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Research article

Life cycle assessment and water footprint evaluation of crude steel production: A case study in China

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A R T I C L E I N F O

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A B S T R A C T

China, as the world's largest crude steel producer, is suffering from water scarcity and pollution. However, only a few systematic analyses on the environmental burdens and improvements of China's crude steel production have been conducted. Therefore, it is important for research to be done how China's steel industry can be improved in environment management. To help decision-makers understand this, a life cycle water footprint analysis including gray and blue water was performed based on the methodology prescribed in the ISO 14046 standard. A life cycle assessment was also conducted to improve the environmental performance of the steel industry. Results of these assessments revealed that gray water footprint, which is mainly derived from aquatic eutrophication, carcinogens, and non-carcinogens, is higher than blue water footprint. Optimizing indirect processes, including iron ore mining, magnesium oxide production, transportation, and electricity generation, played dominant roles in the reduction of gray water footprint. Furthermore, COD, Cr (VI), phosphate, BOD_5, Hg, As, nitrogen oxides, particulates, and sulfur dioxide were the key substances for environmental improvements. The underestimation of direct water footprint showed the importance and urgency of implementing scientific and adequate monitoring indicators. Meanwhile, the environmental burden can be reduced by adopting a reasonable location of the steel industry on the basis of regional water resources and actual transportation status, improving the efficiency of raw material consumption, and optimizing the power structure.

1. Introduction

Water resource shortage is a common global problem, and the world is predicted to face about 40% global water deficit in 2030 (UNESCO, 2015). The China is also identified with water scarcity (UNESCO, 2015), and approximately 32% of the water in China faces various pollution problems (NBSC, 2016). China's iron and steel industry (ISI), which has been the world's largest crude steel production industry since 1996 (WSA, 2016), suffers from serious water resources shortage and environmental pollution problems (Gu et al., 2015; MPI, 2016). For example, 14.5% of the total wastewater and gas is produced from ISI in China (Wu et al., 2017). Moreover, the freshwater consumed by China's ISI accounts for approximately 14% of the total industrial water consumption of China (Huang et al., 2011). The wastewater discharged from ISI contains numerous toxic pollutants (e.g., heavy metals, waste oil, and cyanide) that lead to significant environmental degeneration (Gu et al., 2015). Meanwhile, ISI is highly energy intensive which caused inseparable association with water resource shortage and various pollutants emissions during its entire life cycle (Olmez et al., 2016). Those environmental impacts can be passed through the supply chain to downstream products and significantly influence the global environment (Berger et al., 2012; Wang et al., 2014). To deal with water resource problems caused by ISI, the Chinese government has enacted increasingly stringent standards to control wastewater from ISI and encourage enterprises to improve water consumption and recycling efficiency (MPI, 2016). A systematic assessment of water discharge and consumption is therefore necessary.

Water footprint (WF) is a comprehensive indicator for assessing water resource consumption and pollution caused by anthropogenic activities in geographical and temporal dimensions (Hoekstra et al., 2011). This indicator considers direct and indirect processes. To the best of our knowledge, only few analytical studies on WF have examined crude steel production. One of these limited studies is that of Gu et al. (2015), who performed a case study on ISI in Eastern China via chain summation and stepwise accumulative approach. However, this study hardly identified the key factors that contribute to WF during the whole life cycle. Moreover, the environmental fate of pollutants among various media (i.e., water, soil, and atmosphere), exposure analyses,

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and toxic effects on humans and the environment are ignored. The International Organization for Standardization (ISO) proposed the life cycle assessment (LCA) method as an international standard for WF analyses to address these problems (ISO 14046, 2014). LCA is a powerful method that quantifies various environmental effects associated with the entire life cycle of certain products, processes, or activities (Finnveden et al., 2009). Currently, most life cycle WF analysis is oriented toward the impact of water scarcity on human health and ecosystem (Hoekstra, 2016; Berger et al., 2014; Boulay et al., 2011). However, the toxicity impact which is related to the changes in water quality also plays indispensable roles in WF evaluation (ISO 14046, 2014; Ridoutt and Pfister, 2013). The limited research based on toxicity impact uses the LCA model (e.g., ReCiPe model) directly (Ridoutt and Pfister, 2013). However, direct application of the LCA model to WF analyses produces inaccurate result (Ma et al., 2018; Bulle et al., 2013). ISO also pointed out that only the influence related to water quality should be considered in WF analysis (ISO 14046, 2014). Meanwhile, few studies have focused on the LCA analysis of crude steel production. These LCA studies are meaningful for other environment issues, such as global warming and fossil depletion. Rossi et al. (2017) focused on the life cycle assessment of steel bridge. Bieda (2012) reported the life cycle inventory of Polish steel production, and Burchart-Korol (2013) and Olmez et al. (2016) conducted LCA analysis of Polish and Turkish ISI, respectively. However, the LCA model applied in previous studies (i.e., IMPACT 2002 + and ReCiPe H) is applicable to Europe; hence conducting LCA analysis of China's ISI via above model may lead to inaccurate results (Li et al., 2016a; Chen et al., 2016). Moreover, the limited LCA research in China mainly concerns air emissions (Li et al., 2016b), and no life cycle water footprint analysis of China's crude steel production has been found.

Thus, the present study aims to (1) perform a life cycle WF assessment based on ISO 14046 standard and a LCA analysis of China's crude steel production, (2) quantify gray and blue WFs of ISI at the national level including direct and indirect processes, (3) analyze the key direct and indirect influencing factors in all crude steel production stages in China, and (4) provide useful suggestions for reducing the environmental burdens of ISI.

2. Methodology

2.1. Scope definition

In this study, the functional unit is a ton of steel billet (i.e., crude steel), which is a quantified reference for inventories and results (ISO 14040, 2006). Fig. 1 illustrates system boundary, and Supplementary Information S1 provides detailed information. Molten iron smelting, steelmaking, on-site reuse of various byproducts (e.g., crude oil and blast furnace gases), and raw material production were all considered in this study. All these processes involve transportation, waste disposal, direct waste emissions, and land occupation. Infrastructure was excluded for its minimal contribution to the overall impact (Frischknecht et al., 2005) and the lack of detailed data. Direct WF represents water consumption in the operation stage and on-site waste (i.e., wastewater, waste gas, and solid) emissions, whereas indirect WF includes the water consumed and the waste discharged in the supply chain (e.g., raw materials production, landfill, and transportation). Additionally, steel billets produced by converter steelmaking technology, which is applied in this study, account for approximately 95% of Chinese crude steel output (CISA, 2016).

2.2. Methodology

Gray (i.e., water resources used to assimilate various pollutants), blue (i.e., consumptive use of surface and groundwater), and green (i.e., rainwater insofar as it does not become run-off) WFs are generally involved in WF analyses (Hoekstra et al., 2011). However, green WF was excluded in this study because rainwater is generally ignored in industrial activities (Berger et al., 2012). The LCA model used in this study (Fig. 2) is a combination of IMPACTWorld + model (Plouffe et al., 2012), IPCC report (IPCC, 2014), and ReCiPe model (Huijbregts et al., 2017). Meanwhile, updated characterization factors of carcinogens, non-carcinogens, and freshwater ecotoxicity was conducted based on USEtox™ model (Huijbregts et al., 2010) by Li et al. (2016a) and Chen et al. (2016). Different from the quantification of updated characterization factors of the aforementioned categories in LCA analysis, the quantification of characterization factors for WF evaluation considered only the intake routes, exposure pathway, and influence related to water quality (Ma et al., 2018). Detailed calculation process is shown in Supplementary Information S2. Moreover, the characterization factor of the remaining midpoints in gray WF evaluation (i.e., aquatic eutrophication) was similar to that of the LCA model in this study. Blue WF evaluation was conducted according to the investigations reported by Berger et al. (2014). Furthermore, the water press index was used to assess the proportion of WF in China's per capita water resources in different regions (NBSC, 2016). The uncertainty analysis results can be obtained from Supplementary Information S3.

2.3. Data sources

The on-site monitoring data on the operation process (e.g., raw material and energy consumption, water use, land occupation, and waste generation) used in this study were collected from an iron and steel plant located in Shandong Province, China. Its annual steel billet (i.e., crude steel) production capacity is approximately 5 million tons. A life cycle inventory was built and is shown in Table 1. Meanwhile, the detailed information of secondary database is shown in Supplementary

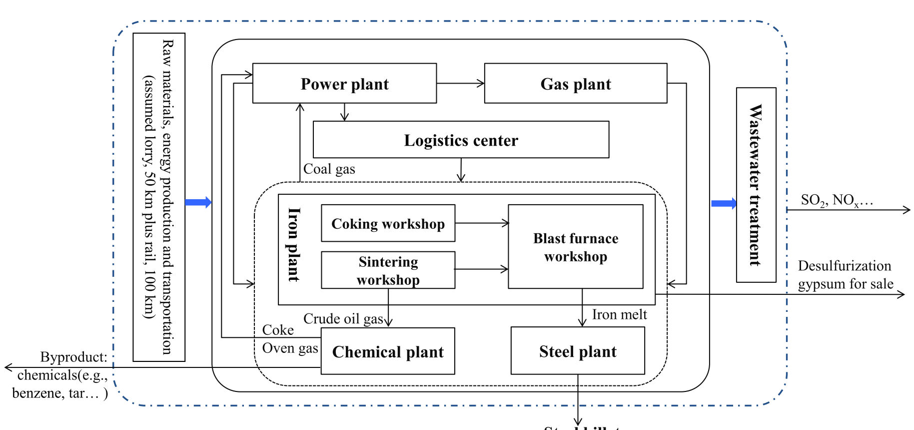

Fig. 1. System boundary.