Exploring the Emission Characteristics and Reduction Potential of Air Pollutants From Chinese Aluminum Industry: 2005–2025

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Abstract Amidst the rising desire for environmental governance in China, the aluminum industry has aroused more extensive attention because of the intensive energy consumption. Based on the process-based life cycle assessment (PLCA) method, emissions of nine typical air pollutants (PM, SO2, NOx, VOCs, CO, CO2, fluoride, asphalt fume, and PFCs) by the primary aluminum industry in China over the period 2005–2017 were calculated. The production process of aluminum industry was decomposed into three primary processes (alumina, carbon for aluminum, and electrolytic aluminum), and corresponding emission sources (fuel combustion, power consumption, and production process) were identified. The contributions of different processes and emission sources were then compared and spatiotemporal changes and their relation with existing policies were determined. The results show that the production of aluminum and the indirect source of electricity power are the dominant driving forces of air pollutants emissions of China’s primary aluminum industry and aluminum production process, respectively. Pollutant-emitting areas of the aluminum industry differed considerably. The country’s industrial policies were discovered to strongly influence the emissions of aluminum industry. Based on the emission inventory, three scenarios were established to project the potential of emission reduction of air pollutants from the aluminum industry in China until the year 2025. In addition, the effectiveness of China’s heavy pollution emergency response policy was evaluated. It suggests differentiated emergency control mode would be a more effective pathway for reducing the emissions of air pollutants by the aluminum industry.

1. Introduction

Aluminum is one of the crucial raw materials for the national economic development of China. The aluminum industry of China has gained global prominence after decades of development. Especially, the production of electrolytic aluminum was 33.28 million metric tons (Mt) in 2017, approximately accounting for 60% of the global production (National Bureau of Statistics of China (NBSC), 2018).

A wide variety and large quantity of air pollutants can be emitted from the production processes of aluminum industry. It was reported that the production of electrolytic aluminum was the major source of fluorine of the environment (Y. Yang et al., 2013). The extraction of aluminum from bauxite consumes considerably more energy than the extraction of other metals, and this process emits large amounts of greenhouse gases (GHGs) (Cheng et al., 2020; Norgate et al., 2007; Shao et al., 2014; W. Zhang et al., 2014). Given the equal emphasis placed on national development and environmental protection, the pollution caused by aluminum industries has become a pressing concern that can no longer be ignored in China.

The negative effects of the development of electrolytic aluminum industry have garnered increasing attention, leading to a turning point in policy development. In the past few decades, China has established and enforced a series of policies, guidelines, and laws and regulations with the aim of adjusting the structure of
industry, controlling production expansion, upgrading technological facilities, reducing environmental pollution, and facilitating the steady and healthy development of nonferrous metal industries including the aluminum industry. The Chinese government is particularly focused on environmental policies regarding electrolytic aluminum, and the technologies and pollution control facilities of the upstream-downstream industries of electrolytic aluminum industry are continually being updated and perfected. However, tasks relating to the prevention of air pollution and promotion of energy conservation and emission reduction still exhibit a pessimistic outlook in light of various confounding factors such as a considerable increase in demand for primary aluminum, fugitive emissions, and the lag in replacement of pollution control facilities.

It is thought that the primary aluminum production has the greatest environmental impact among the whole aluminum industry (Chen et al., 2009). However, few studies have comprehensively examined the interannual variation in the emissions of Chinese aluminum industry. Moreover, an emergency management and control mode for heavily polluted weather (the average value of air quality index is greater than 200 within 24 h) has recently been implemented under the pressures of global climate change and environmental governance in China since 2017. The implementation of this air pollution control mode has been effective in various industries. Nonetheless, because of the unique characteristics of its production processes, the aluminum industry may generate large amounts of pollutants once it resumes operation after a suspension in production activity in response to a heavy pollution alert. It is necessary to determine whether this type of management and control mode is suitable for aluminum industries. Therefore, to bridge this research gap, the present study assessed the amounts of primary air pollutants emitted from the aluminum industry in China to accurately measure the effects of each influence factor. The temporal and spatial characteristics were illustrated with the analysis of the emission of air pollutants from the aluminum industry between 2005 and 2017. On the basis of the emission inventory and industrial policies of the aluminum industry, three emission reduction scenarios were considered and pollutant emissions forecast in these scenarios. The actual benefits to the aluminum industry of the policy on emergency control of heavily polluted weather enforced in 2017 were also determined. The findings of this study can facilitate the formulation of more realistic emissions reduction targets and prevention policies and the promotion of green development for the benefit of environmental governance in China.

2. Data and Calculation Methods

2.1. Activity Intensity

Figure 1 shows that a few decades ago, the whole aluminum industry in China underwent vigorous development, leading to increased output of electrolytic aluminum from 7.8 Mt in 2005 to 33.28 Mt in 2017, an annual average growth rate of 12.8%. After 2011, the overall output decreased because of the adjustment of industrial structure and strict environmental protection policies (Ministry of Ecology and Environment of China (MEEC), 2018a; Sun et al., 2015). Upstream production of alumina and carbon for the aluminum industry was positively correlated with the production of electrolytic aluminum, as reflected by the increase in alumina (carbon for aluminum) output from 8.59 (4.79) Mt in 2005 to 69.01 (20.02) Mt in 2017, an annual average growth rate of 19.0% (12.7%) (National Bureau of Statistics of China (NBSC), 2017).

With the application of advanced technologies and equipment, the production techniques in the Chinese aluminum industry were majorly improved. In China and overseas, electrolytic aluminum is produced through molten salt electrolysis in a fluoride salt-alumina system, a mature technique that employs an electrolytic cell containing a molten fluoride salt bath, alumina solute, carbon anode, and graphite cathode. The electrolytic cell technologies used in China conform to international standards, and more large-scale electrolytic cells are being developed in the country. However, the general equipment and automatic control of auxiliary facilities (e.g., the assembly system) in electrolytic cell technology do not meet quality standards (MEEC, 2018b). High consumption of the carbon anode and a short lifespan of electrolytic cells are inherent problems in the production of electrolytic aluminum within prebaked cells in China, problems that do not occur in the advanced systems used in foreign countries (S. Guo et al., 2018).

The technological level of upstream industries in the production of alumina and carbon for aluminum is a key factor influencing electrolytic aluminum production. The sintering process, a highly polluting process,
was typically used in China for alumina production. Subsequently, the Bayer process, which is widely used abroad, was modified to be suitable for Chinese origin bauxite, leading to a method that combines the sintering process and the Bayer process. The combined process enables flexible production of alumina and recovers a large amount of alumina without emitting as much pollutant as the sintering process; it has thus become a technique widely employed by alumina plants in China. Regarding the production of carbon for aluminum, the electrolytic aluminum production method that employs self-baked cells was basically discarded in China at the end of 2005. Subsequently, industries have used large prebaked cells with advanced technologies, and this change caused a rapid increase in the production of prebaked anodes. The procedure employed to produce prebaked anodes involves the crushing of raw materials, calcination, asphalt melting, green anode manufacturing, baking, carbon block storage, residual treatment, etc. Excluding semigraphite cathode carbon blocks, which are no longer used, two types of cathode carbon blocks are employed in the production of aluminum: high-graphite-content and graphitized cathode carbon blocks (H. Yang, 2017; H. Zhang & Bai, 2018). Beginning in 2017, graphitized cathode carbon blocks have sometimes been used in large electrolytic cells in China, resulting in favorable production operation indexes (H. Yang, 2017).

The manufacture of electrolytic aluminum is an energy-intensive and highly polluting process. Production technologies consume considerable electricity, causing indirect pollution emissions (Farjana et al., 2019; Hou, 2015; Y. Zhang et al., 2016). In 2016, the total power consumed by the electrolytic aluminum industry was almost 10.5% of the power consumed by all Chinese industries and 78.8% of the power consumed by all non-ferrous metal industries (NBSC, 2018). In the production of electrolytic aluminum, procedures involving anode assembly, residual treatment, the mixer furnace, electrolytic cells, and so on are polluting
processes that generate particulate matter (PM), sulfur dioxide (SO2), nitrogen oxide (NOx), and fluoride pollutants (S. Guo et al., 2018; MEEC, 2013a). Pollution is generally controlled using facilities such as bag filters, electrostatic precipitators, closed hoods for the collection of flue gas from electrolytic cells, and the dry adsorption of fluoride in alumina (He et al., 2015; MEEC, 2018a).

The main pollutants emitted during alumina production are PM and SO2. Air pollution in the sintering and combined processes primarily originates from the clinker kiln and from the aluminum hydroxide baking furnace. A clinker kiln is not used in the Bayer process; hence, the main source of air pollution from this process is the aluminum hydroxide baking furnace. Flue gas from a clinker kiln and aluminum hydroxide baking furnace is first processed in a cyclone dust collector before entering an electrostatic precipitator or bag filter (MEEC, 2018b).

The main source of air pollution in the production of carbon for aluminum is the anode baking furnace, which emits flue gas containing pollutants such as asphalt fume, fluoride, and SO2. A large amount of dust is emitted during the main processes in prebaked anode manufacturing; specifically, asphalt melting, kneading, and molding produce considerable flue gas containing asphalt fume, dusts, and water vapor. The flue gases are typically processed using the combustion, absorption, and adsorption methods, and an electrostatic precipitator is employed as the air pollution control measure (L. Wang, 2013).

2.2. Calculation Method
2.2.1. Process-Based Life Cycle Assessment
Life cycle analysis or life cycle assessment (LCA) is a method for assessing environmental impacts by identifying and examining the inputs and outputs throughout the life cycle of a product or system (Chen et al., 2009). Process-based LCA (PLCA) is a form of LCA based on inventory analysis (ISO14040:2006, 2006; C. Wang et al., 2015). Numerous studies have employed LCA to assess the environmental impact of industrial pollutant emissions. Studies on the aluminum industry have focused mostly on a specific company or city (S. Wang et al., 2018), being thus region specific, or on estimating the amounts of pollutants at a specific stage in a country (Farjana et al., 2019; Hou, 2015). Thus, the results of these studies cannot be compared with specific situations on the level of a country’s industrial technology at different stages.

In this study, air pollutant emissions from China’s aluminum industry were analyzed over a long period. This study employed PLCA to establish a life cycle inventory of air pollutants emitted from the aluminum industry in China on the basis of national statistics and relevant parameters. The inputs and outputs in the aluminum production process were determined to identify the sources of air pollutant emissions, which are electric power consumption (an indirect source), fuel combustion, and process engineering. The main air pollutants from these three types of emission source are discussed separately, quantified using emission factors, and systematically analyzed to discover the spatiotemporal distribution of air pollutants from the aluminum industry.

2.2.2. Research Content and Boundaries
Using the available data, this study examined the air pollutants emitted from fuel combustion, power consumption, and production process in the primary production processes of primary aluminum, including the production of alumina, carbon for aluminum, and electrolytic aluminum (Figure 2).

2.2.3. Calculation Methods
The air pollutants emitted during aluminum production within the aforementioned boundaries are as follows: PM, SO2, NOx, volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO2), fluoride, asphalt fume, and perfluorocarbons (PFCs; two types of PFC, tetrafluoromethane [CF4, PFC-14] and hexafluoroethane [C2F6, PFC-116], are produced during anode reaction in the production of electrolytic aluminum) (NDRCC, 2011). A bottom-up emission factor approach was used to calculate the emissions of pollutants as follows, and the details of the parameters and calculation processes can be seen in Tables S1–S16 of the supporting information.

\[
    E = E_{ep} + E_f + E_p, \tag{1}
\]

where \( E \), \( E_{ep} \), \( E_f \), and \( E_p \) are the emissions (t) of all air pollutants of the whole processes, indirect air pollutants originating from electric power consumption, air pollutants originating from fuel combustion, and air pollutants originating from process engineering, respectively.
\[ E_{cp} = AD_{cp} \times EF_{cp}, \]  

where \( AD_{cp} \) is the net amount of electric power (kW h) used, and \( EF_{cp} \) is the emission factor of electric power consumption (t/kW h).

\[ EF = \sum_{i,j} (AD_j \times EF_{i,j}) \times (1 - \eta_{i,j}) \times 10^{-3}, \]  

where \( AD_j \) is the net amount of fuel \( j \) (t) used; \( EF_{i,j} \) is the emission factor of pollutant \( i \) in fuel \( j \) (kg/t); and \( \eta_{i,j} \) is the efficiency of a pollution control device to remove pollutant \( i \) in fuel \( j \).

\[ E_p = \sum_{i} (A_{AlO} \times EF_i) \times (1 - \eta_i) \times 10^{-3}, \]  

where \( A \) is the output of alumina, carbon for aluminum, and electrolytic aluminum (t); \( EF_i \) is the emission factor of pollutant \( i \) (kg/t) from process engineering; and \( \eta_i \) is the efficiency of a pollution control facility to remove pollutant \( i \).
2.3. Data Sources

2.3.1. Activity Data
Data on the outputs of electrolytic aluminum and alumina were obtained from the annual statistics published by the Bureau of Statistics in China, the Yearbook of the Nonferrous Metals Industry of China, and by provincial governments. Data on the output of carbon for aluminum were obtained from the China Industry Statistical Yearbook and related studies. Data on electric power consumption and intensity of fuel combustion activities were obtained from related studies (C. Wang et al., 2015; H. Zhang & Bai, 2018). The details of activity data used in this study can be seen in Tables S4–S9 in the supporting information.

2.3.2. Emissions Factors
Regional grid emission factors published by national authorities were selected for use as the emission factor for CO₂ originating from indirect sources of emissions (electric power consumption) (National Development and Reform Commission of China (NDRCC), 2014). Because access to data was limited and the power plants in China are mostly coal-fired power plants, the emission factors of coal-fired power plants were obtained from available literatures (China Electricity Council (CEC), 2018; MEEC, 2016; J. Zhang et al., 2011) and employed to calculate the emission factors of PM, SO₂, and NOₓ, which originate from indirect electric power sources. According to regulations on the execution time of emissions limit stipulated in the Emission Standard of Pollutants for the Aluminum Industry (Environmental Protection Bureau of China (EPBC), 2010a), in selecting the emission factors of process engineering pollutants (i.e., PM, SO₂, NOₓ, fluoride, and asphalt fume), the recommended values in the National General Survey of Pollution Sources (Environmental Protection Bureau of China (EPBC), 2010b) were used in the calculation of data for 2005–2010. And the actual situations of enterprises were investigated and findings converted to reflect interannual changes. The emission factors of fuel combustion pollutants (i.e., PM, SO₂, NOₓ, VOCs, and CO) were selected from the recommended values in the technical manual (He, 2018) according to the types of fuel combusted. In addition, the emission factors of CO₂ and PFCs were calculated by following the Greenhouse Gas Emissions Accounting Methods and Reporting Guidelines for Electrolytic Aluminum Manufacturers in China (National Development and Reform Commission of China (NDRCC), 2011), and parameters were obtained from the values recommended by the China Nonferrous Metals Industry Association. The details of emission factors used in this study can be seen in Tables S10–S16 in the supporting information.

The comparison between the emission factors used in this study and those compiled from other studies can be seen in Figure S1 in the supporting information (J. Guo et al., 2014; S. Guo et al., 2018; Hao et al., 2016; Hou, 2015; Y. Zhang, 2016; Y. Zhang et al., 2016; R. Zhao et al., 2016; H. Zhao et al., 2016). In general, the research results of this study were consistent with the previously obtained findings. However, the PM and SO₂ emission factors of electrolytic aluminum production of this study are lower than those of other study. The current emission of air pollutants was overestimated compared with the date reported by Hou (2015), probably because the emission factors were compiled from the data published before 2010.

3. Results and Discussion

3.1. Emissions of Air Pollutants From the Chinese Aluminum Industry in 2017
In 2017, the emission of PM, SO₂, and NOₓ from the aluminum industry in China were approximately 9,775, 34,917, and 39,544 t, respectively, accounting for 0.1%, 0.3%, and 0.3% of the total emissions in China.

The PM, SO₂, and NOₓ emissions from the production of electrolytic aluminum, carbon for aluminum, and alumina differed considerably. The emissions of PM, SO₂, and NOₓ from the production of electrolytic aluminum were 76%, 79%, and 64% of the total emissions of the aluminum industry, respectively. VOCs were emitted primarily during alumina production, and CO and asphalt fume during the production of carbon for aluminum. The emissions of fluoride, as the typical pollutants emitted during electrolytic aluminum production, were lower than those reported in other studies, probably because fugitive emissions were not considered in the present study. It is reported that fugitive emission of fluorine in 2017 was 67% of the fluorine emission during electrolytic aluminum production (S. Guo et al., 2018).

Figure 3 shows that in 2017, GHG emissions from the production of electrolytic aluminum accounted for approximately 87% of all GHG emission in the aluminum industry. And indirect emissions from electric power consumption accounted for approximately 70% of the total GHG emissions from the electrolytic aluminum production process. These results are in agreement with previous findings (Wu et al., 2010).
Moreover, PFC emissions caused by anode reactions accounted for approximately 16% of all GHG emissions of the aluminum industry.

### 3.2. Spatiotemporal Distribution of Air Pollutant Emissions of China’s Aluminum Industry

Output of electrolytic aluminum and alumina by region in China between 2005 and 2017 can be seen in Figure 4. In recent years, alumina in China has mostly been produced in resource-abundant areas (the main bauxite-mining area), including Shanxi, Henan, Guangxi, and Shandong province, which has ports and convenient transport. Shandong is also China’s main electrolytic-aluminum-producing area, where 26.5% of all electrolytic aluminum is produced. Because of electricity costs, Henan’s output of electrolytic aluminum is declining. China’s electrolytic aluminum production capacity is relocating in Northwest China, which has rich energy sources, and Xinjiang has become China’s second largest producer of electrolytic aluminum, with output of 19.4% of the total domestic output. The electrolytic aluminum outputs of Inner Mongolia,
Gansu, and Qinghai have also increased dramatically (Diao et al., 2016). In 2017, the summed output of electrolytic aluminum of Shandong, Xinjiang, and Henan province accounted for 54.4% of China’s output. The rapid development of the electrolytic aluminum industry has boosted the growth of industries that manufacture carbon for aluminum (National Bureau of Statistics of China (NBSC), 2017). Prebaked anodes, belonging to carbon for aluminum, are mostly produced in Shandong and Xinjiang province. Most large electrolytic aluminum plants are equipped with a prebaked anode production system. The cathode materials in aluminum electrolytic cells are not consumables in the production process, and new cathodes are thus required only when building or repairing cells. Therefore, electrolytic aluminum plants are generally not equipped with cathode material production systems. The Chinese manufacturers of cathode carbon blocks are primarily located in Shanxi, Henan, Shandong, Ningxia, Guizhou, and Yunnan province (S. Guo et al., 2018).

Figure 5 shows that the emissions of air pollutants exhibited large regional differences. In 2017, Shandong had the most air pollutant emissions, primarily because this province is the largest producer of aluminum in China. Fluorine pollution causes endemic diseases (Liu et al., 2013; Zuo et al., 2018). In addition, excessive fluorine is toxic to animals and plants, particularly crops and livestock (Ando et al., 2001; Tian et al., 2019). Besides, the global warming potential of PFCs is thousands of times stronger than CO2 (Hou, 2015; X. Li et al., 2016). Asphalt fume contains a complex mixture of compounds and substances, including phenols and benzopyrene, that are harmful to humans, animals, and plants (P. Li et al., 2019). Chinese aluminum industry generally emits small amounts of fluorine and asphalt fume; however, the emission intensity of these two pollutants is high in certain regions, which may adversely influence local agricultural and animal husbandry industries, causing severe air and water pollution and eventually soil pollution. This phenomenon was also reported in previous studies (S. Guo et al., 2018; Mikkonen et al., 2018; Singh et al., 2018).

### 3.3. Historical Trend and Emission Reduction Projection

Figure 6 illustrates the historical trend of air pollutant emissions from the Chinese aluminum industry of 2005–2017. Analyzing the announcement and implementation of industrial policies over the period (Figure 7) reveals the effects of policy amendments on pollutant emission trends. Particularly, a series of
policies designed to eliminate outdated capacity, restrict total emissions, and amend environmental standards have been announced and enforced in recent years. Because of increases in the strength of pollution control, these policies have been effective, as reflected by emission trends.

The emissions of common pollutants such as PM, SO$_2$, and NO$_x$, which have been the focus of public attention as well as national control and governance, decreased after the implementation of relevant policies.
Figure 6. Historical trend of the emissions of air pollutants of the Chinese aluminum industry.

Figure 7. The development of control policies of Chinese aluminum industry.
Generally, the total emission of PM has continuously decreased, probably because most of recent policies have aimed at reducing the emissions of fine PM (Intergovernmental Panel on Climate Change (IPCC), 2000; MEEC, 2013a). The decreasing trends in the emission of PM, SO2, and NOx in 2007 and 2011 were probably related to the Eleventh and Twelfth Five-Year Plans, both of which include instructions and opinions concerning the green development of non-ferrous-metal industries and are implemented by related policies. Specifically, the Eleventh Five-Year Plan specified explicit requirements for the comprehensive governance of SO2 in non-ferrous-metal industries and stipulates binding targets. The Twelfth Five-Year Plan for the Aluminum Industry also provided instructions regarding the active promotion of energy conservation and emission reduction and incorporated new NOx emission reduction targets that were based on the SO2 targets in the Eleventh Five-Year Plan. The extent of reduction in NOx emissions was not as great as those of several other types of pollutants between 2007 and 2009, possibly because NOx was not an emission reduction target in the Eleventh Five-Year Plan.

However, Figure 6 shows that the reduction of emissions slowed considerably after 2015 as the aluminum industry entered a relatively stable development stage, which probably indicated little potential of emission reduction in the future. After 2017, China announced a number of policies to regulate and limit the production of aluminum industry in cities of the Beijing-Tianjin-Hebei region and surrounding areas (referred to as “2 + 26” cities). Special air pollutant emission limits were imposed on the “2 + 26” cities in 2018. According to data and related study (Singh et al., 2018), these policies had a strong effect on production in the aluminum industry. In 2018, the Ministry of Industry and Information Technology issued a Notice on Matters Relating to the Implementation of Capacity Replacement by Electrolytic Aluminum Companies Through Mergers and Acquisitions; this notice announces cross-provincial capacity replacement of more than 400 tons of electrolytic aluminum, more than 300 tons of which is to be transferred to energy-rich areas such as Inner Mongolia and Yunnan. Thus, the optimized capacity of these industry may not be limited by the stringent emission standards of key areas. In summary, the emissions of pollutants other than CO2, VOCs, and CO by the aluminum industry might be a slowly downturn after 2017.

The emission of GHGs, specifically CO2, increased slowly and even decreased in the years 2007, 2011, and 2015, when several key policies for capacity control were enforced. However, emissions generally increased between 2005 and 2017, possibly because of a lack of carbon capture and storage measures in the aluminum industry. After 2017, China implemented further control over the capacity of electrolytic aluminum production, and GHG emissions might slowly decline.

The emission of fluoride decreased considerably in 2010, probably because the regulations on the limit of fluoride emissions were made more stringent in the Emission Standard of Pollutants for the Aluminum Industry, which was enforced in 2010. The curves representing VOCs, CO, asphalt fume, and fluoride distinctly increase after 2012, which is probably related to a lack of focus on these pollutants in current policy, and of the advanced control measures of CO. In Figure 6, the rate of increase slowed considerably at several time points, particularly in 2015, when the tightening of capacity policy influenced production output. On the basis of this discussion regarding the trends in policy after 2017, the increasing rate in the emissions of these types of pollutants may decrease further, and the load may even decline.

On the basis of the discussed findings, three emission scenarios were established in this study by referring to the methods proposed in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (IPCC, 2000) and relevant literature (Wakiyama & Kuramochi, 2017; Zhou et al., 2016). These scenarios were the emissions scenario of baseline (ESB), policy (ESP), and enhanced policy (ESEP) (see Figure 8).

The ESB is a baseline scenario that considers only the current air pollutant emissions by the aluminum industry on the premise that no major changes are made to policies and technologies. The ESP assumes that government-imposed capacity control policies and emission restrictions can be achieved, including policies proposed to achieve ultralow emissions from coal-fired power plants by 2020, to increase the amount of flue gas desulfurization in non-ferrous-metal industries, and to achieve the CO2 emission target by 2030 (General Office of the State Council of China (GOSCC), 2016a, 2016b, 2018; Hongyuan Futures, 2019; MEEC, 2018a, 2018b; Ministry of Industry and Information Technology of China (MIITC), 2013; Xinhua News Agency, 2015). The ESEP represents the ideal scenario in which (1) major initiatives enhance energy performance, adjust economic and industrial structures, protect the environment, and promote technological
advancements; (2) policies for industrial structure optimization and total emission control are perfectly implemented; and (3) economical and feasible technologies and facilities are used for the collection and treatment of CO₂, VOCs, asphalt fume, and other pollutants (Fasihi et al., 2019; MEEC, 2013a, 2013b; Schiavon et al., 2017; R. Zhao et al., 2016; H. Zhao et al., 2016).

3.4. Analysis of Profit and Loss of Pollutant Emission Reduction Under the Staggered Peak Production Policy

According to the staggered peak production plan for the aluminum industry in the Work Plan of Air Pollution Control in Autumn and Winter Between 2017 and 2018 in the Beijing-Tianjin-Hebei Area, the aluminum industry was to implement staggered peak production in the 2017–2018 autumn and winter (MEEC, 2017). However, the actual emission reduction situation is complex for the aluminum industry. From the perspective of the aluminum industry, specifically regarding electrolytic aluminum production, production conditions are abnormal for approximately 3 months from the time electrolytic cells are reactivated. Because numerous operating procedures are required during the baking initiation period, the electrolytic cell cover plate cannot be sealed before a crust forms on the electrolyte and purification cannot commence, resulting in high temperature and high volatility. Thus, large quantities of asphalt fume, fluoride, SO₂, dust, and other harmful gases are produced and cannot be sent directly through purification equipment. Consequently, considerably higher amounts of pollutants are emitted during the abnormal production period (3 months) compared with the normal production period.

Using real-life data of an electrolytic aluminum plant in China, calculations and comparisons (Figure 9) were conducted on the degree of
emission reduction (E1) during staggered peak production in 233 electrolytic cells (i.e., the amount of pollutant emitted when production is normal and the electrolytic cell is suspended) and emissions of main pollutants (E2) under abnormal production conditions caused by the reactivation of electrolytic cells. Moreover, an electrolytic cell must be overhauled (i.e., the cathode and cell lining replaced) when its operation is suspended; otherwise, thermal expansion and cold shrinkage can cause leakage when the cell is reactivated and may even lead to major safety incidents. The cost of a major overhaul for each electrolytic cell is approximately RMB 1.5–2 million, and minor to moderate overhaul costs approximately RMB 0.5–1 million. After staggered peak production plan was launched in 2017, certain electrolytic aluminum plant spent more than RMB 100 million on the repair and maintenance of electrolytic cells.

4. Conclusions and Policy Implications
The following conclusions were drawn on the basis of the aforementioned results and discussion. First, more than half of the main pollutants emitted by the aluminum industry in China originated from electrolytic aluminum production, with indirect emission from electric power consumption accounting for most of these emissions. Hence, comprehensive implementation of policies requiring ultralow emissions from Chinese electric power plants may facilitate the emission reduction of the aluminum industry. Regarding spatial distribution, the aluminum industry in China is concentrated in certain provinces, which may adversely affect the atmospheric environment in these provinces. To address this problem, the governments of major aluminum industry areas such as Shandong should conduct research on the local aluminum industry and formulate targeted policies and emission standards.

Second, national policies are a critical factor influencing the emissions of air pollutants originating from the aluminum industry. According to scenario-based forecasting and comparison, existing policies are expected to achieve favorable outcomes in the long term; nevertheless, pollutants that have not yet attracted attention because of their low total emissions—such as VOCs, fluoride, and asphalt fume—could be greatly reduced through policy implementation.

Finally, because the electrolytic aluminum production process is unique, the current policies of emergency management and control mode for heavily polluted weather, including staggered peak production and emergency response for heavily polluted weather, may not be applicable to electrolytic aluminum industries. Regarding emergency response measures of the aluminum industry in China for heavily polluted weather, this study recommends strengthening systematic control of industrial emissions, implementing special emission and even ultralow emission limits, using a differentiated emergency management and control mode, and increasing the control of fugitive emissions to gain strong control of air pollutant emissions from all aluminum industry processes.

Data Availability Statement
All the data used in this analysis are openly available as indicated in the data sources and in the supporting information. The activity data are from National Bureau of Statistics of China (http://www.stats.gov.cn/), Ministry of Ecology and Environment of China (http://www.mee.gov.cn/), and China Electricity Council (http://www.cec.org.cn/).

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