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Integrated assessment of exergy, energy and carbon dioxide emissions in an iron and steel industrial network

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HIGHLIGHTS

- Exergy, energy and CO_2 emissions assessment of iron and steel industrial network.
- Effects of industry symbiosis measures on exergy, energy and CO_2 emissions.
- Exploring the environmental impact from exergy losses.
- The overall performance indexes are proposed for iron and steel industrial network.
- Sinter strand and the wet quenching process have the lowest exergy efficiency.

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ABSTRACT

Intensive energy consumption and high pollution emissions in the iron and steel industry have caused problems to the energy system, in the economy, and in the environment. Iron and steel industrial network as an example of energy conservation and emissions reduction, require better analysis and assessment. The present study comprehensively assesses an iron and steel industrial network and its environmental performance with respect to exergy, energy and CO_2 emissions. The results show that the sinter strand needs to be greatly improved and the wet quenching process needs to be completely redesigned. The overall exergy efficiency and energy efficiency can be improved by adopting industrial symbiosis (IS) measures. We found that adjusting the energy structure to use renewable energy and recycling solid waste can greatly reduce CO_2 emissions. Moreover, the maximum exergy losses occurred in the blast furnace with the maximum CO_2 emissions. The iron making plant exerted a strong effect on the environment based on the equivalent CO_2 emission potentials. Many performance indicators of the entire industrial network were also examined in this work. It can be seen that integrated evaluation of energy and CO_2 emissions with exergy is necessary to help to mitigate adverse environmental impacts and more effectively fulfill the goals for energy conservation and emissions reduction.

1. Introduction

As one of the most important economic sectors, iron and steel industry has been characterized as a heavy consumer of energy and emitter of air pollution [1,2]. Currently, the iron and steel industry is the second-largest industrial user of energy and contributes approximately 6.7% of total CO_2 emissions across the world [3–6]. China has become the largest iron and steel producer and consumer in the world, with the energy consumption from producing crude steel alone accounting for 13.35% of energy consumption by all industries in China in 2012 [7]. Currently, CO_2 emissions account for 18% of total emissions in China [8,9]. Extensive investigations have been conducted to seek effective measures for energy conservation and emissions reduction in the iron and steel industry [2,10–13].

The effects of numerous energy-saving and emissions reduction measures, such as raw materials substitution, waste heat recovery, power production, and CO_2 fixation, have been assessed using economic and energy-related indicators including energy intensity and energy efficiency [14–18]. It is known that, analogous to natural ecological systems, industrial system metabolisms obey the fundamental laws of thermodynamics [19]. However, the application of energy-based methods cannot be used to assess quality losses within a given system [20], which demonstrates that using only energy-associated indicators has limitations in identifying effective measures to save energy and reduce emissions during operations.

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Unlike the first law of thermodynamics, the second law of thermodynamics emphasizes that each process generates entropy, which indicates that the loss of energy quality plays an important role in the calculation of energy efficiency. However, general energy analysis does not assess the quality and usefulness of energy [21]. To solve this problem, it is necessary to use the concept of "exergy," based on the second law of thermodynamics. Exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it reaches mechanical, thermal, and chemical equilibrium with a reference environment [22]. There have been a number of studies conducted that analyzed the energy and exergy of domestic sectors [20,23–26]. At present, exergy analysis has been applied on a large scale to the industry sectors [27–29] and to energy conversion and utilization of specific industrial processes [30–33]. BoroumandJazi et al. [34] reviewed exergy analyses of industrial sectors with high-energy consumption, highlighted the differences between energy and exergy efficiency, and determined the importance of exergy analysis for optimizing performance in the industrial sectors. Luis and Van der Bruggen [35] presented a review of analyses of the opportunities and challenges in energy-intensive production processes by considering exergy analysis as the first step that is required (although not sufficient) to advance towards a more sustainable chemical industry, concluding that exergy analysis is becoming a very powerful strategy to evaluate the real efficiency of a process.

Many studies have dealt specifically with the exergy of the iron and steel industry. On a process or plant level, Liu et al. [36] and Feng et al. [37] optimized the waste heat utilization of a sinter cooling process using exergy analysis. Exergy analysis was also conducted on a mixed fuel-fired grate–kiln for iron ore pellet induration to investigate the irreversibility of the process [38]. For a blast furnace iron-making process, an optimization model was established based on material balance and energy balance, in which exergy loss minimization was taken as the optimization objective [39]. Considering thermal parameters of the blast furnace process, Ziebik and Stanek [40,41] put forward an algorithm for process exergy analysis based on simulations and noted thermodynamic optimization opportunities for the blast furnace. Çamdali et al. [42,43] and Hajidavalloo et al. [44] performed an energy and exergy analysis of an existing steel Electric Arc Furnace (EAF) to estimate the potential for increasing the energy and exergy efficiency of the furnace. On a steelmaking site, the exergy concept has been used to describe energy problems for different energy types, and CO_2 emissions were optimized by use of the Pareto method [45]. These works demonstrate the effectiveness of exergy methods for identifying specific processes and plants that have large exergy losses, and they suggest how those processes and plants could be improved with regard to energy consumption and emissions. Other works on the entire iron and steel industrial system include those of Ramakrishna et al. [46], who calculated exergy efficiency in ferrochrome production, and de Beer et al. [47], who used exergy analysis to estimate the exergy in different steel production routes, thereby locating the main exergy losses and evaluating their cause. However, these works emphasize exergy in the entire iron and steel industrial system—considering the typical production process from sintering to steel making—and provide no information on the incorporation of symbiotic relationships internal to the iron and steel industry. In addition, constraints exist on the individual process or plant when there is a need to replace devices and improve productivity.

To address the challenges, the present work introduces an iron and steel industrial network. An industrial network enables separated industries to connect with each other. Industrial symbiosis (IS) can reduce resource consumption and energy dissipation, thereby enhancing efficiency and decreasing environmental impacts to some extent. In previous studies regarding IS and the iron and steel industry, the focus has been on the operation of specific measures [48,49]. Exergy analysis was applied to calculate and compare losses and efficiencies for each symbiotic measure, such as industrial waste heat recovery [50] and recycling materials [51]. Nevertheless, integrated assessments based on exergy analysis of the iron and steel symbiotic network and its environmental performance are still lacking.

In addition, from the perspective of environmental performance, it has been proposed that exergy be seen as a form of environmental free energy to provide a fundamental basis for evaluating environmental impacts, or environmental change [52]. Dincer identified waste exergy emissions as the relation between exergy and environmental impact [53]. To emit less waste to the environment, a direct way is to have more efficient processes and use less resources. Recently, exergy methods have been used to gain insights into energy and resource utilization efficiency to facilitate the development, prioritization and ultimate implementation of rational improvement options [54]. Maximizing energy and exergy efficiency could lead to the highest environmental benefits, but the corresponding process may have large quantities of destroyed exergy and exergy lost to the environment due to the industrial scale. To identify effective energy conservation and emissions reduction measures, it is therefore worth exploring a clearer link between exergy and environmental impact. "Cumulative exergy consumption" was suggested by Szargut as an environmental indicator [55], and extended exergy accounting was also developed for environmental analysis [56]. However, these methods have no direct regard for exergy losses. At present, quantitative measures of environmental impact come mainly from pollutants, such as heavy metal soil contamination and CO_2 emissions. CO_2 emissions from the iron and steel industrial network are produced not only because of the necessary mass balance but also as a consequence of thermodynamic inefficiency [57], therefore, from an exergy and energy point of view, it is more crucial to consider avoiding CO_2 emissions due to exergy losses or exergy destruction [35]. Until now, the analysis of CO_2 emissions in the iron and steel industry has mainly been focused on energy utilization, but there is a lack of studies on CO_2 emissions and exergy losses or exergy destruction.

Based on the previous studies mentioned above, an integrated assessment of energy and CO_2 emissions through exergy analysis in the iron and steel industrial network will be conducted in this paper. The objectives of the present study are: 1. to compare exergy efficiency with energy efficiency to identify improvements in operation or technology which help to design environmentally friendly iron and steel industrial networks; 2. to discern the efficiency of the iron and steel industrial network with industrial symbiosis measures and the effects of IS measures on emissions; 3. to explore characteristics of CO_2 emissions in the iron and steel industrial network, and the link between exergy and CO_2 emissions, the equivalent CO_2 emission potentials due to exergy losses, thereby to find trends in the reduction of carbon emissions; and 4. to establish an overall performance index offering a systematic, quantitative approach for the iron and steel industrial network.

2. Methods

2.1. Exergy accounting

As an open system, the iron and steel industrial network can exchange mass, heat and work with its surroundings. Given the input and output from the iron and steel industrial network, the exergy balance can be described as:

$$Ex_{in} = Ex_{out} + Ex_{destruction} \tag{1}$$