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Cradle-to-cradle modeling of the future steel flow in China

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A B S T R A C T

China is the biggest steel producer and consumer in the world. Therefore, it is important to understand the dynamic mechanisms of the steel flow, to forecast the future trends, as well as evaluate different improvement measures. Although the previous models are able to depict the dynamic material flow, the market dynamics are excluded such as production capacity planning, the cost competitiveness of each route, the market prices of resources, etc. This paper presents a cradle to cradle model to describe the comprehensive mechanism of the steel lifecycle by combining both material and market dynamics. The model is used to predict and quantify the future steel flow in China from 2012 to 2100. The results confirm that the secondary (from scrap) steel production share will increase along with the sufficient scrap supply in the long term. Meanwhile, the analyses also highlight that market dynamics has a profound impact on the steel flow. With the aim of promoting sustainable thinking in steel production and usage, this paper focuses on a number of material efficiency strategies and investigates their impact by using what-if scenario analyses. The results indicate that the benefit of reuse and remanufacturing scrap is limited when the generation of scrap is insufficient in the next two or three decades. The analyses also identified two strategies (i.e. less material for same service and more intensive use) are effective measures to improve the sustainability in China steel industry.

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1. Introduction

Steel has been the most widely used metal to promote strong economic growth in China. However, the current steel production and usage in China has exerted considerable pressure on the supply of energy and virgin resources as well as the environment. For instance, the steel production ranks third to CO2, SO2, NOx, and PM (i.e. particulate matter) emissions in China (Zhang et al., 2014). Moreover, China’s ongoing industrialization and urbanization is projected to cause a significant growth in the demand of steel (Wang et al., 2014). Meeting this demand under sustainable constraints is a crucial challenge involving stakeholders in both China and worldwide. A sustainable thinking from environmental, social and economic aspects is essential to address this challenge, which should be applied for steel production as well as for steel usage (Allwood et al., 2011, 2012; Yellishetty et al., 2011; Duflo et al., 2012). In particular, the notions of energy efficiency and material efficiency were introduced to address this challenge (Milford et al., 2013). Currently, the energy efficiency measures have been intensively studied for China steel industry resulting in significant decline in energy intensity since 1990 (Hasanenbighi et al., 2013, 2014). For the future, however, their benefits will be marginal for China mainly due to the limited potential (Sun et al., 2013), high implementation cost (Wang et al., 2007) and other reasons (Allwood, 2013). Compared with energy efficiency, material efficiency has received very limited attention. However, material efficiency have been highlighted as the key pathway towards solving this challenge by a number of researchers (Behrens et al., 2007; Allwood et al., 2012; Skelton and Allwood, 2013). In this context, there is an urge to analyze and emphasize the importance of material efficiency and clarify their implications for China’s steel case from material flow aspect.

There are a number of studies on China’s steel industry from material flow perspective. Currently, lots of studies solely focused on the steel production stage, in particular, on the prediction on changing from the primary (from ore) production route to the secondary (from scrap) production route (Wang et al., 2007; Hasanenbighi et al., 2014). In addition, a number of publications have highlighted its benefits on energy saving, environmental impact mitigation, and securing long-term access to virgin resources (Yellishetty et al., 2011; Pauliuk et al., 2012; Wang et al., 2014). Meanwhile, some researches (Chen et al., 2014) conducted the

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‘gate to crave’ study by linking the steel production stage with the demand growth patterns of downstream sectors. Since the secondary production route is fed with recycled scrap from the retired societal steel stock, many studies conducted the dynamic material flow analysis on the generation of steel scrap based on lifetime distribution model (Davis et al., 2007; Park et al., 2011). Furthermore, the “stocks-drive-flows” model (reviewed by Müller et al. (2014)) was built to quantify the entire steel cycle driven by the societal stock and was applied widely (Pauliuk et al., 2012, 2013a; Pauliuk and Müller, 2014) in quantifying materials flow and related environmental footprints.

Although the “stocks-drive-flows” model is able to depict the dynamic material flow, this model fails to include the ore reserve and mining stage into steel cycle, which is non-negligible for long-term analysis. Meanwhile, the previous methods quantified the material flow based on sole mass–balance relationship (Wang et al., 2014), and it ignored an important aspect—the market dynamics, such as production capacity planning, the cost competitiveness of each route, the market prices of resources, etc. Considering the market dynamics along with the material dynamics will describe the producers’ decision-making better, and hence it can provide a more reliable prediction of the future steel trends, as well as an in-depth understanding of implementing different material efficiency strategies.

Therefore, this paper will construct a cradle to cradle model covering all the stages and capture the comprehensive mechanisms of the steel flows by combing both material and market dynamics. The rest of this paper is structured as follows. Section 2 presents the system boundary of this study, and describes the details of the proposed model. Section 3 specifies the model input based on the current steel flow in China as the reference scenario, and then Section 4 presents the reference future trends from both physical and economic perspectives. To promote efficient use of steel in China, Section 5 conducts what-if scenario analyses of different material efficiency strategies. The findings of this study are concluded in Section 6.

2. Methodology

2.1. System boundary within this study

With the aim of exploring and quantifying the steel flow in China, Fig. 1 shows the system boundary for this study. The proposed system gives a cradle to cradle perspective which covers mining, production, fabrication, in-use, storing in stock, to waste management stages. For consistency, all materials in this system are converted into the crude steel content. Meanwhile, Fig. 1 identifies the role of the ‘material efficiency’ strategies in the steel cycle. In order to define all steel flow types in the anthropogenic cycle, three layers are distinguished as manufacturing layer, societal layer, and environmental-trade layer. As mentioned before, this study focuses on the impact of implementing material efficiency strategies; thus, the adoption of energy efficiency measures is excluded in this system boundary.

The manufacturing layer contains a series of manufacturing processes, which are energy-intensive, resource-intensive and highly
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