destination and origin areas, respectively. The "Opinions on Advancing the Implementation of Ultralow Emissions in the Iron and Steel industry" (ULE policy) issued by the Chinese government specified that the compliance with ULE standards by newly built (including relocated) iron and steel projects is mandatory.[41] Thus, in the *DULE* (*Relocation as ULE standards by relocated units directly*) scenario and *IULE* (*Relocation as ULE standards by relocated units indirectly*) scenario, the equipments' air pollutant emission concentrations complied with the ultralow emission standards for the relocation units directly or other units induced by relocation in BTH area indirectly. Furthermore, in the *UEAF* (*Relocation as ULE standards and production technology shifts*) scenario, the production structure of the crude steel BOF (basic oxygen furnace)/EAF (electric arc furnace) changed from 90.7/9.3 to 79.6/20.4, following the "Guidelines on Promoting the High-quality Development of the Iron and Steel Industry" (HQD policy),[42] with BOF replaced by EAF in the most polluted relocation plants. The number of cost-effective EAFs is very small in China at the moment mainly due to the scarcity of scrap steel, which however is expected to grow substantially to support the EAF shifts in the future and highly encouraged in both ULE and HQD policies. It is also worth noting that the scope of our study is the relocation-imposed emission reductions mainly from ULE emission standards and technology shifts. By contrast, expected benefits from ISI technology innovation resulting from other policy factors are beyond the scope of this study.

Apart from the air pollutants and health benefits assessment, the ISI relocation also promotes the retirement of small, outdated, and low-efficiency plants, which is used for capacity replacement to build larger and more efficient facilities. By comparing the facility size distribution before and after relocation, we can figure out how relocation contributes to

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX



(c) Scenario descriptions

Scenario Name	Descriptions
Base	This scenario keeps every parameter the same as the year 2018.
EDE	This scenario considers partial relocating capacity to the less populous area according to our collection data, which complies with the destination area's emission standards or emission intensity. This scenario is built upon shutting down the outdated and most pollution-intensive plants in the BTH area referring to the "Plan for Elimination Overcapacity in ISI (2018-2020) in Hebei province" (referred to as the *OD* scenario, details are available in *Materials and Methods & Supplementary figures*).
EOR	The scenario was designed based on the government's request that relocated plants adopt technology that emits the same or lower levels of pollution compared to the original site.
DULE	**The power sector has adopted the ULE retrofit**, and associated emission reduction has been found to be higher than other measures [39-40]. Hence, we designed the scenarios to test the effect of the ULE in the context of ISI relocation. In this *DULE* scenario, the relocated process units are featured with the compliance of ULE standards, which includes three components, the units at the original place (*DULE_O*), relocated units within the same cities (*DULE_WC*), and relocated units across cities (*DULE_AC*).
IULE	In addition to the relocated units, in this scenario, other process units in the same plant also required to achieve ULE compliance induced by the relocated units.
UEAF	Upon *IULE*, we added the measure of replacing BOF (basic oxygen furnace) by EAF (electric arc furnace) when the highest polluting plants are relocated.

Figure 1. Emission and reduction rate under each scenario in 2025. (a) Overall emissions. (b) Emission reduction rate of each scenario. The denominator of the reduction rate represents the total emissions from the BTH area in the *Base* scenario. (c) Scenario descriptions. After 10,000 stimulations, the nine pollutant emissions at seven scenarios varied within ±0.197%−1.985%, in terms of 2 standard deviations, indicating the robustness of the modeling results.

accelerating the industrial structure upgrade by eliminating outdated and inefficient capacities. These can be found in the Discussion and Policy Implications.

2.4. Uncertainty Analysis. We conducted a series of uncertainty analyses to verify the reliability of our estimations. There are uncertainties and limitations associated with the unit-based emission inventory and health benefits evaluation model in this study. The limited coverage of CEMS data and theoretical flus gas volume are important sources of uncertainties of emission inventory, which have been proven to be limited.[38,43−45] Employing a reliable emission inventory, we further examined the uncertainties of emission reduction potential considering the uncertain future activity level by employing a Monte Carlo approach.

The activity data, as important input data in the emission estimation, should be considered in the uncertainty analysis. The production data at the unit level for 2025 were assumed to follow a normal distribution with coefficients of variation of 5% (CV, the standard deviation divided by the mean).[44] A Monte Carlo approach was applied to generate random values for activity level data. Relying on 10,000 stimulations, the nine pollutant emissions at seven scenarios were modeled to examine the uncertainties of the results.

2.5. Data Sources. The data on ULE emission standards are presented in Table S1.[41] The data about indirect emission factors from the electricity generation are shown in Table S2 and Figure S3, and the electricity emission factors are drawn from previous studies,[46−48] while geographic electricity mix disparity was taken into consideration.[49]

3. RESULTS

3.1. Overall Emission Mitigation Potential of ISI Relocation. Based on the unit-level emission inventory and relocation database developed in this study, we assess the changes in air pollution levels in the BTH megalopolis area and the destination region in 2025 under seven possible scenarios described in Figure 1(c) (Materials and Methods and Supporting Information, Sections 1 and 2).

Our scenario analysis results follow the Pollution Haven Hypothesis in the *EDE* scenario, which assumed that emission

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

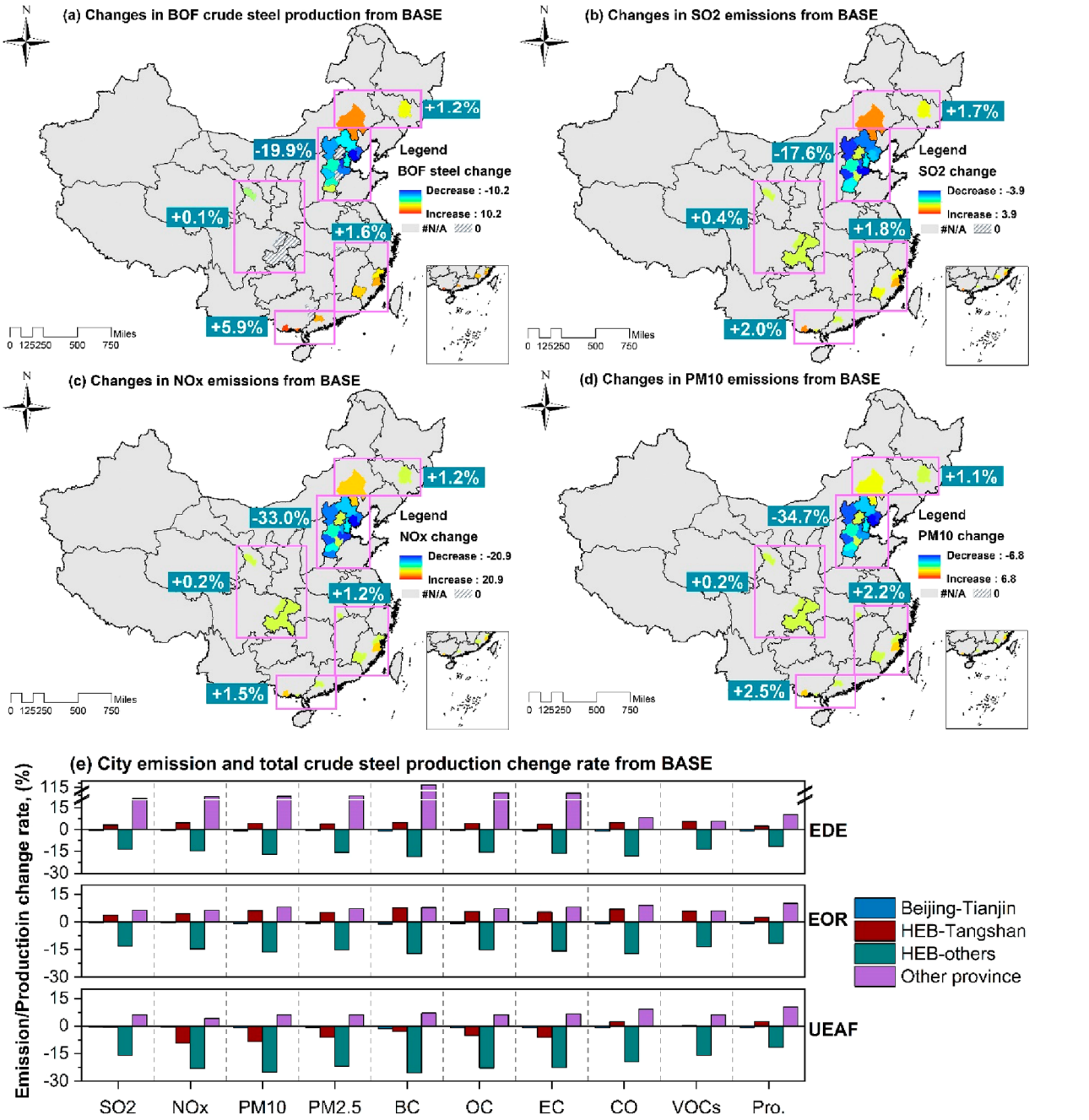


Figure 2. Crude steel production and emission shifts across cities under selected scenarios. (a)−(d) BOF crude steel production and emission shift across cities in scenario *UEAF* for 2025. BOF production relocation implies that the upstream sintering and ironmaking processes are relocated altogether unless no upstream process exists. Color indicates the production or emission change. From top to bottom, left to right, the first box indicates Inner Mongolia−Jilin, second BTH, third Gansu−Sichuan−Chongqing, fourth Hubei−Fujian, and the fifth Guangxi−Guangdong, respectively. Details of production shifting are shown in Figure S5. (e) Distribution of emission or total crude steel production change rate among cities in scenarios *EDE*, *EOR*, and *RLUE* for 2025. Zero represents the emission level in the *Base* scenario. The denominator of the change rate represents the total emissions (or steel production by BOF and EAF) from the BTH area in the *Base* scenario. The change rate indicates the overall change rate in *EDE*, *EOR*, and *UEAF* scenarios from the *Base* scenario for each pollutant. For various pollutants, the Beijing−Tianjin area presents a slight reduction rate by less than 1.5% in the three scenarios. Other scenarios are shown in Figure S4.

standards in the destinations areas would be adopted by relocated units after relocation. However, our results for other scenarios show that the net emission mitigation for all air pollutants could be as high as 28.8% (NO_X) and 28.6% (PM_{10}) in *UEAF* against the *Base* scenario when ISI enterprises in BTH are relocated with upgraded production technology and stricter emission standards (Figure 1). The SO_2 presents a relatively smaller emission reduction percentage by 11.7% in *UEAF* than that of the *Base* scenario. The potential larger NO_X reductions are closely related to the strict ULE standards, reducing the NO_X limits by up to 83.3%, as compared to 80.0% and 80.6% for PM and SO_2, respectively. Notably, the considerable emission reduction of NO_X is even higher than the overall NO_X emission reduction target (>15%) in polluted areas (including BTH) proposed by the "Blue Sky Defense War".[40] The benefits of overall emission reduction reject the

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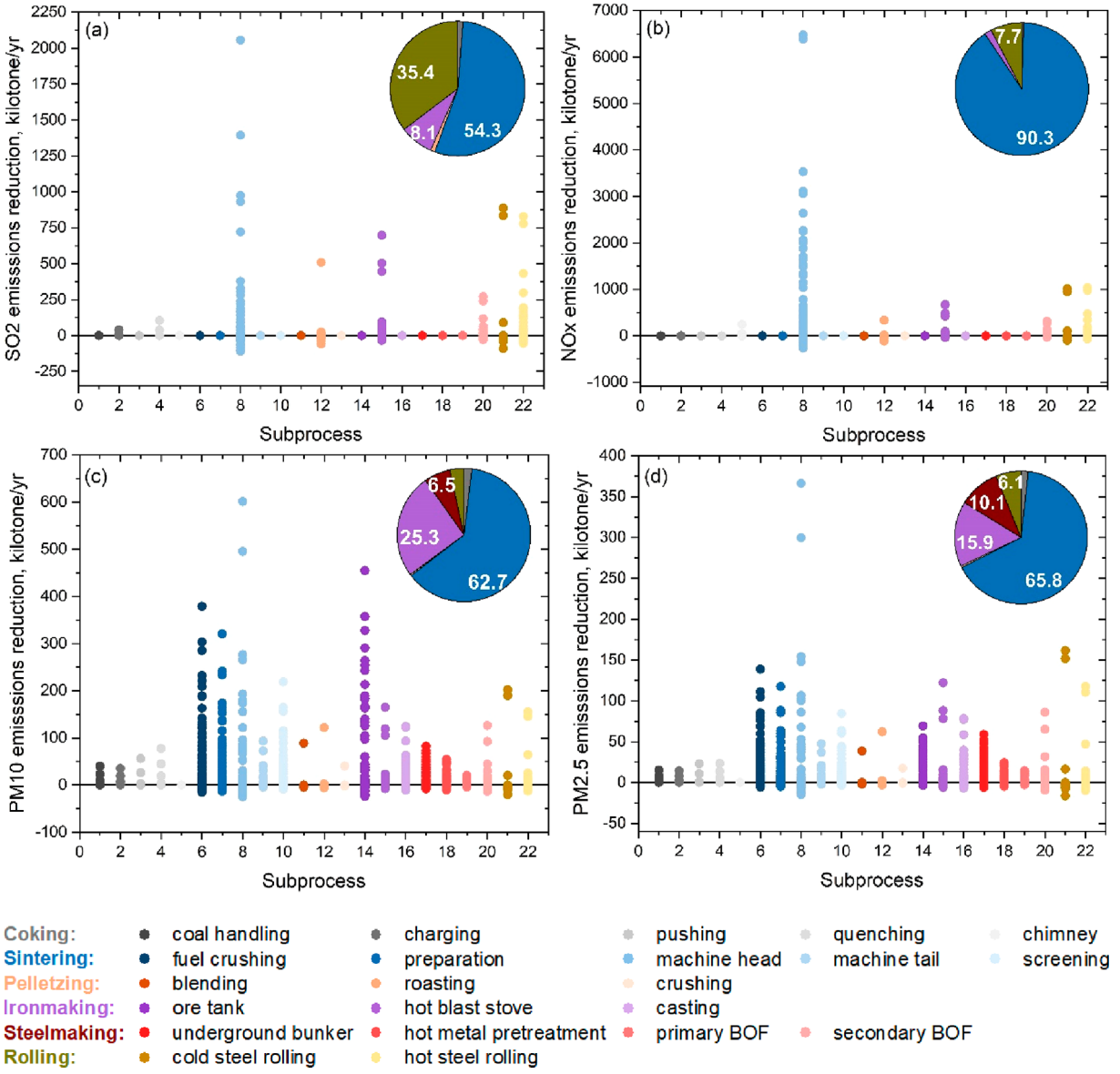


Figure 3. Unit-level absolute air pollutant emission reductions from subprocesses and reduction rates of production processes under scenario *IULE*. Each dot in the upper portion (above the horizontal line at 0) of this plot represents emission reduction of a subprocess in one unit (sorted by subprocesses). Each dot in the horizontal line at 0 represents no emission reduction from the subprocess. On the contrary, each dot in the lower portion of this plot represents overall emission increases of subprocess in other units. The pie charts indicate the emission reduction rates of processes. Steelmaking includes BOF and EAF. EAF is not shown in the bar chart due to the net emission increase. Values (higher than 5; unit, %) in brackets represent the contributions of the reduction of the process to the total reduction of the *IULE* scenario from the *Base* scenario. Details for ISI processes and all pollutants can be found in Figures S6−S8.

PHH hypothesis, in contrast to the findings of several existing trade-related studies.[10,50] We find that the emission mitigation is the result of air pollution control measures implemented during relocation, while other studies assume that "relocation with low cost but more polluted technology".[13,24]

A similar reduction pattern is observed for seven air pollutants under these scenarios, with ULE standards responsible for the most significant pollution reduction during the domestic relocation. The CO and VOCs were not considered in *DULE* (ULE adoption for relocation units) and *IULE* (ULE adoption for both relocation units and others within the same plant) due to the limited sources and significant uncertainties in the emission factor estimation when utilizing different pollution abatement technologies to meet ULE standards. In subsequent analyses, the seven pollutants evaluated do not include CO and VOCs unless specified. In scenario *DULE*, we observe emission reduction benefits ranging from 7.3%−18.6% at the overall scale for seven air pollutants. There are three contributors to overall emission reduction through compliance with ULE during relocation: the units at the original place (*DULE_O*), relocated units within the same cities (*DULE_WC*), and relocated units across cities (*DULE_AC*), in which *DULE_WC* and *DULE_AC* are major contributors. When other units were required to meet the ULE standards induced by the relocated units indirectly, the abatement in overall air pollutant emissions increase by 5.0%−11.0% compared to *DULE*.

Apart from stringent emission standards, our results show that shifting the production technology from BOF to EAF contributes to emission reduction on a scale of 0.9%−7.7%

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

compared to *IULE*, except for SO_2 and NO_X, which is noteworthy. This result is due to the replacement of long process (BOF) by short process (EAF) steelmaking. Short process steelmaking relies on scraps as inputs, which reduces both direct and indirect emissions derived from sintering and ironmaking. Although the electricity intensity of the EAF process is higher than that of BOF (353.05 kWh/t EAF crude steel vs 50.1 kWh/t BOF crude steel), the emission reduction benefit at the upstream processes exceeds the loss in the electricity intensity.[51,52]

3.2. Emission Shifting between Cities Due to Relocation. To further understand the environmental impact of industrial relocation, we show the emission displacement across cities from two perspectives: emission shifting to the regions outside BTH (interregional relocation) and emission mitigation outcomes within BTH (intraregional relocation). Figure 2(e) shows the distribution of emission reductions of nine pollutants (SO_2, NO_X, PM_{10}, $PM_{2.5}$, BC, OC, EC, CO, and VOCs) among cities in scenarios *EDE*, *EOR*, and *UEAF* (other scenarios are shown in Figure S4). Using the example of BOF steel production and pollutants SO_2, NO_X, and PM_{10}, Figure 2(a)−(d) illustrates the shift of both the production and emission in scenario *UEAF* when all air pollution control measures are applied. For example, with 19.9% of the BOF production relocation out of BTH, the simulation shows a 35% drop in PM_{10} pollution within BTH at the cost of PM_{10} emission displacement (+6%) to the receiving provinces. The negative spillover effect to these provinces is fairly small considering the gain on the overall scale. In particular, Guangxi−Guangdong receives 5.9% of relocated BOF production with an increase of +2.5% emission shifting.

Our results show that the emission displacement to other provinces is +5.9%−121.4% and +6.0%−9.1% in scenarios *EDE* and *EOR*, respectively, for the nine air pollutants (relocation without any control). Compared to *EOR*, such an impact can be reduced by 7.2%−33.8% in scenario *UEAF* when ULE standards are adopted (as shown in Figure 2(e)). This result highlights that the negative environmental impact on destination cities will be significantly mitigated if the air pollution control measures are taken into consideration during the industrial relocation, which in turn generates more benefits from industrial relocation at the overall scale factoring in both origin and destination emissions.

Within the BTH area, several pieces of empirical evidence have identified the ISI as the key source of air pollution.[44,53] In a bid to reduce the impacts of emissions on the capital city through air pollutant transport, cities in Hebei province adjacent to Beijing (e.g., Zhangjiakou and Langfang) were under pressure to relocate the pig iron and crude steel industries. Our results show that industrial relocation is effective: the highly polluted Hebei province (excluding Tangshan) turns out to be the biggest beneficiary of the industrial relocation in scenario *UEAF* (Figure 2(e)). Compared to this region's emission level in the *Base* scenario, there is a 16.0%−25.4% emission reduction for nine air pollutants in this scenario.

Tangshan is the major relocation destination within the BTH area. Tangshan receives an emission displacement of +3.0%−5.5% (*EDE*) and +3.7%−7.7% (*EOR*), respectively (Figure 2(e)), for different air pollutants due to receiving around 3.0% production capacity displacement in ironmaking and BOF steelmaking. As one of China's largest coastal iron and steel manufacturing bases, Tangshan has long suffered from extreme air pollution due to ISI.[28,39] However, it is interesting to see that the net emission reductions of NO_X, PM_{10}, and $PM_{2.5}$ can be achieved by ULE standards compliance of the relocated units, including three components, i.e., the units at the original place, relocated units within Tangshan, and relocated units from outside to Tangshan. Taking NO_X as the example, the emission increase in the *EDE* scenario (10.2 Kt) is offset by the reduction derived from compliance with ULE standards by the three components in the *DULE* scenario (−18.5Kt). Eventually, after ULE standards compliance and EAF upgrade, it has become the beneficiary of industrial relocation (except CO and VOCs, which are not considered in scenarios with ULE standards). For NO_X and PM_{10}, Tangshan accounts for as much as one-third of the overall emission reductions (Figure 2(e)). Our study suggests that enforcing ultralow-emission (ULE) standards during relocation plays a vital role in the overall pollution abatement of ISI relocation. To gain more insight into the effect of ULE standards, we examine the distribution of emission reduction among production processes.

3.3. Targeted Emission Opportunities at the Unit Level during Relocation. Figure 3 illustrates the contribution of main production processes to the emission reduction under the *IULE* scenario. The sintering process is the major contributor to the emission reduction, accounting for 23.7%−90.3% of the *IULE* reduction of each pollutant. The ironmaking process is another leading contributor of most air pollutants (except SO_2, NOx, and VOCs), accounting for 15.9%−50.4% of overall emissions. This is mainly because of the high emission intensities of the sintering and ironmaking processes. In contrast, other processes such as basic oxygen furnaces and steel rolling account for only 5.0%−22.1% and 2.1%−8.1% of overall emissions, respectively. As a result, sintering and ironmaking processes have more potential for emission reductions in terms of the ULE standards because 68.3% of sinter machines units and 33.1% of blast furnaces units do not meet the ULE standards (for PM), compared to 29.0% for basic oxygen furnaces. For pollutants SO_2, NO_X, and VOCs, processes such as steel rolling (35.4%, 7.7%, and 40.3%) contribute more to emission reduction.

We further examine the unit-level emission reduction pattern of 22 subprocesses in the *IULE* scenario, which could serve as the foundation for implementing detailed measures to control air pollution. For instance, the high SO_2 and NO_X emission concentrations of a machine head makes it the largest contributor to the air pollutant emissions in the sintering process, especially for SO_2, NO_X, CO, and VOCs emissions, followed by hot or cold rolling. More complicated subprocesses are involved and require attention in PM-relevant emissions. These include fuel crushing, preparation in the sintering process, blast ore tank, and blast furnace casting in the ironmaking process. The compliance of large plants for ULE standards dominates the overall pollution reduction, regardless of how the plants relocate (whether direct relocation or capacity replacement). Identifying main production processes and their key subprocesses provides insights into the development of future policy interventions to mitigate multiple air pollutant emissions.

4. DISCUSSION AND POLICY IMPLICATIONS

Our study reveals that the industrial relocation policy could achieve pollution emission mitigation at both the local and national scales, despite limited spillover effects to other

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

receiving regions. In particular, our research has the following implications for other industries and emerging economies:

Implementation of stricter emission standards during the relocation of industries, which is mandatory generally, could achieve win−win pollution reduction benefits in both origin and destination regions. The ULE emission standard is hugely significant in cutting down local air pollution emissions as confirmed by Tang and co-workers in other related sectors such as power[38,44,46] and avoiding the Pollution Haven Hypothesis, i.e., higher overall emissions after relocation. A large portion (∼20%) of plants nationwide had attained ULE levels for all pollutants by the end of 2018.[45] It indicates the operational feasibility and technical viability of the ULE standards. Relocation provides an opportune time to upgrade the original units to more advanced technologies. For less developed regions receiving heavy industries to boost economic development,[54] our findings suggest that the local government could raise the entry barriers to reinforce that relocated plants meet certain pollution emission limits.[55] Other regulation tools, such as environmental impact assessment (EIA), should be conducted to enforce compliance with stricter emission standards by the relocated plants.[56] The results demonstrate that relocation induces around half of the BTH units production to meet ULE standards. Specifically, the major destination city, Tangshan, received 2.5% of the BOF capacity in BTH, being the largest contributor to the overall PM_{10} and NO_X reduction, which largely benefits from the diffusion of innovation with clustering of industrial clean technologies.[57] Meanwhile, despite the fact that the destination cities outside BTH suffered from emissions increases, further or net emission reductions could be expected if emission standards enforcement of local units induced by relocation are fully taken into account.

Moreover, to meet ULE standards, we identify targeted emission mitigation opportunities in terms of both processes (e.g., sintering, ironmaking) and subprocesses (e.g., machine head, blast ore tank) according to different pollutants for the relocated plants. The ULE compliance of large relocated plants is particularly crucial for pollution reduction. Various abatement technologies have been proposed and evaluated,[58−60] including multiple flue gas treatment facilities, sintering flue gas desulphurization, and flue gas denitrification. Thus, appropriate timetables for relocations and specified technology retrofit pathways to comply with ULE, which varies according to different plants, avoid the PHH and promote ULE implementation across the entire nation.

Shifting from BOF to EAF leads to further pollution reduction benefits during relocation. The EAF technology is one of the commercial production routes with comparable levelized cost of steel production with BF-BOF technology worldwide.[61] The shift from BOF to EAF induced by relocation contributes slightly to reducing the negative spillover of air pollution and, by extension, the PHH. In contrast, the limited emission mitigation contribution is mainly due to the indirect emission increases with higher penetrations of EAF, which accounts for 58.6% in total SO_2 emissions under 20% EAF (*UEAF*) scenario. Thus, the promotion of renewable sourced electricity in EAF is highly recommended. Moreover, it is worth noting that the availability of recycled steel scraps in China limits the EAF production scale for now,[62] lower than the national average target of 20% in 2025.[63] There have been debates on the feasibility of scrap resources to support high EAF production.[64] For example, according to Wang et al.'s estimates, China will become the largest scrap steel supplier after 2035, which can enable the growth of scrap-based EAF production.[65] In addition, the spatial and temporal analysis of in-use stock of steel showed that provinces (e.g., Jiangsu, Shandong, and Henan) with high in-use stock could prioritize EAF in relocation.[66] However, in practice, scrap steel recycling is affected by a number of factors, such as product designs, social behavior, governmental regulation, and policies. Furthermore, the scrap quality remains a huge challenge for high-quality steel production comparable to that from the BOF route.[67] Thus, more attention should be paid to the development of smart sorting, separation, and refinery production as well as measures to improve the quality of secondary steel production.

Economies of scale along with equipment enlargement induced by relocation presents potential opportunities for pollution mitigation. Our results indicate that industrial relocation played a crucial role in accelerating the industrial structure upgrade by eliminating outdated and low-efficiency capacity and promoting manufacturing units with higher levels of efficiency. After the relocation in 2025, the average size of equipment increases; for example, blast furnace increases from 971 to 1370 m^3, falling into the *Encouraged* category (Figure S9). Larger equipment is associated with energy efficiency improvement as presented in the Clean Production Standards for ISI (2018) (Table S3). Although there is a lack of data detailing the air pollution mitigation potential of energy efficiency improvement, its effectiveness has been well recognized in previous studies.[68−70] For example, the energy efficiency improvement options for the U.S. industry has helped to achieve environmental and energy security goals with varied levels of societal cost effectiveness.[71] Targeted measures may include process optimization and integration and upgrading process equipment to the commercially available best available technology (BAT), such as recovering and transforming excess energy into useful energy throughout the existing ISI production processes.

There are other promising air pollution abatement measures along with relocation, such as improving the quality of raw materials and fuels and promoting clean fuels and material input efficiency in facilities and buildings.[45,61,72] Future research opportunities exist to quantify the air pollution mitigation potential of these measures when data become available. Meanwhile, the cost increment and technology readiness levels of varied measures could be further investigated to explore the practical and feasible pathways for relocation companies. Moreover, following the GHG Protocol Scope 1, 2, and 3 Guidance,[34] it is paramount to take life cycle emissions into consideration during the development of a corporation's emission strategy. We recommend to choose the emissions of an entire supply chain as absolute reduction targets and to provide ISI relocation companies guidance with to what extent and in which sector they should engage with for upstream emissions reductions.[73]

Trade-offs analysis is required in the selection of relocation sites. The complicated $PM_{2.5}$ air quality modeling for the original and destination location is shaped by both the anthropogenic abatement measures and meteorological conditions.[53] Previous studies show that surface temperature, surface wind speed, and precipitation play crucial roles in the $PM_{2.5}$ concentrations by affecting the formation, dispersion, and scavenging of aerosols.[74] The air quality improvement resulting from the relocation is evidenced by the decrease of

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

$PM_{2.5}$ concentration extracted from the Tracking Air Pollution in China Database, for example, 11.5% reduction after Shijiazhuang Iron and Steel Co., Ltd. moved out in 2020.[75] Based on a simplified health impact modeling, relocation helps to avoid the PHH in terms of health impacts due to the difference in population density (Supporting Information, Sections 3 and 4, Figure S10). Results show that relocation contributes to 24.5% reduction in $PM_{2.5}$-related excess deaths in the *UEAF* scenario from the *Base* scenario, higher than that without considering population density, i.e., $PM_{2.5}$ emissions (23.3%). It is interesting to note that industrial relocation without additional measures (i.e., EOR) except population density changes outperformed other air pollution measures (e.g., production structure shift, ULE) in terms of benefits in avoided $PM_{2.5}$-related excess deaths. Although equity loss when shifting air pollution to less developed and sparsely populated areas is a concern,[76] it is possible to gain net environmental−health−economic benefits for destinations such as Tangshan in our study. Tangshan achieves a reduction of 5.5% in $PM_{2.5}$-related excess deaths (total $PM_{2.5}$-related excess deaths from BTH in the *Base* scenario as the dominator) in the *EOR* scenario, in which relocating to less populous areas is one of the major contributors. Thus, the win−win outcomes of ISI relocation for both move-out and move-in regions (e.g., Tangshan city) can be achieved when both local and move-in units associated with relocation renovate for stricter emission standards, shift to greener technology, and move to lower population density places. Relocation site selection should fully consider trade-offs among different impacts and regions.[77] Population density, differential environmental carrying capacity, transportation conditions, demand, jobs, relocation costs, and city development planning are all potentially influential factors. The BTH case shows that the ecological industrial parks and high technology industrial development zones, especially in the less populous south and west regions, are potential relocation destinations.[78−81]

The energy-intensive heavy industry is fundamental to many emerging economies, especially China, India, and Pakistan (Figure S11), at the expense of severe air pollution as well as mortality threats,[82,83] which call for sustainable transformation.[84−87] The ISI in other countries or other industries (e.g., glass, cement, fertilizer industry) could learn from the experience of ISI relocation in BTH. A nationwide, multi-industrial, multipollutant, high spatial resolution database can be developed to examine the environmental−health impacts of relocation. This database should cover multiple industries, resources, and pollutants across the entire country. In addition, the cumulative air pollutant benefits can be estimated by figuring out the accurate timing of the relocations and addressing the potential uncertainties carefully, thus inspiring early relocation actions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c02710.

Additional details regarding the relocation database compilation and health impacts assessment method, details regarding results of premature mortality prevention by relocation, and details regarding data sources and results including figures and tables (PDF)

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Notes

The authors declare no competing financial interest.

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