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# EXERGOECONOMIC ANALYSIS OF IRONMAKING PROCESS CONSIDERING ENVIRONMENTAL IMPACT COST

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Abstract. *Under the conditions of economic marketization, the evaluation mechanism without considering the environmental costs is not conducive to comprehensively and objectively understand the composition of product costs, and fails to achieve the purpose of resource optimization. The comprehensive costs of the ironmaking process is affected by multiple factors of energy, environment and economy. Based on the combination of the environmental cost obtained by the life cycle assessment method and the exergoeconomic theory, an exergoeconomic evaluation model of the ironmaking process considering the environmental cost is created and realizes the comprehensive evaluation of the cost of the ironmaking process. Its serious environmental impact categories are metal depletion, freshwater eutrophication, marine ecotoxicity, natural land transformation and freshwater ecotoxicity. The law of comprehensive cost formation considering energy environment in ironmaking process is traced. Sinter, pellet and pulverized coal are the three key factors affecting the cost of ironmaking. After considering the environmental impact, the cost ratio of sinter and pulverized coal increases by 10.85% and 9.31% respectively, while the ratio of pellet has little change. This study can help steel enterprises to analyze the production costs of each unit after considering the overall environmental impact, accurately locate the implementation points of energy conservation and emission reduction, and provide ideas and basis for scientifically guiding the sustainable development of enterprises.*

**Keywords:** Ironmaking, Exergoeconomic, Environment impact, Product cost

## 1. Introduction.

The iron and steel industry is a pillar industry for the development of the national economy, as well as an energy-intensive industry. China's steel industry has developed rapidly and has now become the world's largest steel producer. China's crude steel production accounted for the share of global crude steel output from 53.3% in 2019 to 56.5% in 2020 [1]. Steel production consumes a lot of energy and resources; at the same time, it will inevitably have a great impact on the environment. China's iron and steel industry has reached a critical point on the extensive economic growth, and it is no longer able to continue extensive and rapid development at the cost of sacrificing

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resources and polluting the environment. Therefore, it is very necessary to realize the sustainable development of the steel industry and comprehensively analyze the energy, economic and environmental problems of the steel industry.

While environmental issues are being highly valued, discussions on environmental costs have begun around the world. Environmental economic evaluation is a bridge linking environment and economy. There are still many schools of thought on this concept, and its complete concept is still under discussion [2]. Cost-benefit analysis is the earliest application in the economic evaluation of environmental impacts of actual systems [3]. Senaratne et al. [4] used cost-benefit method to analyze the best combination of natural aggregate and recycled aggregate with steel fiber added. It was found in the investigation and experiment of six factories in Sydney that the best combination was 30% recycled aggregate substitute and 0.6% steel fiber. The additional cost of utilizing steel fibers can be offset by aggregate recovered in the optimal combination. Chang et al. [5] conducted research on cost-benefit analysis methods of typical solid waste treatment systems, and allocated different waste streams according to market demand and possible carbon control. His research suggests giving priority to material recycling options and then disposing the waste streams in landfills can maximize net benefits and minimize global warming potential. Stenis [6] regarded industrial waste and conventional products as the same type of output, the cost expression of industrial waste was given, and the true cost of industrial waste in combination with the cost-benefit method was estimated, and he founded the negative impact of industrial waste on profits and helped guide companies improve resource utilization. Cost-benefit can combine environmental cost with product revenue, but the cost-benefit model cannot match with life cycle assessment (LCA) model, and there are many difficulties in the subsequent evaluation of combining LCA.

At the same time, some scholars conduct research on life cycle cost analysis [7,8]. Li et al. [9] used life cycle cost analysis to compare the advantages and disadvantages of three schemes using straw, imported deinked pulp and imported wood pulp as raw materials in China's recycled paper industry, which is of great guiding significance for paper companies under the background of China's tightening of waste paper import quota. Girardi et al. [10] carried out a life cycle cost analysis targeting electric, petrol and diesel private cars. The method applied in Italy resulted in 12.07€/1000 km for electric cars, 21.30€/1000 km for petrol cars and 24.25€/1000 km for diesel cars. The results provided data support for guiding the government and environmental protection enthusiasts to make decisions. Di et al. [11] analyzed the environmental and economic impacts of four different disposal options for construction waste in Flanders Belgium, such as landfill, degraded recycling, advanced recycling, and selective demolition and recycling. The results showed that the total cost of landfilling is the highest, followed by selective recycling. Decision makers can clarify the environmental and economic factors and impacts of the construction waste treatment process. Although life cycle cost analysis can compare the advantages and disadvantages of different schemes from the perspective of cost, it is difficult to explore the environmental and economic cost of each sub-link of the system and its impact on the whole.

With the development of science and technology, industrial systems are becoming more and more integrated. In products, some common factors not only affect the environment, but also put pressure on resource depletion and economic costs. Therefore, how to conduct a comprehensive evaluation of the environment and economy has become a more concerned issue. Many scholars have studied this. Lei and Yin [12] established a hierarchical linear model, analyzed the environmental efficiency of the steel industry with company-level and provincial-level data, and analyzed the factors affecting the efficiency. It was found that the environmental and economic efficiency of the iron and steel industry was greatly affected by the company size, ownership, product category and the economic development of the province where it was located. [13] used TOPSIS method to analyze the environmental economy of iron and steel production in central Iran. After identifying the plant area, possible environmental pollution sources and adverse influences on air quality, water, soil, biological environment, socio-economic and cultural environment, as well as employee health and safety were considered. Li and Qiu [14] used the data envelopment analysis method and took 19 steel companies as decision-making units to study the environmental performance of Chinese steel companies, and explored the specific influence of various input and output variables on the decision-making units. From the perspective of industrial symbiosis (IS), Dong et al. [15] evaluated and compared the number, scale, and related environmental and economic benefits of IS activities in the steel-centered industrial zone in Liuzhou, Jinan, China, and in Kawasaki, Japan. IS can achieve environmental and economic benefits at the same time, and quantifying the scale and importance of IS benefits is very valuable for the promotion of IS.

The above studies, whether from fuzzy analysis method, the analytic hierarchy method or data envelopment analysis, all carry out environmental and economic analysis on the steel industry or other industries from the enterprise or regional level. It is difficult to evaluate the internal environmental economy in steel production process. Based on the above research, this study uses life cycle assessment theory, environmental cost analysis and exergoeconomic analysis methods to conduct environmental and economic comprehensive evaluation of the steel production process, aiming to reveal the formation law of comprehensive cost in the ironmaking process and help enterprises to save energy and reduce emission in a scientific and reasonable way. The organization of this article is as follows. The next section explains the main methods. Section 3 explains the results of the environmental impact and economic assessment. In the last part, the results are discussed and some conclusions are drawn.

## 2. Materials and Methods.

### 2.1. System description.

The complete life cycle of a product is usually from cradle to grave. In order to reduce the complexity of the life cycle assessment and improve its operability, the boundary definition chosen is “from cradle to gate”, due to the numerous uncertainties caused by the use, recycling and disposal of the product. The ironmaking process starts from the raw materials entering the ironmaking station, smelting into molten iron by the blast furnace, and ending with the blast furnace, which involves all the materials and energy consumed by the equipment used for production. One ton of molten iron is used as the functional unit of this study to provide a life cycle list as a quantitative benchmark for all analysis results [16].

The boundary definition of the ironmaking system in this study is shown in Figure 1. Each process considers the input of raw materials, transportation, energy generation and consumption, direct waste emissions (for example, dust, nickel, $SO_2$ and $NO_x$) and land occupation.

### 2.2. Data source and life cycle inventory.

The entry analysis of the ironmaking process uses a survey model to collect and sort out the raw materials, transportation, energy, direct discharge and waste disposal in the different steps of each process. In this study, most of the analysis data of energy resource consumption and pollutant emission inventory of an actual ironmaking process (obtaining 1t of molten iron products) was collected from a group company in Shandong Province, including raw materials, auxiliary materials, energy media, products, by-products, solid waste, gas emissions and water

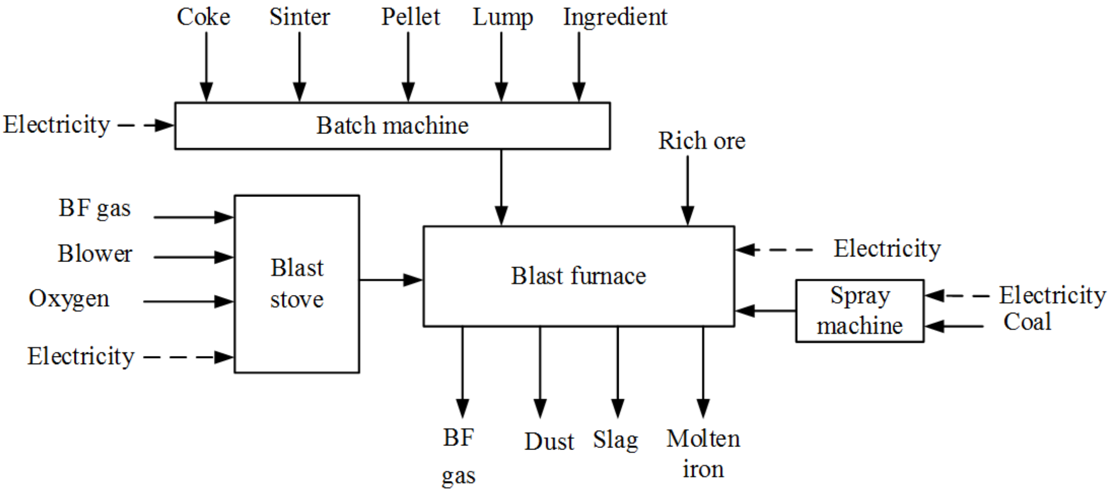


Figure 1. Simplified scheme of ironmaking processes

Table 1. Life cycle inventories of molten iron. Value are presented per ton.

| Inputs and outputs | Value | Unit |
|---|---|---|
| Inputs | | |
| Pellet | 415.7 | kg |
| Sinter | 1151 | kg |
| Coke | 390 | kg |
| Lump | 31.9 | kg |
| Oxygen | 28.28 | $m^3$ |
| Coal | 139 | kg |
| BF gas | 20 | $m^3$ |
| Coke oven gas | 12.15 | $m^3$ |
| Steam | 13 | kg |
| Nitrogen | 12 | $m^3$ |
| Electricity | 26.65 | kWh |
| Water | 3 | $m^3$ |
| Outputs | | |
| Molten iron | 1000 | kg |
| BF gas | 800 | $m^3$ |
| Slag | 200 | kg |
| $CO_2$ | 1100 | kg |
| $SO_2$ | 0.3 | kg |
| Nitrogen oxide | 0.3 | kg |

emissions, and part of the data comes from data analysis and cleaner production indicators in [17]. The life cycle list of molten iron products is shown in Table 1.

### 2.3. Exergoeconomic method.

Exergoeconomic combines exergy analysis and economic principles to provide system designers or operators with information that cannot be obtained through conventional energy analysis and economic evaluation. This is very valuable for the design and operation of the system. It points out how to use resources more efficiently to save resources from the perspective of energy economy.

Given a system, its boundary conditions are determined, and the distribution of each subsystem and exergy in the system is known; after the event matrix $A$ is introduced, the exergy balance equation of the system is shown in Equation (1):

$$A \times X = X_S \tag{1}$$

Among them, $A$ is the event matrix, $X$ is the exergy vector, and $X_S$ is the exergy loss vector of the subsystem. This system has 12 exergy inputs and 6 exergy outputs. The non-energy cost vector includes depreciation fees, management fees etc. $c_{xp,i}$ and $c_{xp,j}$ are the unit prices of the input and output systems, respectively. $E_{xi}$ and $E_{xj}$ are the $i$th input stream and $j$th output stream, and $Z_k$ represents the non-energy cost vector. The balance formula of this subsystem is shown in Formula (2):

$$\sum_{i=1}^{12} c_{xp,i} E_{xi} + Z_k = \sum_{j=1}^{6} c_{xp,j} E_{xj} \tag{2}$$

The system has $m$ subsystems, and $m$ cash balance equations can be obtained. The matrix expression form is shown in Equation (3):

$$A \times X_d \times C_P + Z_k = 0 \tag{3}$$

Among them, $X_d$ is the diagonal matrix of the $X$ vector, and $C_P$ is the unit exergoeconomic cost vector $(n * 1)$.

For any system, where the number of exergy flows $n$ is greater than the number of subsystems $m$, a unique solution for each flow is required, and $(n - m)$ supplementary equations need to be established. The matrix expressions are as shown in Equation (4):

$$X_C \times X_d \times C_P - W = 0 \tag{4}$$

Among them, $X_C$ is a matrix with $n - m$ rows and $n$ columns, which is a supplementary matrix, and $W$ is an $n - m$ dimensional column vector, which is the price vector of the input exergy.

Combine Formulas (3) and (4) to obtain Formula (5):

$$\bar{A} \times X_d \times C_P + \bar{Z} = 0 \tag{5}$$

where $\bar{A}$ is the extended event matrix, $\bar{A} = \left(\frac{A}{\alpha}\right)$, which is an $n \times n$ matrix, $\bar{Z}$ is the extended non-energy cost, $\bar{Z} = \left(\frac{Z_k}{-W}\right)$, which is an $n \times 1$ matrix, through the supplementary equation, the matrix $\bar{A}$ has full rank, and the unit exergoeconomic cost can be obtained from the above formula, that is Formula (6):

$$C_P = -(X_d)^{-1} \times \bar{A}^{-1} \times \bar{Z} \tag{6}$$

2.4. **Exergoeconomic analysis with environmental impact cost.** This article uses the Recipe Midpoint approach to quantify the lifecycle environmental impact results, which contains 18 midpoint categories. In this paper, Simapro software is used for calculation. Environmental impacts can generally be quantified through environmental taxes and charges for pollutant discharge [13]. For impacts that cannot be quantified in this way, such as human health, they can be quantified through WTP, that is, the amount consumers are willing to pay for a certain amount of consumer goods or services. In terms of environmental impact, it refers to the cost that consumers are willing to pay to reduce environmental impact.

Based on the above theory, this paper converts environmental impact into economic value. The environmental monetization factors refer to [18]. The external cost of life cycle inventory assessment (LCIA) is obtained by Formula (7):

$$C_{ew} = \sum C_{e,j} P_{e,j} \tag{7}$$

Among them, $C_{ew}$ represents the external cost, $C_{e,j}$ represents the unit cost of the $j$th pollution category, and $P_{e,j}$ represents the value under the characteristic unit of the $j$th pollution category.

In the previous section of the exergoeconomic analysis, the exergoeconomic cost of the ironmaking process was obtained, which combined energy with economy. The external cost of environmental impact can be obtained by monetizing the results of life cycle environmental impact assessment, adding the external cost of environmental impact to exergoeconomic cost, a comprehensive assessment of energy, economy and environment in the ironmaking process can be realized, as shown in Equation (8):

$$C_{exz} = \sum C_P + C_{ew} \tag{8}$$

## 3. Results and Discussion.

### 3.1. LCA result.

Through the Recipe evaluation method, the LCIA midpoint result based on the functional unit of the ironmaking process is obtained. The median value of LCIA used for 1 ton of molten iron production on climate change is 916.68 kg $CO_2$ equivalent, the impact on terrestrial acidification is 6.24 kg $SO_2$ equivalent, and the environmental impact of particulate matter formation is about 6.37 kg PM10 equivalent, which contains a total of 18 intermediate points. The detailed values are shown in Table 2.

Table 2. Life cycle assessment midpoint results of molten steel

| Impact category | Unit | Value |
|---|---|---|
| Climate change | kg $CO_2$ eq | 916.6781 |
| Ozone depletion | kg CFC-11 eq | 0.000106 |
| Terrestrial acidification | kg $SO_2$ eq | 6.236366 |
| Freshwater eutrophication | kg P eq | 0.556808 |
| Marine eutrophication | kg N eq | 0.272932 |
| Human toxicity | kg 1,4-DB eq | 471.6345 |
| Photochemical oxidant formation | kg NMVOC | 10.47486 |
| Particulate matter formation | kg PM10 eq | 6.368042 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0.05256 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 9.958137 |
| Marine ecotoxicity | kg 1,4-DB eq | 9.882375 |
| Ionising radiation | kBq U235 eq | 0.895146 |
| Agricultural land occupation | $m^2a$ | −60.8358 |
| Urban land occupation | $m^2a$ | 20.27518 |
| Natural land transformation | $m^2$ | 0.187895 |
| Water depletion | $m^3$ | 4.333159 |
| Metal depletion | kg Fe eq | 1229.684 |
| Fossil depletion | kg oil eq | 449.5392 |

In order to compare the different impact categories of each midpoint and analyze the impact of each midpoint on the overall situation, standardization analysis was conducted in this study. The standardized midpoint results of each functional unit are shown in Figure 2. The severely affected categories are five categories: metal depletion, freshwater eutrophication, marine ecotoxicity, natural land transformation and freshwater ecotoxicity. From Figure 2, it can be found that the most severely affected metal depletion is mainly affected by sinter and pellets. The second-ranked freshwater eutrophication is mainly caused by coke and sinter.

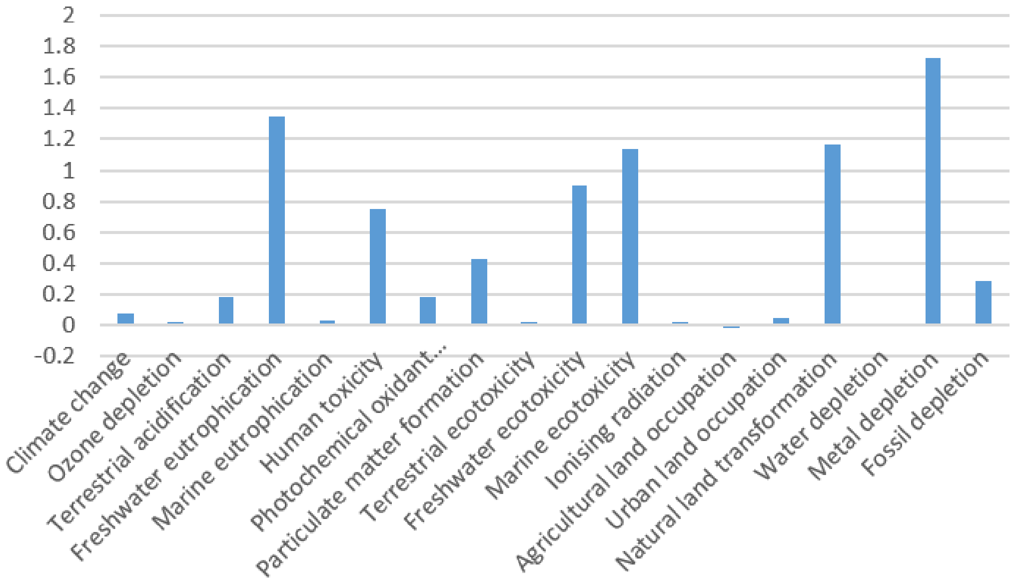


Figure 2. Normalized midpoint results

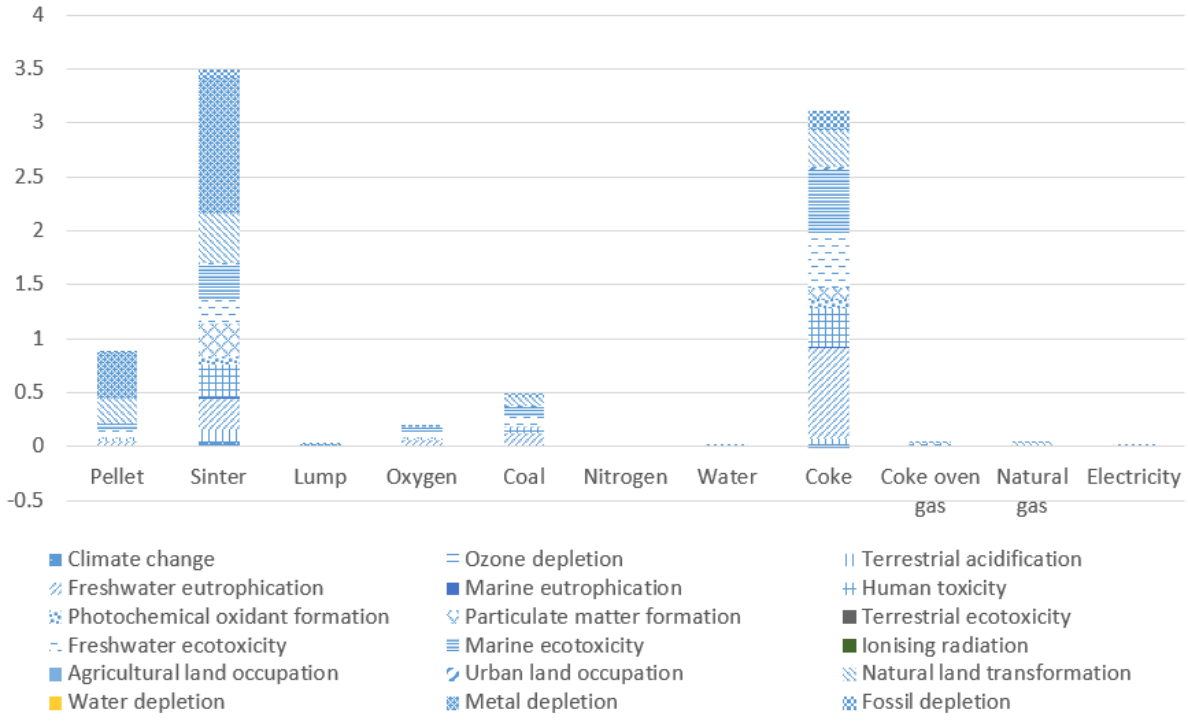


Figure 3. Standardization results of the environmental impact of each substance

Figure 3 shows the standardized results of life cycle assessment of ironmaking process, which are weighed by the classification of the values of all intermediate damage types. It can be seen from Figure 3 that sinter, coke and pellets have a greater impact on the environment. The environmental impact standardized value of sinter is 3.5, and the sinter damage value to the impact categories of metal depletion, natural land transformation, and particulate matter formation is relatively large. The environmental impact standardized value of coke is 3.1, of which coke has a greater damage value for the impact categories such as freshwater eutrophication and marine ecotoxicity. This is basically consistent with the results in Table 2, and also consistent with [19]. The impact of pellets and coal on the environment is second, and the impact of electricity and fuel is negligible.

3.2. **Comprehensive cost analysis.** Based on the data of the ironmaking process and the exergoeconomic analysis method, the exergoeconomic cost of the ironmaking process and the proportion of the exergoeconomic cost of each unit are obtained. As shown in Figure 4, the exergoeconomic cost of sinter is 806.5 CNY, accounting for 46%, followed by the coke, which is 450 CNY, accounting for 26%. These two costs account for more than 70% of the total internal cost, while water, electricity and gas make relatively small contributions to the exergoeconomic cost.

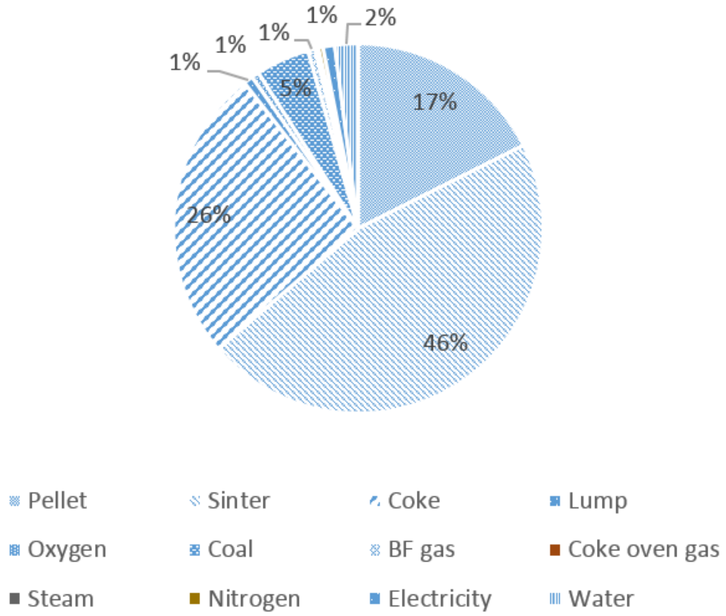


FIGURE 4. Exergoeconomic cost ratio of ironmaking process

The external cost is obtained from the environmental impact characteristic value and the environmental impact economic value obtained from the life cycle assessment. As shown in Figure 5, the external cost of sinter is 1003 CNY, contributing 47%. Secondly, the cost of pulverized coal and pellets is 346 CNY and 224 CNY, contributing 16% and 11%, respectively. These three items account for the total 74% of the cost, and other materials such as oxygen-enriched gas and coal gas contribute little to external costs.

The total cost of the ironmaking process considering the environmental impact is the sum of the exergoeconomic cost and the external environmental cost. As shown in Figure 6, the total cost of the ironmaking system is 3152 CNY, of which the sinter is 1810 CNY, accounting for 57% of the total cost; the pellets and pulverized coal is 531 CNY and 428 CNY, accounting for 17% and 14% respectively; the oxygen, water and gas is relatively small, accounting for 12% of the total cost of the ironmaking system. Comprehensive consideration of environmental cost and exergoeconomic cost can guide iron and steel enterprises to carry out environmental governance and resource allocation more scientifically and objectively.

3.3. **Key factors.** According to the results of standardization evaluation, the most important potential environmental impacts in the entire life cycle of molten iron products are freshwater eutrophication, human toxicity, particle formation, freshwater ecotoxicity, marine ecotoxicity, natural land transformation and metal depletion. Therefore, it is

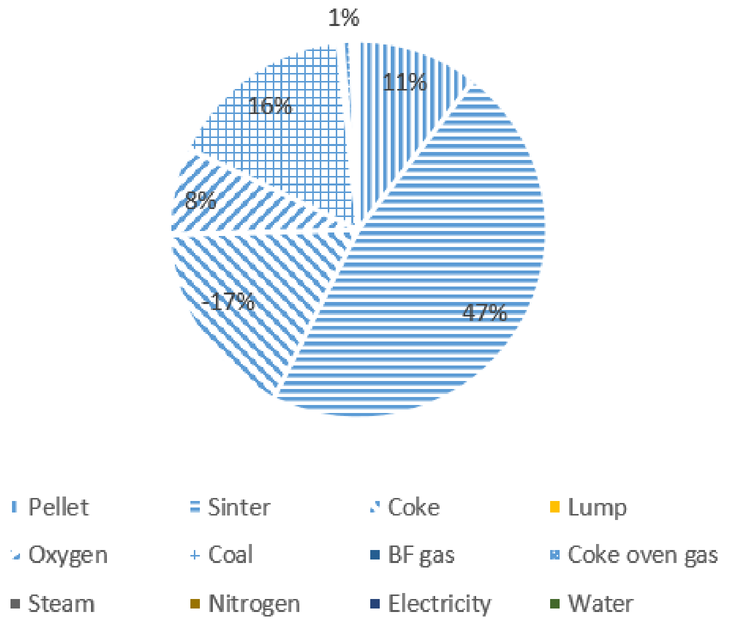


Figure 5. External cost ratio of ironmaking process

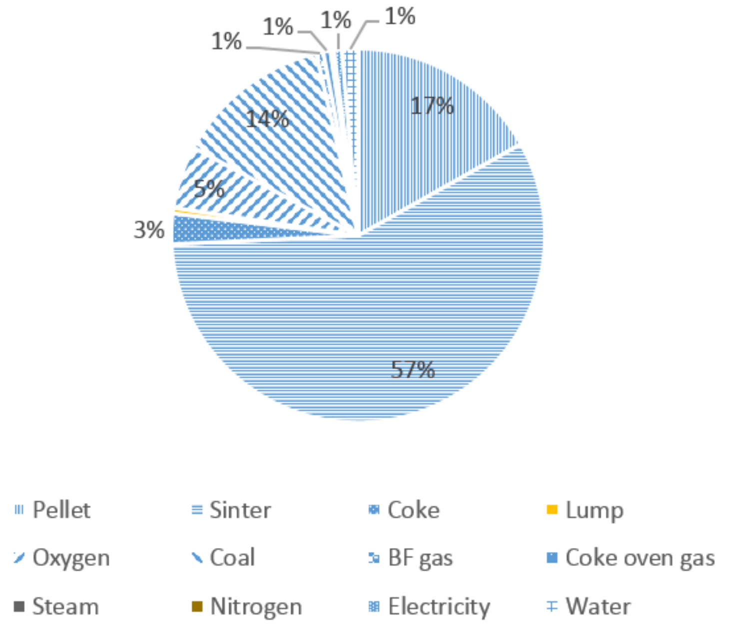


Figure 6. Total cost ratio of ironmaking process

necessary to identify and analyze the key factors that cause the above-mentioned environmental impact, so as to make relevant suggestions. Based on the evaluation results, the key factors are identified, and the results are shown in Figure 7. It can be seen from Figure 7 that for the above-mentioned impact categories, sinter and coke are the most important environmental contributors, and their impact on most environmental categories accounts for more than 50%. Sintering has a particularly significant impact on the consumption of metal resources and the particulate matter formation, its contribution can reach more than 70% of its total environmental impact, and it also has a significant impact on human toxicity and natural land transformation. At the same time, the contribution of coke to freshwater eutrophication and freshwater ecotoxicity cannot be ignored.

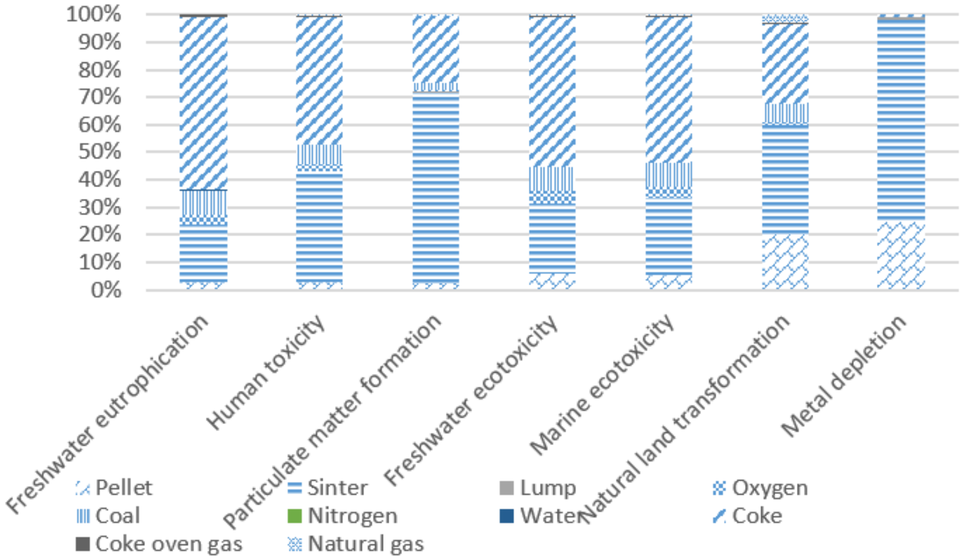


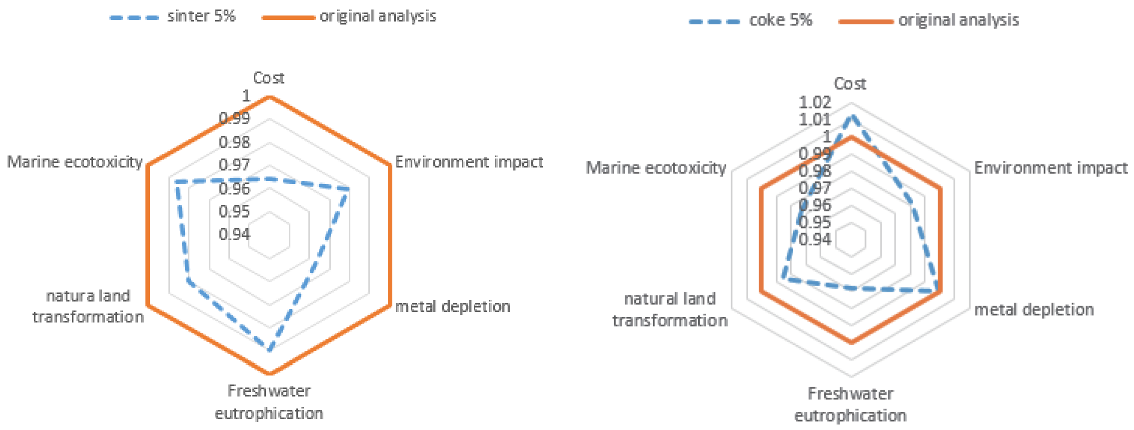
FIGURE 7. Key factors that contribute to significantly affected categories

3.4. **Sensitivity analysis.** Sensitivity analysis can effectively test the sensitivity of the life cycle inventory input data to the evaluation results, usually based on the percentage adjustment rule of input and output parameters [20]. In this paper, a sensitivity analysis was conducted by changing the material input amount by 5% at a time [21]. By reducing the sinter input by 5%, the results are shown in Figure 8(a). The overall environmental impact is reduced by 2%, the economic cost is reduced by 4%, and the major environmental impact categories, such as Marine ecotoxicity, natural land reconstruction, freshwater eutrophication and metal depletion, are fluctuated by 1.5%, 2%, 1% and 4% respectively. It can be seen that sinter has the greatest impact on the total cost and metal depletion, and has little impact on freshwater eutrophication and marine ecotoxicity.

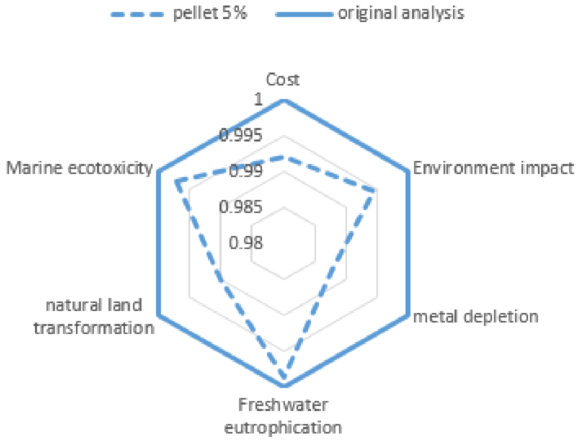
By reducing the input of coke by 5%, the result is shown in Figure 8(b). The overall environmental impact decreased by 2%, economic costs increased by 1%, major environmental impact categories such as marine ecotoxicity, natural land transformation and freshwater eutrophication fluctuated by 4%, 2% and 4% respectively. Therefore, coke has a greater impact on marine ecotoxicity and freshwater eutrophication, but less impact on economic cost.

By reducing the input of pellets by 5%, the result is shown in Figure 8(c). The overall environmental impact is reduced by 0.6%, and the economic cost is reduced by 0.8%. Major environmental impact categories, such as marine ecotoxicity, natural land transformation, freshwater eutrophication and metal depletion, changed by 0.3%, 1.1%, 0.2% and 1.3% respectively. It can be seen that the impact of pellets on both cost and environment is smaller than that of sinter and coke, but its impact is mainly on metal depletion and natural land transformation, which cannot be ignored.

4. **Conclusions.** This article uses life cycle environmental assessment methods, China's environmental protection tax, and the theory of willingness to pay to obtain the external costs of environmental impacts. Overall evaluation of energy, economic and environmental performance of ironmaking process was carried out by combining life cycle environmental assessment method with exergoeconomic. Through analysis, it is found that the main environmental impact categories of the ironmaking process are metal depletion, freshwater eutrophication, marine ecotoxicity, natural land transformation, and freshwater ecotoxicity. Through the comprehensive evaluation of the ironmaking process, the total cost of



(a) Sinter sensitivity analysis (b) Coke sensitivity analysis



(c) Pellet sensitivity analysis

Figure 8. Sensitivity analysis

the ironmaking process is 3152 CNY, of which the sinter is 1810 CNY, accounting for 57% of the total cost, and the pellets and coal powder is 531 CNY and 428 CNY, accounting for 17% and 14% of the total cost respectively. Through the sensitivity analysis of the main influencing factors, it is found that the change of sinter is the most sensitive to the total cost. The sensitivity of sinter and coke to the environmental impact is the same, while the sensitivity of pellets is low. Through the identification of key factors and sensitivity analysis, it is concluded that sinter is the unit that has the largest influence on the ironmaking process. The composition of product cost after considering environmental cost can be determined scientifically and directly, which provides a theoretical basis for environmental governance and resource allocation of iron and steel enterprises.

As the country, society and users pay more and more attention to green development, the high-consumption and high-polluting steel industry will be the focus of regulation. How can environmental economic analysis play a greater role in the green development of the steel industry? It is necessary to study the economization of environmental impact in depth so as to provide a more scientific basis for environmental economic evaluation.

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