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Sustainability evaluation of a steel production system in China based on emergy

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ABSTRACT

The huge energy consumption and high pollutants emission have restrained the sustainable development of China's iron and steel industry. It is very necessary to explore those underlying obstacles which hinder the sustainable development of this industry from a systematic point. This paper adopted an improved emergy based method and a set of indicator system to evaluate the sustainability of steel production enterprises, in which dilution method, disability adjusted life years (DALY) method and potentially disappeared fraction (PDF) method were integrated into classic emergy analysis to quantify the impact of emissions, and then the related indicator system characterizing the industrial production process was put forward. One steel production enterprise in Sichuan Province, China, as a case, was studied using the proposed methods and indicator system. The research results show that this enterprise is not sustainable in the long term, due to large share of nonrenewable inputs and strong dependence on imported inputs; emissions' impact further aggravates this situation due to the increasing environmental loading; the proposed methods and indicator system can act as one of helpful tools for decision-making in steel & iron industry. Finally, this paper gives some corresponding suggestions so as to improve the comprehensive performance of this enterprise.

1. Introduction

Steel, as one of important construction and manufacturing materials, has been widely used all over the world. This material plays a particular role in China's economic development. Infrastructure construction and real estate, as two of the main driving forces of this country's economy, depend heavily on steel materials. With the rapid growth of the Chinese economy, the crude steel output grew at an average annual growth rate of 9.63% from 31.78 million tons in 1978 to 723.88 million tons in 2012 (China Iron & Steel Industrial Association, 2014). In 2011, Chinese crude steel production reached 683.3 million tons, accounting for 45.9% of world's steel production (National Bureau of Statistics of the People's Republic of China (2012); Worldsteel, 2011). Though impressive progress has been made, this industry still faces many problems, such as low resource and energy efficiency, and heavy environmental pollution (He et al., 2013). This industry consumed about 15.2% of the national total energy and generated about 14% of the national total wastewater and waste gas and 6% of the total solid wastes (Guo and Fu, 2010). These issues are challenging the sustainability of this industry, and they also further threat the sustainability of China's economy. Obviously, two urgent issues need to be addressed in Chinese steel production in future: one is the low production efficiency (He et al., 2013), and the other is the serious environment problem, like depletion of non-renewable resources, global warming, acidification, depletion of water resources and potential threats to health and safety of employees (Yang and Liu, 2002; Rajesh et al., 2007).

Therefore, enhancing the productive efficiency and mitigating the emissions' impact have become two of the major tasks of Chinese iron and steel enterprises, since the Ministry of Industry and Information Technology of China published "the '12th Five-Year'

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development plan of the iron & steel industry" (Ministry of Industry and Information Technology of China (2011)). According to the plan, energy consumption per unit industrial added value needs a 18% reduction, and the related pollutants emissions (including CO_2, SO_2 and COD) should be cut by 18% during the "12th Five-Year" period accordingly, based on the level of "11th Five-Year". Therefore, it is urgent to call for a systematic method to measure the comprehensive performances of steel & iron industry.

Some works have been carried out to evaluate the performances of China's iron and steel industry. Therein, Movshuk (2004) examined changes in technological efficiency, technical progress and total factor productivity (TFP) growth of Chinese iron & steel industry during 1988–2000 using a stochastic frontier model. They found that the technical efficiency of this industry had not been improved significantly, and even been deteriorated since the mid-1990s. Zhang and Wang (2008) used the Cobb–Douglas (C–D) type production function to estimate the impact of energy saving technologies and innovation investments on the productive efficiency of Chinese iron & steel enterprises during 1990–2000. They found that, with the increase of technique updating and transformation investments driven by energy conservation, the productive efficiency of Chinese iron & steel enterprises had been enhanced. Lin et al. (2011) evaluated the potential future energy efficiency gap of China's steel industry, and they found the energy-saving potential of China's steel industry exceeded 200 million tons coal equivalent in 2008 based on Japan's energy efficiency level in the same year. Lin and Wang (2014a,b) analyzed the energy conservation potential in China's iron & steel sector using the co-integration method and scenario analysis. They found that there is a long-term relationship between energy intensity and factors (such as research and development (R & D) intensity, labor productivity, enterprise scale, and energy price, etc.). However, these researches have not investigated the related environmental issues, which are necessary factors in assessing the sustainability of this industry.

Meanwhile, some scholars have begun to investigate the related environmental problems and ecosystem's contributions in providing services and products in this industry. The Sustainable Process Index (SPI), developed by Krotscheck and Narodoslawsky (1996), seems to measure and relate the ecological impact of a process with respect to the quantity and the quality of the energy and mass flows it induces by taking into account the dual function of area as a recipient of solar energy and as a production factor (Niederl-Schmidinger and Narodoslawsky, 2008). However, SPI methodology ignores some important factors, such as emissions' impacts, wastes recycling, etc., although it accounts for the area to absorb some emissions (such as CO_2) formed during the production; meanwhile, the degree of sustainability in the final indicator is not explicit because it does not make a clear distinction between finite nonrenewable sources and renewable ones. Besides, Rajesh et al. (2007) presented composite sustainability performance index (CSPI) for steel industry by using analytical hierarchy process (AHP). Though economic, environmental and societal issues have been taken into account, different experts' subjective judgments make the results dubious. Nowadays the major methods used to evaluate steel industry include: (a) Substance flow analysis (Michael, 1999; Michaelis and Jackson, 2000a,b). This method does not comprise ecosystem's contributions in making products and services. In addition, it also does not quantify each kind of substance's contributions in the production process. (b) Life cycle assessment (Huang et al., 2010). It does not comprise ecosystem's contributions in making products and services; meanwhile, the results also depend on human preferences. (c) Economy analysis. This method relies on artificial markets or shadow pricing, which makes the results inevitably subjective. (d) Energy analysis (Lin and Wang, 2014a,b). This method does not make the differences between all kinds of energy resources which have different quality; meanwhile, different flows of energies, materials and services are usually not comparable due to their different functions. (e) Exergy analysis. This method does not consider environmental contribution to human economic system.

Comparatively speaking, emergy approach (Odum, 1988, 1996; Lan et al., 2002; Brown and Ulgiati, 2004a, 2004b, 2005) has the huge advantage to evaluate the sustainability of the steel production. Emergy theory, created by Odum (1988), considers the historical accumulation of all kinds of energy used in a production process and provides a universal measure for the different kinds of energy flows in a system network. A system is evaluated through analyzing its energy, mass, information, and currency flows in terms of emergy (Sciubba and Ulgiati, 2005; Bastianoni et al., 2007). This method has been widely adopted to analyze industrial production systems. Brown and Ulgiati (2002) integrated the environmental services into the related emergy indicators to evaluate the sustainability and the environmental loading of an electricity production system. Lou et al. (2004) investigated the issues of optimal operation of an industrial ecosystem under uncertainty through an emergy analysis based on the game theory. Wang and Zhang (2005) applied emergy analysis to evaluate the sustainability of an eco-industrial park with power plant using improved emergy based indices. Geng et al. (2010) presented an emergy-based method to evaluate the environmental performance and sustainability of the industrial park, and their research highlighted the potential of emergy synthesis method as an environmental policy making tool at the industrial park level. Yuan et al. (2011) evaluated different technology solutions for construction and demolition wastes recycling through the emergy theory and method, and they demonstrated that the close-loop recycling option is better than the open-loop recycling option for construction and demolition wastes. Song et al. (2013) used emergy analysis and the LCA approach to quantitatively investigate the effectiveness of an e-waste treatment trial project in Macau through introducing two new emergy based indicators (emergy recovery and technical efficiency). Besides, this method has been also introduced to evaluate steel production systems. Therein, Bargigli and Ulgiati (2001) presented a comprehensive mass, energy, exergy and emergy evaluation of the whole chain of processes from ore mining to refined steel and compared the production of primary steel, secondary steel and a weighted mix of the two, and the environmental and energetic related advantages of steel scraps recycling were univocally underlined. Zhang et al. (2009) applied emergy analysis to evaluate the sustainability of Chinese steel production during 1998–2004, and the results reflected that its sustainability was very low and declining in this study period, and emissions' impact reduced the sustainability of this industry obviously. Zhang and Chen (2010) evaluate the sustainability of an iron and steel eco-industrial park in China based on emergy theory, and the results indicate that its comprehensive performance is improved after implementing material cycling and energy cascade use compared to that before. Giannetti et al. (2013) used emergy synthesis to evaluate a reverse logistics network for steel recycling, and emergy ternary diagrams were used to interpret the results. Their case research shows that the proposed method and indicator system are feasible to evaluate the comprehensive performance of this industrial system.

Therein, most of these researches have not quantified emissions' impacts on environment, economy and human health; however, this kind of impact should not be ignored in emergy evaluation of ecological economic systems because the impact of emissions from human-dominated systems requires environmental services to mitigate or eliminate the damage so as to keep systems'