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Assessment on the energy flow and carbon emissions of integrated steelmaking plants

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ABSTRACT

China's iron and steel industry has developed rapidly over the past two decades. The annual crude steel production is nearly half of the global production, and approximately 90% of the steel is produced via BF–BOF route that is energy-intensive. Based on the practice of integrated steelmaking plants, a material flow analysis model that includes three layers, i.e., material, ferrum, and energy, was constructed on process levels to analyze the energy consumption and carbon emissions according to the principle of mass conservation and the First Law of Thermodynamics. The result shows that the primary energy intensity and carbon emissions are 20.3 GJ/t and 0.46 tC/t crude steel, respectively, including coke and ancillary material's preparation. These values are above the world's average level of the BF–BOF route and could be regarded as a high-performance benchmark of steelmaking efficiency. However, the total energy consumption and carbon emission from steelmaking industry were approximately 13 095 PJ and 300 MtC, respectively, on the best practice estimation in 2011, and are still large numbers for achieving the goal of reducing global warming. The potential carbon reduction will be limited if no significant changes are undertaken in the steel industry.

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1. Introduction

The climate change has been a hot issue around the globe since the agreed framework for all international climate change deliberations, the United Nations Framework Convention on Climate Change (UNFCCC), ratified in 1994 and implemented in the Kyoto Protocol in 1997. Currently, China has become the world's second-largest economy and the biggest energy consumer. The iron and steel industry is one of the most important industrial sectors in term of CO_2 emissions which is a major factor in global warming. China alone responsible for over 50% of CO_2 emissions from global steel production, and the climate change objectives – keeping global warming to below 2 °C by 2050 – will not be achieved without the full participation of Chinese steel industry (European Steel Association, 2009).

In the current steel industry, there are two main process routes for crude steel production: the blast furnace and basic oxygen furnace (BF–BOF) steelmaking and the electric arc furnace (EAF) steelmaking. The former is based on the use of coal and iron ore, which is a traditional way of steel production; the latter is based on the use of scraps and electricity. The BF–BOF route consumes significantly more energy and produces more carbon emissions than the EAF route. Besides, the BF–BOF steelmaking also produces significant amounts of energy byproducts, such as coke oven gas, BF-gas, BOF-gas, and steam. If these gaseous energy carriers are recycled, the energy efficiency will be improved significantly. As the world's largest steel producer, China produced 683 Mt crude steel in 2011, and about 92% of the steel were produced via the BF–BOF route (World Steel Association, 2011).

After the Circular Economy Promotion Law of China had been ratified in 2008, the concept of circular economy in the iron and steel industry was adopted broadly. This law encourages energy saving, emission reduction, material and energy recycling as necessary foundations. Current steelmaking industry has widely deployed various energy saving technologies such as Coke Dry Quenching (CDQ), Top-pressure Recovery Turbine (TRT), Coal Moisture Control (CMC), continuous casting, slab hot charging and delivery, and recovering energy from coke oven gas, BF gas, con-

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vert gas and steams, all of which have improved energy conservation and emission reduction impressively (Zhang and Wang, 2008; Chen et al., 2014). Many studies have been conducted to analyze the reduction options of carbon emission within the iron and steel industry from the engineering or economic perspectives (Worrell et al., 1997, 2001; Price et al., 2002; Wu et al., 2006). Different methods have been adopted to evaluate the energy efficiency and reduction potential for carbon emissions and the driving forces for emission changes at present and in the future, which range from empirical analyses and decomposition analyses to scenario analyses, using various data models such as Malmquist Productivity Index (MPI) model, Data Envelopment Analysis (DEA) model, Conservation Supply Curve (CSC) model, logarithmic mean Divisia index (LMDI) model, and the China TIMES model developed within the Energy Technology System Analysis Program (ETSAP) of the International Energy Agency (Liu et al., 2007; Wang et al., 2007; Wei et al., 2007; Guo et al., 2011; Choi et al., 2012; Bian et al., 2013; Tian et al., 2013; Lin and Wang, 2015; Ouyang and Lin, 2015; Zhang and Da, 2015). This paper provides an approach carried by the process of life cycle inventory to estimate the energy intensity and carbon emissions in China's integrated steelmaking plants, which offers some essential benefits that cannot be obtained from other ways when the inventory is considered (Iosif et al., 2010). This approach is based on the principle of mass conservation and the First Law of Thermodynamics, which deal with the amounts of materials and energy of various forms transferred between a system and its surroundings and also deal with the changes in the mass and energy stored in the system. This approach is convenient for studying changes in energy consumption and carbon emissions; however, it is insufficient for forecasting future emissions. This inadequacy can be remedied by empirical and scenario analyses.

2. Data and methodology

2.1. Boundaries

To analyze the potential for energy conservation and carbon reductions, we disaggregated the integrated steel plants by major steelmaking processes. Materials, energy, and ferrum flows were identified and analyzed in each process under a unified framework. The system boundary includes four processes, coking, sintering, iron making, and steel making, based on available data. Fig. 1 shows the interconnection of these processes. The processes of steel casting, hot rolling, cold rolling, galvanizing and coating were excluded because of their relatively less energy consumption and carbon emission. For example, the average primary energy intensity for casting and rolling that use thin slab is merely 0.6–0.9 GJ/t steel (Worrell and Moore, 1997).

Products imported to these processes such as oxygen, fresh water and electricity were counted by adding the energy used for producing these products to the total energy input. The electricity required to operate the processes was considered within the system, which included an internal power station using the steelwork gas (e.g. BF gas, Coke gas, and BOF gas). For the first stage of this study, the system does not count the embodied energy of scraps used in the BOF process and the energy demands for mining and beneficiation of raw materials, their transportation, and the waste storage.

2.2. Data description

The heating value of a fuel source represents the amount of heat released during combustion. This study uses the lower heating value (LHV) to convert the physical quantities of fuels to a common energy unit by the convention of China's energy statistics. The conversion rates are provided in the General Principles for Calculation of the Comprehensive Energy Consumption, GB2589-2008 (Standardization Administration of China, 2008a). Table 1 provides the conversion factors of fuels and energy carriers used in this analysis. CO_2 emissions are expressed in metric tons of carbon. The carbon conversion factors for calculating carbon emissions from energy consumption are derived from the National Development and Reform Commission of China (NDRCC). We define the energy intensity in terms of physical output rather than others, e.g. economic output.

The carbon emissions caused by the decarbonization of limestone ($CaCO_3$) and dolomite ($MgCO_3$), which act as fluxes in ironmaking, were not counted, and these emissions amount to 0.44 t CO_2/t limestone and dolomite (Gielen, 1997). The carbon content in the crude steel, usually less than 1.7%, were not subtracted from the primary steel production.

In the sintering model, we assume the iron contents in ores are between 62% and 65% Fe, because the Australian iron ores (62% Fe) are the benchmark throughout the industry, and the grade of Brazilian iron ores is usually between 63.5% and 65% Fe. Both Australia and Brazil are the major sources of iron ores for China. Meanwhile, low-quality ores ($\leq$60% Fe) were restricted to be imported by the official China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters, known as CCCMC, from 2010.

As an illustration, Table 2 shows the major materials in the MFA model. When data on specific processes were not available, substitute values were adopted from the recent relevant literature based on process energy intensity or just left it blank.

2.3. Material flow analysis

Material flow analysis (MFA) is a procedure to quantify and evaluate the flows and stocks of goods and substances in the perspective of sustainable use of materials. It is used in the field of industrial ecology on various spatial and temporal scales (Brunner and Ma, 2009). Over the past decades, MFA has become a reliable instrument to describe material flows and stocks within varied systems.

MFA is based on the principle of mass conservation, which assumes that mass cannot vanish and could be expressed in the simple form of balance equation (1) below. Meanwhile, the energy consumption obeys the First Law of Thermodynamics, which could also be used to establish the energy balance for process investigation.

$$\sum Inputs = \sum Outputs + Changes\ in\ stock. \quad (1)$$

These principles serve as means of control in the case where all flows are known, and they can be used to determine one unknown flow per process. Therefore, we constructed an MFA model that includes three layers (material, ferrum, and energy) to count both the material and energy consumption in integrated steelmaking plants.

In this paper, the aim of MFA is to describe and analyze the steelmaking system as simple as possible, where only the primary inputs and outputs are of interest, but it is in enough detail to make right results to evaluate the energy efficiency and carbon emissions. This MFA model can also effectively avoid the double counting of material and energy consumption by considering the interactions between processes.

In this model, we assume that all the materials and energy in the system boundary are used to preheat material handling equipment, and the transfer efficiency of substance and energy between processes is not examined.

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