

Research Article

Performance Evaluation of an Ironmaking System with Environmental Costs

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This paper proposes an exergoeconomic analysis method that considers environmental costs to make up for the lack of description of environmental costs in the traditional matrix model exergoeconomic analysis method. This method tracks the formation process of the product cost through life cycle and makes a useful exploration for revealing the true cost of the system product. According to actual needs, the principles for the construction of environmental emissions of products are proposed, and a detailed exergoeconomic analysis model is established by taking the iron smelting system as an example. Through calculation and analysis, the formation process and change rule of unit exergoeconomic cost of products in the system are revealed. Especially, considering the exergoeconomic cost of carbon emissions, the results show that the three most influential substances are sinter, coke, and pellets. When carbon dioxide emissions are considered, the total cost will increase by 165.3 CNY/t iron, and unit exergoeconomic cost gradually increases with the progress of the production process.

1. Introduction

At present, energy conservation and environmental protection issues have attracted much attention. The rapid development of China's industries has a great impact on the environment. The rapid development of industries consumes a lot of energy, and the carbon dioxide produced cannot be ignored [1]. The carbon dioxide in the steel industry accounts for 10% of the domestic total. In addition to the power and construction industries, the steel industry is the third largest industry for carbon dioxide emissions [2]. The concept of green development is more conducive to promoting industries to save resources and protect the environment [3–6]. Some scholars have conducted research about CO₂ emission reduction measures [7–9], emission reduction costs [10, 11], and emission forecast in the steel industry. These studies have a profound impact on energy conservation and environmental protection in the steel industry, but most of them only focus on industrial emissions, and few specific studies focus on enterprise emissions. Therefore, how to reasonably evaluate the carbon emissions

of the ironmaking systems is very meaningful to the product cost of the ironmaking systems. For energy conservation, some scholars conduct research from the perspective of exergy.

On the basis of the laws of thermodynamics, some scholars tried to use the exergy method [12–16] to study how to reduce the energy consumption and environmental impact of blast furnace ironmaking [17–23]. Szargut [24] used exergy in metallurgy earlier. Akiyama and Yagi [17] used the same method to study the energy use of blast furnaces. Ziebig and Stanek [19] improved the existing mechanism model on the basis of experiments and proposed a calculation method for blast furnace performance. They not only obtained the main parameters that affect the performance of the blast furnace but also pointed out that the exergy loss in the compression and waste heat process is the largest. Ziebig and Stanek [20] analysed by using energy and exergy and found that the amount of coke seriously affects blast furnace performance. Zhang [21] also analysed the performance of the blast furnace through the exergy method and found the reason for the low efficiency of the blast furnace. In addition,

the efficiency can be improved by increasing the temperature and coal ratio of the blast furnace. Guo et al. [22] established a blast furnace exergy analysis model with coke oven injection and analysed its influence. In addition, Wang [23] showed that after considering the injection of coke oven gas, the exergy and thermodynamic performance improved significantly.

Although the exergy method can reflect the level and reason of the thermal efficiency of the system, it still has shortcomings in reflecting the internal costs of the system. The exergoeconomic analysis combined with energy and economy can reflect internal costs and make up for the deficiency of the exergy method [25]. In addition, the research of Blumberg et al. [26] showed that it is very beneficial to reduce the cost of multiproduct systems. Uysal et al. [27] used the exergoeconomic analysis method to analyse coal-fired boilers. Wang et al. [28] conducted an exergoeconomic analysis to evaluate a cogeneration. Hofmann et al. [29] applied the exergoeconomic method to the CHP plant and carried out a useful exploration of the internal cost of the CHP plant.

Environmental impact analysis involves many factors. Some scholars first simplified the environmental impact to CO₂ emissions and then used the exergy economic method to conduct research and obtained some results in the model [29, 30]. Holmberg et al. [29] studied not only the fuel cost distribution of cogeneration plants but also the carbon dioxide emissions of cogeneration and used the exergy method and market method for analysis and comparison.

The above research analysed the performance of the ironmaking system from the perspective of exergy or exergoeconomics, but the effect of CO₂ emissions on the exergoeconomics of the ironmaking system is not taken into account. This part of the cost cannot be ignored. This article consists of five sections. Section 2 shows a general description of the ironmaking system and its main input and output materials. Section 3 establishes the exergoeconomic and the environmental cost model considering CO₂ emissions. The performance evaluation results and the main impact substances are shown in Section 4. Conclusions are given in Section 5.

2. System Description

Figure 1 shows a schematic diagram of the ironmaking process, which defines the research boundary. Steel manufacturing involves sintering, coking, ironmaking, steelmaking, and rolling. The energy sources of the sintering process are mainly fuel and electricity. During sintering, various iron-containing raw materials are mixed with appropriate amount of fuel and solvent and an appropriate amount of water is added to cause a series of physical and chemical reactions to produce sintered ore. Controlling the ignition temperature, changing the material state, and optimizing the proportion of the mixture can reduce the energy consumption of the sintering process [10, 31]. In the coking process, coal is subjected to high-temperature dry distillation to produce coke, and other chemical products such as coke oven gas and tar are recovered. In the ironmaking

process, sintered ore, coke, and solvent are charged from the top of the furnace, hot air is blown in from the tuyere at the lower part of the blast furnace, and fuels such as oil, coal, or natural gas are injected. Oxygen burns with coke at high temperatures. Carbon monoxide is produced and flows upward through the blast furnace. Carbon and carbon monoxide reduce the iron ore to obtain iron. The gas produced in the blast furnace will be recycled and reused in processes such as coking and rolling. The molten iron is sent to the converter, and high-pressure and high-purity oxygen is injected into the furnace. The oxygen reacts with iron to remove the carbon in the iron to obtain crude steel. Converter gas is also recycled and reused [32]. Herein, this article focuses on the ironmaking process, and the main equipment and materials are described in Figure 1.

Because there are a lot of physical and chemical reactions during ironmaking, in order to obtain better results, some reasonable assumptions need to be made when establishing an analysis model as follows. (1) The physical and chemical reactions in the whole process are in equilibrium. (2) The substances involved in the reaction are assumed to be ideal mixtures. (3) The temperature of the raw materials entering the blast furnace is assumed to be the ambient temperature, which is 298 K, and the remaining parameters are determined by the actual production situation.

3. Methods

3.1. Exergoeconomic Analysis. Exergy analysis should be completed first, which is necessary for both new analyses. This is the general expression of exergy. The exergy method includes the first and second laws of thermodynamics. The first law and the second law of thermodynamics make up the exergy methods. This is a great evaluation method. The general exergy balance is shown as follows:

$$\sum Ex_{in} = \sum Ex_{out} + \sum Ex_{dest}, \quad (1)$$

$$\sum Ex_{in} = [Ex_{out,useful} + Ex_{loss}] + \sum Ex_{dest}, \quad (2)$$

where “ Ex_{in} ,” “ Ex_{out} ,” “ Ex_{dest} ,” “ $Ex_{out,useful}$,” and “ Ex_{loss} ” are exergy input, exergy output, exergy destruction, useful exergy output, and exergy loss, respectively.

Exergy analysis was described in detail in literature [16].

The mass balance is shown in the following formula:

$$\sum m_{in} = \sum m_{out}. \quad (3)$$

The general energy balance is shown in the following formula:

$$Q_{net,in} - W_{net,out} = \sum m_{out}h_{out} - \sum m_{in}h_{in}, \quad (4)$$

where Q is the rate of heat transfer, W is the rate of work, m is the mass flow rate, and h is the enthalpy.

The efficiency of the first law of thermodynamics is given as follows:

$$\eta_1 = \frac{\sum E_{out}}{\sum E_{in}}. \quad (5)$$

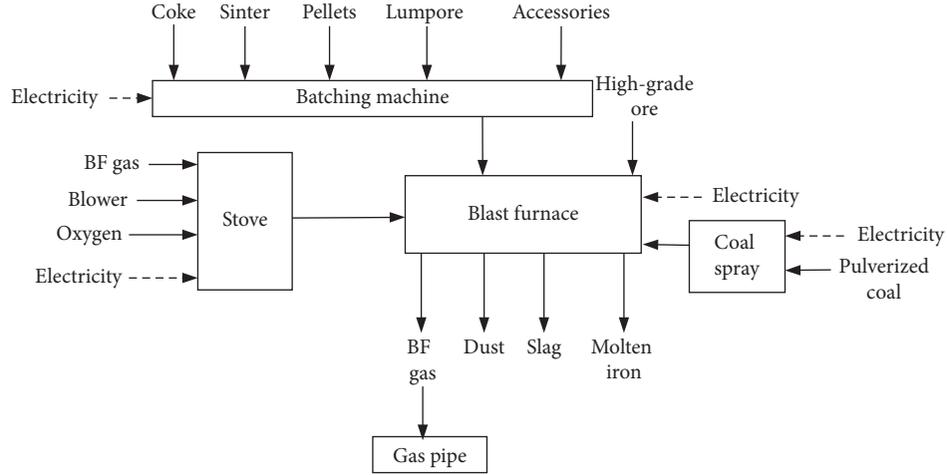


FIGURE 1: Simplified scheme of iron and steel production routes and processes.

The second law of thermodynamics and the general exergy balance are expressed as follows:

$$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_{dest}, \quad (6)$$

$$\sum \left(1 - \frac{T_0}{T_p} \right) Q_p - W_{net,out} + \sum m_{in} \phi_{in} - \sum m_{out} \phi_{out} = \sum Ex_{dest}, \quad (7)$$

where Q is the rate of heat transfer through the boundary at temperature T_p and the subscript zero indicates properties at dead state of P_0 and T_0 . Equation (8) shows the flow exergy with negligible kinetic and potential energies:

$$\varphi = (h - h_0) - T_0(S - S_0). \quad (8)$$

The exergy destroyed is expressed as follows:

$$Ex_{dest} = T_0 S_{gen}, \quad (9)$$

where S_{gen} is the ratio of entropy generation.

The efficiency expression of the second law of thermodynamics is shown in the following formula:

$$\eta_{II} = \frac{\sum Ex_{out}}{\sum Ex_{in}}. \quad (10)$$

System designers or operators obtain energy efficiency through energy analysis and obtain system economic distribution through economic analysis, while exergy economic analysis can obtain energy expenditure, which is not available through energy and economic analysis. This is very important for system design and operation evaluation. It is convenient to reveal how to use resources more efficiently to save resources.

When performing economic analysis of the system, the expenditure of the entire system needs to be provided. Fuel cost, operation, and maintenance are all basic data, while during the whole operation period, the cost of equipment is changing. Therefore, the equivalent annual value method is generally used in the economic analysis of the system [26].

$$A = CRF \sum_{m=1}^n P_m,$$

$$P_m = C_m \frac{1}{(1+j)^m}, \quad (11)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1},$$

where A is the average cost, P_m is the present value of investment, j is the depreciation rate, CRF is the capital recovery factor, n is the investment period, and i is the interest rate.

Evaluating the expenditure of the flow in the factory is helpful for understanding the cost formation process from the input of resources to the final product [33]. There are three steps in this method. The first step is to identify exergy. In the second step, the fuel and product of equipment in the system are to be defined. The third step is to configure the cost balance, as shown below.

3.2. Definition of Exergy Flow.

$$\begin{aligned} C_i &= c_i Ex_i = c_i (m_i \varphi_i), \\ C_e &= c_e Ex_e = c_e (m_e \varphi_e), \\ C_w &= c_w Ex_w, \\ C_q &= c_q Ex_q. \end{aligned} \quad (12)$$

For a unit that consumes power and radiates heat outward, its balance is shown in the following equation [34]:

$$\sum_i c_i Ex_i + c_w Ex_w + Z_K = \sum_e c_e Ex_e + c_q Ex_q. \quad (13)$$

3.3. *Exergoeconomic Analysis with CO₂*. The production process of iron is a typical chemical process of iron and coal. The input of carbon, that is, the source of CO₂ emissions, mainly comes from the burning of fuels and the

decomposition of limestone. Assume that all carbon-containing raw materials and fuels are eventually emitted in the form of carbon dioxide. Other forms of emissions, such as CO₂ and alkanes, are eventually oxidized to carbon dioxide, so all carbon released can be counted as carbon dioxide emissions. If the sintering, coking, and blast furnace iron-making processes are used as a balance system, then the carbon input of all raw materials is identified and defined, and the carbon dioxide emissions of the fixed carbon equivalent within the boundary and the carbon emissions of all products are calculated. Figure 2 shows the carbon emission model of the ironmaking system. The carbon input of the model includes some carbon energy, substances (such as solvents), and carbon emissions, including carbon dioxide emissions from the process and fixed carbon contained in products and secondary products.

We calculate emission factors according to China's "General Principles of Comprehensive Energy Calculation" and strive to be consistent with China's actual carbon emissions. The carbon emission factors are defined as follows:

$$EF = Q \times C, \quad (14)$$

where Q is the calorific value of the material or product, $GJ(t)$ or $GJ(m^3)$, and C is the conversion rate, $t_{CO_2}(GJ)$.

Formulas for calculating carbon dioxide emissions for each process and ironmaking system are given as follows:

$$E_{CO_2} = \left(\sum_{i=1}^M M_i \times EF_i + \sum_{i=M+1}^m M_i \times EF'_i \right) - \sum_{j=1}^n D_j \times EF_j, \quad (15)$$

where E_{CO_2} is the total carbon dioxide emissions, t ; M_i is the consumption of carbonaceous materials; D_j is the output of products and secondary products; EF_i is the direct carbon emission factor of carbon-containing raw fuel; EF'_i is indirect Carbon; and EF_j is the carbon offset of the product (by-product).

Combine the above two formulas to obtain

$$E_{CO_2} = \left(\sum_{i=1}^M M_i \times C_{Mi} \times Q_{Mi} + \sum_{i=M+1}^m M_i \times C'_{Mi} \times Q'_{Mi} \right) - \sum_{j=1}^n D_j \times C_{Dj} \times Q_{Dj}. \quad (16)$$

where C_{Mi} , C'_{Mi} , and C_{Dj} are the conversion factors input carbonaceous materials, noncarbon materials, and output products (by-products), respectively; Q_{Mi} , Q'_{Mi} , and Q_{Dj} are the calorific value of the conversion factors input carbonaceous materials, noncarbon materials, and output products (by-products).

The exergy method can evaluate the environmental factors in economic analysis because it can track the process of energy input to consumption [35]. EXENEC analysis uses

the parameter " C_{CO_2} " (\$/time) for determination. This parameter gives the price information of CO₂ emissions in a given time as follows:

$$C_{ECO_2} = E_{CO_2} \times C_{CO_2}. \quad (17)$$

4. Results and Discussion

4.1. Exergoeconomic Analysis of the Blast Furnace. Taking a certain ironmaking system as the research target and using the exergoeconomic model established above, we calculate and analyse the exergy economic cost of the blast furnace.

The internal exergy of the system is divided into 18 streams, of which 12 are imported from the outside and 6 are output to the system. The equations are established through the exergoeconomic balance and solved by MATLAB to obtain the cost of each stream as shown in Table 1.

Exergoeconomic cost analysis shows that sinter has the largest influence, followed by coke and pellet, which are the main components of ironmaking product cost. Among them, sinter accounts for 46.15% of the input cost, coke accounts for 25.74%, and pellet accounts for 17.56%.

4.2. Exergoeconomic Analysis with CO₂ of the Blast Furnace. The model uses the raw fuel consumed to produce one ton of molten iron as the unit of measurement and determines the consumption and heat income and expenditure of each material on the basis of the material and energy balance. The main chemical components of the raw fuel used in the calculation are described in Tables 2 and 3. The constitution of coke oven gas is presented in Table 4 [35].

Regarding the environmental cost of the system, in order to simplify, we only consider the CO₂ emissions. According to the previous model, the content and calorific value of carbon-containing raw materials and non-carbon-containing raw materials are calculated. At present, carbon dioxide billing is still under discussion. We assume that carbon dioxide is 140 CNY/t [36]. According to the above equation, the unit environmental cost of each stream of the system is calculated for the design of the ironmaking system, and the results are listed in Table 5.

Exergoeconomic analysis and exergoeconomic analysis considering carbon dioxide emissions are applied to an ironmaking system. The results of exergoeconomic analysis that does not consider CO₂ and exergoeconomic analysis considering carbon dioxide emissions are described in Tables 1 and 5. At the same time, the comparison results of two different analysis methods for the ironmaking system are shown in Figure 3. The highest exergoeconomic cost is sintered ore, which is 306.95 CNY, followed by coke, which is 449.86 CNY, and the third influence is pellets, which is 306.95 CNY. When carbon dioxide emissions are considered, the exergoeconomic costs of each stream have changed as shown in Figure 3. The major changes are coke, pulverized coal, and electricity. The thermal economic cost of coke was 535.96 CNY, an increase of 87.1 CNY, followed by coal powder, which increased by 46.284 CNY, and finally, electricity cost increased by about 28 CNY.

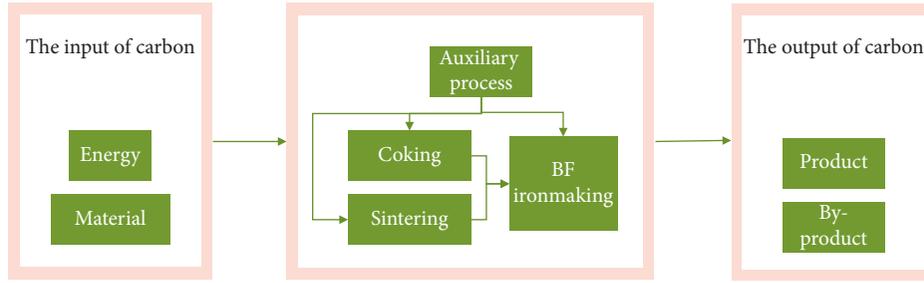


FIGURE 2: The boundary of the carbon emission model of the ironmaking system.

TABLE 1: Exergoeconomic cost of the ironmaking system.

Fuel (CNY/t molten iron)			Product		
Item	Cost	%	Item	Cost	%
Pellets	306.95	17.56	Molten iron	1508.83	86.33
Sinter	806.5	46.15	BF gas	24.84	1.42
Coke	449.86	25.74	Slag	209.33	11.98
Lump ore	14.46	0.83	Scrap iron	3.6	0.21
Oxygen	11.28	0.64	Residual heat water	0.25	0.014
Pulverized coal	81.9	4.69	TRT electricity	0.8	0.046
BF gas	10.9	0.63	Total	1747.65	100
Coke oven gas	3.2	0.18			
Low-pressure steam	2.31	0.13			
Nitrogen	6.77	0.39			
Electricity	17.9	1.02			
Industrial water	35.62	2.04			
Total	1747.65	100			

TABLE 2: Main chemical composition of raw materials.

Item	TFe	Fe ₂ O ₃	FeO	SiO ₂	CaO	MgO	Al ₂ O ₃	MnO	S
Sinter	58.3	17.354	6.93	5.86	7.74	1.53	1.94	0.34	0.0055
Pellets	64.13	26.815	0.64	3.81	3.4	1.2	0	0	0.005

TABLE 3: Main chemical composition of fuel.

Item	C	Volatile					Ash					S _{ORG}	
		CO ₂	CO	H ₂	CH ₄	N ₂	SiO ₂	CaO	MgO	Al ₂ O ₃	S		P
Coke	85.76	0.434	0.459	0.074	0.05	0.223	6.355	0.636	0.508	5.084	0.057	0.009	0.58
Pulverized coal	83.55	1.763	0.993	1.347	0.689	4.660	0.460	0.370	3.720	0.041	0.006	0.56	

TABLE 4: Coke oven gas composition.

Constitute	H ₂	CH ₄	CO	CO ₂	N ₂	C _n H _m
%	57.4	26.4	8.60	2.00	3.60	2.00

After quantitative analysis, the proportion of flow cost in the total cost is shown in Figure 4(a). To simplify the consideration of the environment, CO₂ is only considered as a pollutant, and its impact on the total cost ratio is not obvious. However, if we take the difference in the share of flow cost per share, as shown in Figure 4(b), it can be seen that the impact of carbon dioxide on the cost is different. Considering the carbon dioxide emissions, the total production cost of the ironmaking system becomes higher and the expenditure of links with

a large impact of carbon dioxide will also increase, such as 2.33% increase in coke and 2.11% increase in coal powder.

The cost of the part with less carbon dioxide impact decreases accordingly, such as pellets reduced by 1.28% and sintered ore reduced by 4%. It is worth noting that although the cost of electricity has increased, the increase in the proportion of its cost is negative (0.17%). This is because the increase rate of electricity cost is less than the increase rate of total cost.

TABLE 5: Exergoeconomic cost with CO₂ of the ironmaking system.

Fuel (CNY/t molten iron)			Product		
Item	Cost	%	Item	Cost	%
Pellets	306.95	16.05	Molten iron	1674.134	87.52
Sinter	806.5	42.16	BF gas	24.84	1.3
Coke	536.96	28.08	Slag	209.33	10.94
Lump ore	14.46	0.75	Scrap iron	3.6	0.19
Oxygen	11.28	0.59	Residual heat water	0.25	0.01
Pulverized coal	128.184	6.7	TRT electricity	0.8	0.04
BF gas	13.84	0.73	Total	1912.954	100
Coke oven gas	4.18	0.21			
Low-pressure steam	2.31	0.12			
Nitrogen	6.77	0.35			
Electricity	17.9	2.4			
Industrial water	35.62	1.86			
Total	1912.954	100			

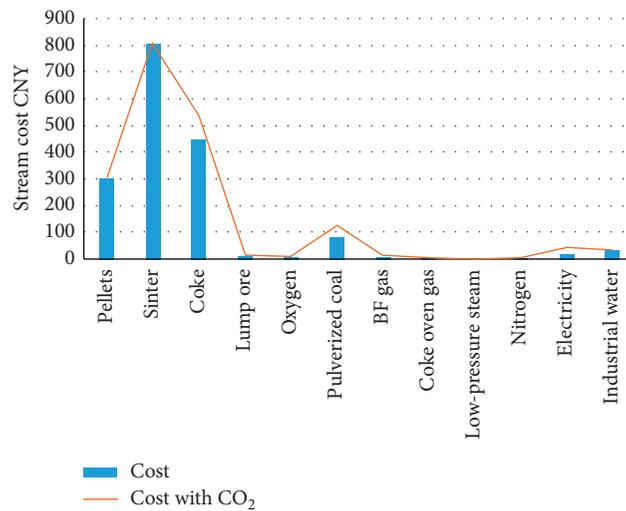


FIGURE 3: Cost of each stream.

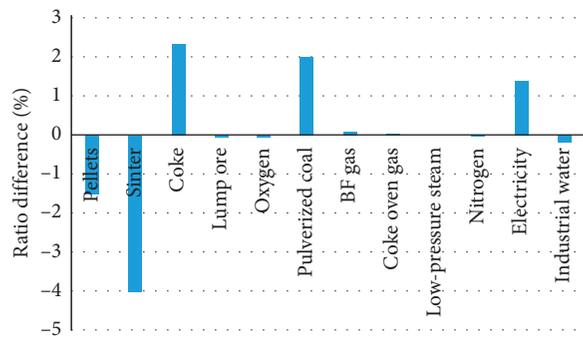
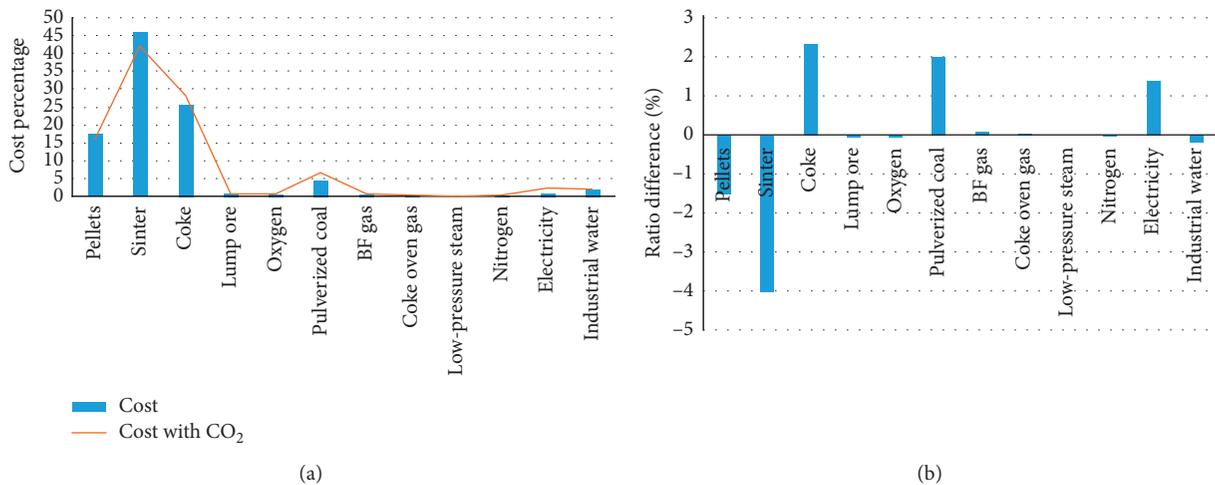


FIGURE 4: (a) Cost percentage of each stream. (b) Cost ratio difference.

Through the above chart, we can intuitively obtain the exergoeconomic cost and exergoeconomic environmental cost in the production process of the ironmaking system, thereby revealing the exergoeconomic and environmental characteristics of the ironmaking system.

5. Conclusions

Based on the traditional thermoeconomic analysis, this paper considers the carbon emission of pollutants as an environmental factor and establishes an exergy economic model of the ironmaking system. The main conclusions are as follows:

- (1) Through the exergoeconomic analysis of an actual ironmaking system, the unit exergoeconomic cost and unit environmental cost of its operation are analysed and calculated, the formation process of the cost is found, and the system is comprehensively analysed from thermodynamic, economic, and environmental factors.
- (2) Based on the exergoeconomic analysis of the ironmaking system, the three highest exergoeconomic costs are sinter, coke, and pellets, accounting for 46.15%, 25.74%, and 17.56%, respectively. When considering carbon dioxide emissions, the exergoeconomic costs are 42.16%, 28.07%, and 16.28%, respectively. After considering carbon dioxide emissions, the total cost will increase by 165.3 CNY/t iron.

In this paper, the consideration of pollutant is simplified to carbon dioxide in the analysis of the ironmaking system, but the method in this paper can be extended to other environmental considerations and can also be applied to other energy systems. Although the way to consider carbon dioxide is still under discussion and the impact of other pollutants on the ecological environment is not included in the enterprise cost, they have caused a certain economic impact, which will be further considered in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

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