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Life cycle assessment of the comprehensive utilisation of vanadium titano-magnetite

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ABSTRACT

This study describes the life cycle assessment (LCA) of the comprehensive utilisation of vanadium titano-magnetite (VTM) through the integrated steel production and valuable element (V and Ti) extraction route. The major sources of environmental impacts are described and pollution prevention methods are proposed. The LCA methodology is based on the ISO 14044 standard, which uses GaBi 6.0 software and the Ecoinvent database, and the life cycle inventory (LCI) data (input and output) are from Pan. Steel. Impact assessment results indicate that production of pig iron in blast furnace (BF) exerts the most extensive impacts on global warming potential for the time horizon of 100 years (GWP_{100}) and fossil fuel consumption. By contrast, iron ore mining dressing and sintering contribute the most to acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (PCOP) because of dust and pollutant gas emissions. When indicator contributions are considered, the observed impacts on AP (50.88%), GWP_{100} (24.25%) and photochemical ozone creation potential (POCP) (19.51%) are higher than those on EP, human toxic potential (HTP) and abiotic depletion potential (ADP). Therefore, when processes with environmental impacts are taken into account, the iron mining and dressing, iron ore sintering and BF iron-making processes must be considered, when category indicators are taken into account, AP, GWP_{100} and POCP must be considered.

1. Introduction

China, South Africa, Russia and the USA are rich in VTM resources; in fact, the potential reserves of these countries respectively account for 36%, 31%, 18% and 10% of the world's total reserves. Compared with other iron ore resources, VTM has much higher comprehensive utilisation value because it can associate with many other valuable elements, such as iron, vanadium and titanium. VTM is mainly used in China to produce crude steel, vanadium pentoxide and ilmenite through the BF iron-making → BOF vanadium extraction → semi-steel smelting route (Chen and Chu, 2014a, b).

Since the 2000s, rapid increases in the comprehensive utilisation of VTM have been observed in China. For example, the yield of crude steel derived from VTM was as high as 18.53 million tonnes in 2013; this figure is 2.4 times the crude steel yield in 2004 (Fig. 1). Production of steel, which is an important raw material for national economic development, is associated with resources, energy and environment (Bieda, 2012a; Price et al., 2002; Worrell et al., 2001). Thus, comprehensive utilisation of VTM is a long process that requires environment impact assessment.

LCA is an environmental assessment method used to evaluate the impacts a process may exert on the environment over the entire period of its life, from raw material extraction to its manufacturing, use and end-of-life processes (Burchart-Korol, 2011). An increasing number of researchers in many countries, such as Poland, Australia, Japan and the USA, amongst others, have focused on the steel industry and stressed the importance of LCA in environmental assessment. Burchart-Korol (2013) conducted a case study to define the major sources of environmental impacts and proposed pollution prevention methods for the steel industry of Poland (Burchart-

Abbreviations: LCA, life cycle assessment; VTM, vanadium titano-magnetite; LCI, life cycle inventory; LCIA, life cycle impact assessment; Pan. Steel, Panzhihua Iron and Steel Co. Ltd.; BF, blast furnace; GWP_{100}, global warming potential for the time horizon of 100 years; AP, acidification potential; EP, eutrophication potential; PCOP, photochemical ozone creation potential; HTP, human toxic potential; ADP, abiotic depletion potential; BOF, basic oxygen furnace; COG, coke oven gas; BFG, blast furnace gas.

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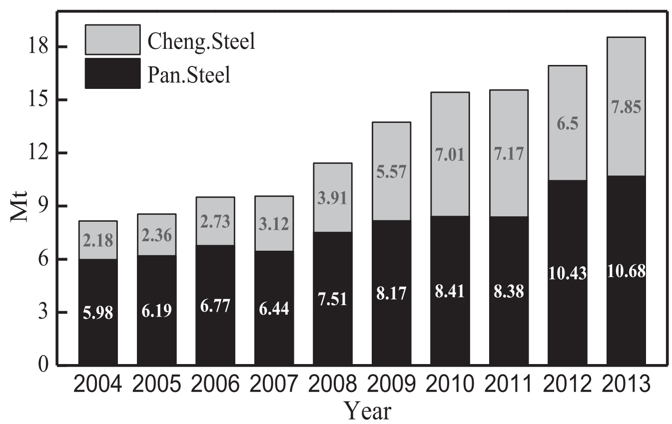

Fig. 1. Crude steel production from 2004 to 2013.

Korol, 2013). Bieda (2012) presented LCI data from Arcelor Mittal and analysed the results of environmental impacts on iron-making and steel-making plants (Bieda, 2012a, b). In Australia, Norgate et al. used the LCA to estimate the environmental impacts of ferroalloy and metal (copper, nickel, aluminium, lead, zinc, steel, titanium) production processes (Haque and Norgate, 2013; Norgate et al., 2007). To address climate change and the energy shortage, a several LCAs have discussed the energy and carbon emission reduction potential of steel industries around the world (Iosif et al., 2008; Tongpool et al., 2010; Yang and Chen, 2014). In China, however, no related studies on the use of a thorough life cycle method to assess the environment impacts of the comprehensive utilisation of VTM have been reported.

In this paper, a cradle-to-gate life cycle study is conducted using averaged data from Pan. Steel, the world's largest comprehensive user of VTM (10 million tonnes per year). After defining the goal and scope of the study and performing LCI analysis and LCIA, environmental assessments of the process and cumulative environmental performance of Pan. Steel are carried out and compared in detail.

2. Case study

2.1. Introduction of the Pan. Steel process

In this study, Pan. Steel is chosen as the research object. The main process of mining and dressing, sintering, pelleting, BF iron-making, BOF vanadium extraction and semi-steel smelting consists of five steps. The raw materials are VTM, limestone, coal and coke.

After mining, VTM is transformed to produce VTM concentrate and ilmenite. The VTM concentrate obtained from mining and dressing is partly mixed with coal, coke and limestone to produce sinter ores, and the rest of the material is mixed with bentonite to produce pellet ores. Next, pig iron is manufactured in BF through combustion of sinter ores, pellet ores, lump ores and coke. Coal powder is also co-fired with the coke. After these processes, Pan. Steel employs a characteristic two-step pre-treatment process called preliminary desulphurisation and BOF vanadium extraction to obtain pig iron and vanadium-bearing slag with acceptable quality. This process requires three ladles with average capacity of 140 tonnes each, five desulphurisation setups and two vanadium extraction BOFs. The sulphur content of the pig iron after processing is less than 0.005%, and the recovery of vanadium is about 85%. Finally, crude steel is manufactured from the pig iron and vanadium pentoxide is manufactured from the vanadium-bearing slag.

2.2. Goal and scope of analysis

The LCA method follows the ISO 14040 standard and includes four stages: determination of the goal and scope, inputs and outputs inventory analysis, environmental impact assessment, and results interpretation with proposals for improvement (ISO, 2006).

The goals of this study are as follows:

1. Quantitatively describe the environmental loads and analyse and compare the environmental impacts of different indicators including GWP_{100}, ADP, EP, AP, POCP and HTP on steel production and valuable element extraction.
2. Illustrate the cumulative environmental performance of the Pan. Steel process for comprehensive utilisation of VTM.

The scope of this study includes the preparation of auxmary materials (i.e., lime production, coal washing and coke production) and steel manufacturing (i.e., ore mining and dressing, iron ore sintering and pelleting, BF iron-making and BOF steel-making) to valuable element extraction (i.e., ilmenite production and vanadium pentoxide production). The system boundary and process flow diagram are shown in Fig. 2. The functional unit (Yu and Zhang) of this study is one tonne of crude steel produced in steel plants.

2.3. LCI

The LCI for the main process is obtained from Pan. Steel in China and the time horizon is from 2005 to 2007. Data of other stages, such as quicklime production, coal washing and coke production are based on the literature and GaBi 6.0 software (Ai et al., 2006; Cai et al., 2012; Hu et al., 2007; Luo et al., 2008). The data inventory used to assess environmental impacts and pollution prevention includes raw material consumption, energy consumption, by-products recycling and environmental discharge (i.e., atmosphere discharge and waste discharge) analysis results.

In this study, all of the raw materials and energy required to operate the process are considered in system boundaries, and a detailed LCI of the main input and output (materials and energy) flows required to produce one tonne of crude steel is presented in Table 1. As shown in Fig. 2, recycled fuels and materials (COG, BFG and iron-bearing materials) are also considered. Solid residues mainly include tailings, high titanium slag ($22\% \leq TiO_2 \leq 24\%$) and vanadium-bearing slag. The tailings and vanadium-bearing slag are used to produce ilmenite and vanadium pentoxide. Although many studies have reported the utilisation of high titanium slag (Ai et al., 2006; Bonsack and Schneider, 2001; Han et al., 2012; Sui et al., 2014), no research applying this material in industrial production is yet available. Therefore, during LCA evaluation, the high titanium slag is discharged as solid waste alongside the Jinsha River.

The data show that raw material with the highest consumption is iron ore (4533 kg/FU), followed by coal (1079.4 kg/FU) and limestone (409.5 kg/FU). As well, the electricity consumption is 263.2 kwh/FU.

The environmental discharge inventories for electricity generation (Di et al., 2007), coal production, coke production, limestone production, quicklime production, and main process are shown in Table 2. In this study, the atmospheric discharge, including dust discharge and gas emissions, is emphasised; these discharges mainly originate from burning of fuels, generation of electricity and physiochemical reactions, amongst others (Huang et al., 2010; Zhang et al., 2012).