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A comprehensive emission inventory of multiple air pollutants from iron and steel industry in China: Temporal trends and spatial variation characteristics

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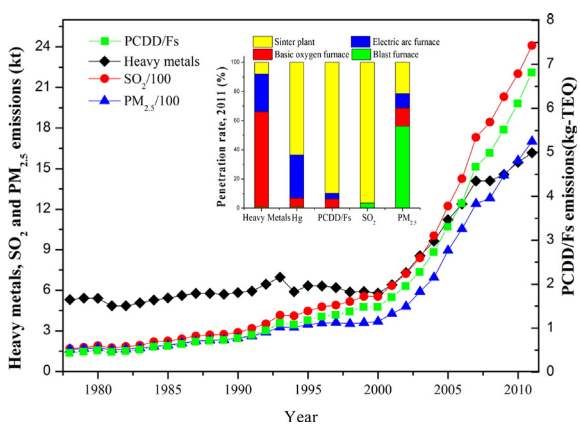
HIGHLIGHTS

- A comprehensive emission inventory for iron and steel industry of China
- Unit-based emissions are specially calculated for iron and steel industry.
- The emission inventory includes 18 pollutants.
- Emission trends for 1978–2050 studied by dynamic emission factor.
- Monte Carlo Simulation is provided to quantify the uncertainties of emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

China has become the largest producer of iron and steel throughout the world since 1996. However, as an energy-and-pollution intensive manufacturing sector, a detailed comprehensive emission inventory of air pollutants for iron and steel industry of China is still not available. To obtain and better understand the temporal trends and spatial variation characteristics of typical hazardous air pollutants (HAPs) emissions from iron and steel production in China, a comprehensive emission inventory of multiple air pollutants, including size segregated particulate matter (TSP/PM_{10}/$PM_{2.5}$), gaseous pollutants (SO_2, NO_x, CO), heavy metals (Pb, Cd, Hg, As, Cr, Ni etc.), as well as the more dangerous PCDD/Fs, is established with the unit-based annual activity, specific dynamic emission factors for the historical period of 1978–2011, and the future potential trends till to 2050 are forecasted by using scenario analysis. Our results show that emissions of gaseous pollutants and particulate matter have experienced a gradual increase tendency since 2000, while emissions of priority-controlled heavy metals (Hg, Pb, As, Cd, Cr, and Ni) have exhibited a short-term fluctuation during the period of 1990 to 2005. With regard to the spatial distribution of HAPs emissions in base year 2011, Bohai economic circle is identified as the top

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Temporal trend and spatial distribution
Scenario analysis

emission intensity region where iron and steel smelting plants are densely built; within iron and steel industry, blast furnaces contribute the majority of PM emissions, sinter plants account for most of gaseous pollutants and the majority of PCDD/Fs, whereas steel making processes are responsible for the majority of heavy metal emissions. Moreover, comparisons of future emission trends under three scenarios indicate that advanced technologies and integrated whole process management strategies are in great need to further diminish various hazardous air pollutants from iron and steel industry in the future.

1. Introduction

As one of pillar industries for Chinese economic development, the iron and steel industry has grown rapidly along with the increasing demand from rapid urbanization and various infrastructure construction activities (buildings, highway, high-speed railway, moto vehicles, etc.). Since 1996, China has become the largest steel producer in the world (Wang et al., 2007) and the volume of crude steel production has rapidly increased from 101 million to 779 million tons in 2013 (CISA, 2012; MIIT, 2014). However, characterized by a large number of small production units built during the past years, a certain amount of China's steel products is made by small mills which applied backward smelting processes and lack of effective flue gas control devices. According to the report of Ministry of Industry and Information Technology (MIIT) of China, the ratio of ten largest iron and steel firms' output to the national gross output is only 39.4% in 2013, far below that of major steel production countries (MIIT, 2014; MEP, 2007). Moreover, as an energy-and-pollution-intensive manufacturing sector, iron and steel industry is claimed to emit more than 30% of total PCDD/Fs emissions in China in 2004 (MEPFECO, 2007) and contribute about 20% of SO_2 emissions, 8% of NO_X emissions and 27% of dust emissions for all key manufacturing industry in China in 2013 (MEP, 2014a).

In general, various hazardous air pollutants (HAPs) emitted from iron and steel industry can be classified into four categories: (1) acidic gaseous pollutants (SO_2, NO_x, etc.); (2) incomplete combustion pollutants (PCDD/Fs, CO, etc.), (3) particulate matter (PM), which can be distinguished into TSP, PM_{10} and $PM_{2.5}$ with respect to the range of particle size, respectively; and (4) toxic heavy metals (Pb, Cd, Hg, As, Cr, Ni, etc.). Therein, SO_2, NO_x and PM are demonstrated to be major conventional air pollutants in the manufactory of iron and steel (Fu et al., 2012). Although the toxic heavy metals and PCDD/Fs are trace species in terms of their emission volume, they captured widespread attention due to their high exposure risks on human health. EU-Project ESPREME addressed the priority toxic metals owing to their poisoning risks, including mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and nickel (Ni) (Theloke et al., 2008). Meanwhile, five heavy metals, including Hg, Pb, Cd, As, and Cr, were designated as priority toxic heavy metals in the Specialized 12th Five-Year-Plan on Comprehensive Control of Heavy Metals Pollution in China issued on 2011 (MEP et al., 2014b). In addition, Stockholm Convention on POPs (persistent organic pollutants), aiming to control and reduce further environmental exposure of unintentional POPs, was adopted in 2001, and came into effect on 2004. Therefore, the emissions of PCDD/Fs and heavy metals should be highlighted and deserve in-depth studies.

Till now, detailed information about the past and present emission situation of various HAPs from iron and steel production has been rather limited. Several studies estimated varied air pollutant emissions in China, most of which treated with iron and steel industry as one part of the whole industrial processes emissions mainly due to data availability limitation, and as a result, lacking of comprehensive and detailed investigations for the iron and steel industry (Lei et al., 2011, 2012; Streets et al., 2005; Tian et al., 2012a). Streets et al. (2005) presented the estimation of mercury emissions from China's iron and steel industry by province with constant emission factor for different process; Lei et al. (2011) estimated the historical PM emissions of China in 1990–2005; Tian et al. (2012a) assessed Ni emissions from Chinese anthropogenic sources, in which Ni emissions from iron and steel production sector were calculated with average emission factor based on steel production. Some studies of CO_2 emissions from the iron and steel industry in China are also reported in terms of greenhouse gases discharge (Wang et al., 2007; Kim and Worrell, 2002; Hasanbeigi et al., 2013). In comparison with the coal-fired power plants (Tian et al., 2011a, 2011b, 2010; Zhao et al., 2008; Zhu et al., 2016), there are few specialized studies targeted to simultaneously evaluate the temporal trend and spatial distribution characteristics of multiple hazardous air pollutant emissions from iron and steel industry in China. A complete and comprehensive atmospheric emissions inventory of multiple air pollutants from iron and steel industry during the long period of 1978–2050, which will benefit for much better understandings of the historical and future trends of various air pollutants emissions for policymaking and pollution control, is urgently needed.

In this study, by using time-varying dynamic emission factors which are determined by considering transition on production process progress and pollution control technology application, the historical temporal and spatial distribution characteristics of typical air pollutant emissions released from iron and steel industry of China, as well as the potential variation trends in the future, are investigated in detail.

2. Methodology and key parameters

The iron and steel industry involves a series of closely linked process steps, including the preparation of raw materials, iron-making, steel-making and finishing processes. Therein, three main routes have been applied in China for steel-making process: open hearth furnaces (OHF) route, basic oxygen furnace (BOF) route and the electric arc furnace (EAF) route. Notably, primarily due to the ever tighter environmental standards, OHF has been eliminated gradually and is considered for only occupying visible market share in crude steel making until 2001 in China. By 2011, the market share of BOF and EAF in crude steel-making is about 89.6% and 10.4%, respectively (CISA, 2013). Different process steps have installed diverse air pollution control devices owing to the varied physical and chemical properties and flue gas conditions. Currently, most of sinter processes adopt electrostatic precipitators (ESP) for PM removal, while fabric filters (FFs) are more widely applied in steel-making and iron–making process (Sofilić et al., 2004).

Ratio of pig iron to crude steel, representing the ratio of the output of pig iron to crude steel, is an indicator of structural variation within iron and steel industry, which is mainly governed by the availability of waste steel and imposes great effects on the penetration rate of EAF and BOF in steel-making process. The ratio of pig iron to crude steel of China is about 0.9 in 2011, and the penetration rate of EAF steel-making in China is only about 11.7%, significantly lower than 41.8% in European countries (Remus et al., 2013). Wei et al. project the ratio of pig iron to crude steel in China will be lowered to about 0.5 by 2050 and it is anticipated that electric arc furnace (EAF) may get more widely used in the future (Wei and Yagita, 2005). Notably, with the increased adoption of EAF route, scrap will be widely used for feed materials of secondary smelting process which may lead to increased formation and discharge of PCDD/Fs and heavy metals with visible contaminants (Remus et al., 2013).

In this study, the historical and future emissions of four categories of hazardous air pollutants from iron and steel industry of China, including 18 pollutants (SO_2, NO_x, CO, PCDD/Fs, $PM_{2.5,}$ $PM_{10,}$ TSP, Pb, Cd, Hg, As, Cr, Ni, Cu, Mn, V, Se, Zn), are estimated by applying unit-based bottom-up