Applied Energy 220 (2018) 192–207

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Assessment of low-carbon iron and steel production with CO_2 recycling and utilization technologies: A case study in China

Qianqian Chen[a,c], Yu Gu[a], Zhiyong Tang[a,*], Wei Wei[a], Yuhan Sun[a,b,*]

[a] CAS Key Laboratory of Low-Carbon Conversion Science and Engineering, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China
[b] Shanghai Tech University, Shanghai 200031, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- Carbon flow of green steel production plants were analyzed.
- Economic feasibility of CO_2 utilization in iron and steel plant was analyzed.
- High value added application of byproduct gas technologies was considered.
- CO_2-CH_4 dry reforming unit to produce reduction gas for DRI production was included.

ARTICLE INFO

Keywords:
CO_2utilization
Carbon flow analysis
Iron and steel industry
Economic assessment

ABSTRACT

Substance flow analysis (SFA) and energy and economic assessment were used in this study to analyze the utilization of CO_2 in the steelmaking system based on four scenarios: the conventional blast furnace-basic oxygen furnace (BF-BOF) process (Baseline case), the BF-BOF process with waste heat and energy recovery (Case-1), the BF-BOF process with CO_2 hydrogenation (Case-2), and the CO_2-CH_4 dry reforming process coupled with an electric arc furnace (EAF) (Case-3). The results suggest that Case-2 is competitive not only in carbon emission but also in energy consumption and economy as it reduces carbon emission and energy consumption by 136 kg and 53.7 kgce respectively. It also increases profits by 9.38 US$ per ton of steel compared to the Baseline case, thus promising to mitigate predicaments in China's present iron and steel industry. With higher levels of hydrogen in the composition of natural gas, Case-3 reduces carbon emission by 40% more than the Baseline case, but its energy consumption is close to that of the Baseline case. Besides, the production cost is 34% higher in Case-3 than in the Baseline case, owing to the high natural gas price in China. Only when the natural gas price falls to the American value, which is 70% lower than that of China, will Case-3 be economically feasible. In short, high production energy consumption and production costs lead to a lack of technical and economic impetus for Case-3 in the current market, even if it is associated with relatively low carbon emission. The key to solving this problem lies in identifying methods to realize reduced gas production with high efficiency and low cost.

1. Introduction

The iron and steel industry plays a key role in the Chinese national economy and is the foundation of China's rapid industrialization and urbanization [1–3]. China has been the world's largest steel producer since 1996 and has produced 683.9 million tons of crude steel in 2011, about 6.4 and 7.9 times as much as that of Japan and the United States, respectively [4]. However, the iron and steel industry is an energy-intensive and highly polluting sector [3], which consumed 464 million tons (Mt) of standard coal and emitted 1.82 billion tons of CO_2 in 2010 [5]. According to the European Steel Association (Eurofer), China alone is responsible for over 50% of CO_2 emissions from global steel production, with the 27 EU member states together contributing only about 8% [6]. Among China's national economic industries, the iron and steel industry is the largest carbon emitter and accounts for more than 30% of the total carbon emissions from industrial sectors. Therefore, it is important to realize its high-efficiency and low-carbon development to meet the climate change objectives proposed by the Chinese government [7–8]. With continuous technological advancements and iron and steel production procedure optimizations, China's

* Corresponding authors at: CAS Key Laboratory of Low-Carbon Conversion Science and Engineering, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China (Z.Tang).
E-mail addresses: tangzy@sari.ac.cn (Z. Tang), sunyh@sari.ac.cn (Y. Sun).

https://doi.org/10.1016/j.apenergy.2018.03.043
Received 20 November 2017; Received in revised form 7 March 2018; Accepted 18 March 2018
0306-2619/

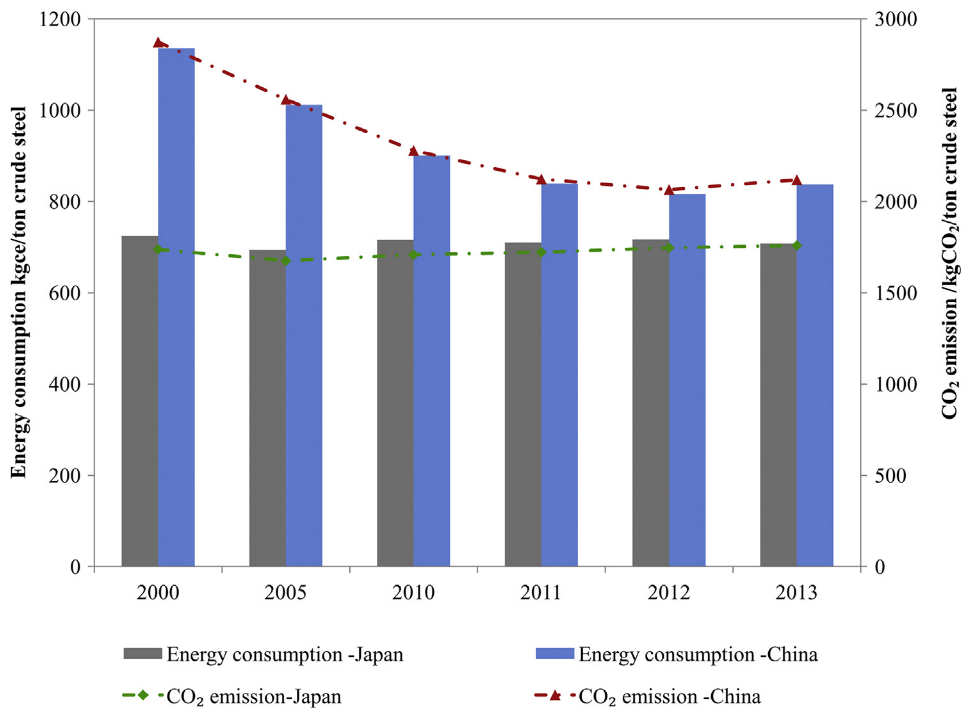

Fig. 1. Energy consumption and CO_2 emission per ton of crude steel in Japan and China.

energy consumption per ton of crude steel in 2013 was 26.2% lower than that in 2000 (Fig. 1) but is still 15% higher than the international advanced level (e.g., that of Japan) [9–11], which indicates that China still has huge energy conservation and carbon emission reduction potential in the iron and steel industry.

With regard to studies on low carbon solutions in China's iron and steel industry, some have focused on the industrial level, which could provide support for governmental policy formation [9,12–14]. For instance, Xu and Lin [12] used a vector autoregressive model to analyze the influencing factors of carbon dioxide emission changes in the iron and steel industry and found that energy efficiency played a dominant role in reducing carbon dioxide emissions. Wen et al. [13] estimated the potential for energy conservation and CO_2 emission mitigation of the iron and steel industry in China based on the Asian-Pacific Integrated Model (AIM). Meanwhile, some studies focused on the technology level, which is more valuable to governments in setting industry benchmarks and will be more practical for enterprises in making choices [15–17]. Li and Zhu [17] selected 41 types of energy saving technologies in China's iron and steel industry and calculated the energy conservation supply curve and CO_2 conservation supply curve under two different discount rates. Morrow and Hasanbeigi [15] analyzed 22 and 25 energy efficiency measures applicable to India's cement and iron and steel industries respectively, and assessed their energy efficiency improvement and CO_2 emission reduction potentials.

Additionally, studies on low-carbon solutions for iron and steel production plants have also attracted wide attention. Zhang and Li [18] studied the carbon emission and mitigation of two iron and steel plants in China via a carbon element flow analysis method. The International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) has long been committed to low-carbon solutions for high energy consumption industries and has put forward detailed techno-economic studies on integrated iron and steel plants with or without CO_2 capture technologies [19]. Na et al. analyzed CO_2 emissions from long steel production process and "Chinese-style" short process by using MFA-based method [20]. These papers presented very important work on energy savings and CO_2 abatement of iron and steel production from different levels and provided a base for the scientific and rational research method used in our study.

With regard to studies on energy conservation and carbon mitigation in the iron and steel industry, most concentrate on recycling waste heat energy generated by each procedure [17–18,21]. Management, optimization, and utilization of by-product gas in integrated iron and steel plants also draws much attention [22–25]. Kong et al. [26], Junior et al. [27] and Zeng et al. [28] tried to solve the problem of by-product gas distribution based on a mixed integer linear programming (MILP) model, with the goal of maximizing energy utilization. Lundgren and Ekbom [22] assessed the techno-economic performance of methanol production from steel-work off-gases and biomass-based synthesis gas. Nowadays, the development and deployment of alternative iron-making technologies along with CO_2 capture and storage (CCS) technology are high priority processes for the mitigation of environmental concerns owing to their remarkable CO_2 emission reduction potential [29–32]. The European H2020 LCE program has been working on the demonstration of advanced precombustion CO_2 removal technology within the framework of the iron and steel industry, aiming to lower the CO_2 footprint of steel production [33–34]. CO_2 abatement technologies involved in the above studies will definitely lead to huge carbon emission reduction in the iron and steel industry. In addition, CO_2 recycling and utilization in steelmaking processes also is an important issue for carbon mitigation [35].

As a kind of carbon source, CO_2 can be used as an alternative raw material to reduce the dependence of conventional high carbon and energy intensive industries on fossil fuels [36–39]. With regard to the CO_2 utilization in iron and steel works, some studies focused on the technical development of conditioning CO_2-rich byproduct gases to synthesize chemicals [40–44]. The FReSMe (From Residual Steel Gases to Methanol) program started a project using CO_2 captured from the steel industry to produce methanol fuel [42]. Kunming Iron and Steel Co. Ltd. (KISCO) analyzed the feasibility of using coal gas from steel-making plants to produce methanol and dimethyl ether [45]. The JFE Steel Corporation also developed technologies to produce methanol from coal gases emitted by steel plants [46]. Some studies concentrated on the utilization of CO_2-rich byproduct gases on the level of integrated iron and steel plant [22,47–50]. Lundgren et al. [22] analyzed the