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Carbon element flow analysis and CO_2 emission reduction in iron and steel works

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A B S T R A C T

As an intensive energy-consuming and carbon-emitting industry, iron and steel manufacturing is vital for meeting the energy conservation and CO_2 emission reduction targets of China. A set of methods has been presented to quantify CO_2 emission, however, no unified standards are available for the iron and steel industry yet. To analyze the CO_2 emission-affecting factors, a carbon flow model and a corresponding calculation method are proposed with consideration of the relationship among emission factor, system boundary, and index. Then, a case study is conducted in two iron and steel mills in China, and carbon element flow diagrams are mapped out graphically. The CO_2 emission-affecting factors were analyzed based on material flow analysis. The results show that the Specific CO_2 emission of two case mills with different material flows and electricity consumption structures are 2035.06 kg/t-cs and 2497.21 kg/t-cs, respectively. Purchased scrap recycled to basic oxygen furnace reduces the CO_2 emission dramatically. By contrast, self-produced scrap, which is controlled by the production yield, increases the emission. Specific CO_2 emission decreases dramatically with the reducing of OPP generation rate, maximum reduction can be up to 334.80 kg/t-cs. Using natural gas or steam coal as substitute for BFG consumed in onsite power plant, Specific CO_2 emission can be reduced by 299.22 kg/t-cs and 86.97 kg/t-cs, respectively.

1. Introduction

Global climate change caused by greenhouse gases has been a critical issue that needs to be addressed (Sodsai and Rachdawong, 2012). As one of the most influential greenhouse gases, CO_2 contributes to climate change and carbon mitigation strategy is important for sustainable development. China is the country with the largest iron and steel production and consumption, contributing around 50% of iron and steel products in the world. The total production of crude steel in China increased from 101.2 million tons in 1996 to 822.3 million tons in 2014 (World Steel Association,2015). China has been the world leader in crude steel output for 19 consecutive years, as shown in Fig. 1. The rapid growth of crude steel production in China has led to high energy consumption and CO_2 emission. It is necessary to pay attention to CO_2 emission due to increasingly severe environmental challenge in China's iron and steel industry.

The iron and steel industry consumes substantial amounts of fossil fuel as reducing agents and fuels. The industry accounts for 17% of the total industrial energy consumption in China, generates significant CO_2 emissions (Hui et al., 2013b), which takes up 10% of the total domestic CO_2 emission, and ranks as the third largest CO_2 emitter behind the power and construction material industries (Zeng et al., 2009). In 2015, the iron and steel industry released 1.94 billion tons of CO_2, accounting for 16.7% of China's total CO_2 emission (Xu et al., 2017). CO_2 emission in the steel sector is primarily the result of fossil fuel combustion during production (Price et al., 2002). As the dominant primary energy source in China, coal accounts for about 80% of total energy consumed and acts as the major source of CO_2 emissions. Between 1980 and 2013, the CO_2 emission in China's iron and steel industry increased approximately 11 times, with an average annual growth rate of 8% (Xu and Lin, 2016). Fig. 2 shows that from 1995 to 2009, the intensity of CO_2 emission (the CO_2 emission of per ton crude steel) in China continue decreasing, whereas the total emission continue increasing. Therefore, China is facing increasing pressure to reduce CO_2 emissions in iron and steel industry.

The two dominant process routes of steelmaking are blast furnace-basic oxygen furnace route (BF-BOF route) and electric arc

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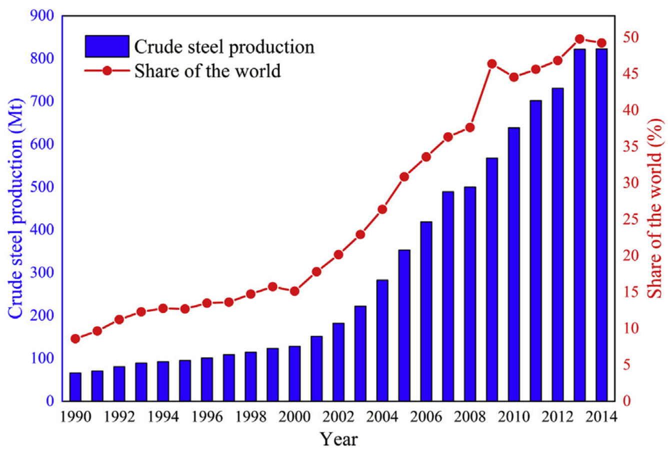

Fig. 1. Crude steel production of China and share of the world production from 1990 to 2014 (source: World steel Association, 2015. Steel Statistical Yearbook.).

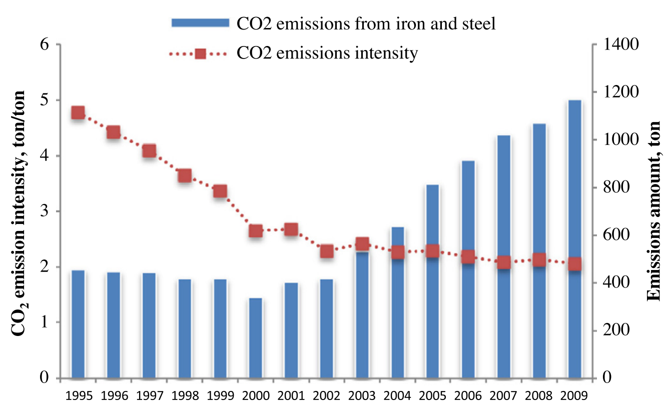

Fig. 2. Amount and intensity of CO_2 emissions from the Chinese iron and steel industry (source: Hui et al., 2013, Investigation of the residual heat recovery and carbon emission mitigation potential in a Chinese steelmaking plant: a hybrid material/energy flow analysis case study.).

furnace route (EAF route); the former accounts for approximately 90% of the total crude steel production in China (Hui et al., 2013a), which is higher than the world average (Hasanbeigi et al., 2014). Energy consumption and CO_2 emission varies remarkably from the production route. For example, the specific energy consumption (SEC) of the BF-BOF route is five times higher than that of the EAF route (Worrell et al., 2001), while the CO_2 emission of the BF-BOF route is approximately 3.5 times higher than that of the EAF route, which is based on scrap (Hans et al., 2001).

A considerable number of studies has been conducted on energy efficiency and carbon emission reduction potential in the iron and steel industry through different models (Karali et al., 2016; Lin and Wang, 2014; Pardo and Moya, 2013; Wen et al, 2014; Chen et al., 2015). Hasanbeigi et al. (2013) used the conservation supply curve model, analyzed the reduction potential of China's iron and steel industry, and emphasized that the cumulative cost-effective fuel savings potential for 2010–2030 is 11,999 PJ, which will reduce CO_2 emission by 1191 Mt. Wang et al. (2007) assessed the CO_2 abatement potential by LEAP software (Long-range Energy Alternative Planning System) and their findings showed that the average CO_2 abatement per year in the recent policy scenario and in the new policy scenario are 51 million tons and 107 million tons, respectively. Ma et al. (2016) simulated the trends of energy consumption and CO_2 emissions during 2010–2050 under a reference scenario and three alternative carbon mitigation scenarios.

Several studies also examined CO_2 emission reduction options (Wang et al., 2009; Sodsai and Rachdawong, 2012; Ribbenhed et al., 2008), emission reduction cost (Li and Zhu, 2014; Moya and Pardo, 2013) and emission prediction (Chen et al., 2014; Juntueng et al., 2014; Karali et al., 2014) in the iron and steel industry. These studies contributed significantly to the iron and steel industry, but most of them focused on the industry level. Proposed emission reduction measures were mostly for policymaking rather than for concrete measures that could be used in iron and steel mills (ISMs). An existing study on the affecting factors of CO_2 emission in the iron and steel industry was mainly based on an analysis of historical data, e.g., studies by index decomposition method pointed out that crude steel production was the main contributor to changes in CO_2 emissions (Kim and Worrell, 2002; Liu et al., 2016; Sheinbaum et al., 2010; Sun et al., 2011). However, these studies were concentrated on historical trends rather than production processes.

Existing research is mostly conducted at the industry level and cannot provide plant-level reduction measures to improve steel production. Thus, the main objective of this paper is to propose a plant-level analysis of the carbon flow of ISMs, including calculating method, analysis of influencing factors, and emission reduction measures for ISMs. Based on the carbon flow model, several issues of special importance are highlighted, such as scrap, electricity, by-product gas and energy-saving technology.

The rest of this paper is organized as follows. Section 2 provides an introduction to the methodology. Section 3 presents the case study. Sections 4 and 5 show the results of the analysis and the factors that influence CO_2 emission. The final section delivers the conclusions.

2. Methods

Carbon consumed in steel production mainly comes from carbon-containing fuels, which serve as fuel and chemical reductants, and ultimately converts to CO, CO_2, by-product gas and corresponding calories. The chemical reduction mainly occurs in the iron making process, with silicon and molten iron oxide reduced by chemical reductants. Waste energy is mainly embodied in products or by-products as sensible heat or as kinetic energy. Kinetic energy of blast furnace gas (BFG) can be recycled through the top gas pressure recovery turbine (TRT). By-product gases, such as BFG, coke oven gas (COG) and converter gas (LDG), are recovered and used as fuels for sintering machines, stoves and boilers.

2.1. CO_2 emission calculation methods in iron and steel industry

Various methods have been used to calculate CO_2 emission in the iron and steel industry, and these methods can be summarized into three categories.

Method 1 is an estimation method recommended by the Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al., 2007), in which CO_2 emission is estimated by the steel production and average emission factor (average CO_2 emission per ton steel), as shown in Eq. (1).

$$CO_2\ \text{emission} = S_{BOF} \times EF_{BOF} + S_{EAF} \times EF_{EAF}, \tag{1}$$

where S_{BOF} and S_{EAF} are the steel products generated through the BF-BOF and EAF routes, respectively, while EF_{BOF} and EF_{EAF} are their average emission factors, respectively.

IPCC (Eggleston et al., 2007), World Resources Institute (WRI), World Business Council for Sustainable Development (WBCSD)