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ENVIRONMENTAL AND ECONOMIC IMPACT ASSESSMENT OF CONVERTER STEELMAKING BASED ON LIFE CYCLE ASSESSMENT

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Abstract. *The steel industry is a pillar industry of the national economy. The production of iron and steel consumes a lot of materials and energy, and produces a lot of harmful substances, which has a serious impact on the environment. Based on the cost analysis method of life cycle assessment, this paper quantitatively analyzes the environmental and economic impact of the steelmaking process, and finds the most important key substances. The results show that the main environmental impact categories are freshwater eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity and natural land modification. The key substances leading to this result are scrap steel, refractory materials and electricity. Quantitative analysis shows that the total economic cost per ton of steel is 2804 CNY, of which internal costs such as raw materials and labor cost account for 72.5%, and external costs such as environmental pollution fees account for 27.5%. The total economic cost is mainly the cost of raw materials, and the cost of molten iron accounts for 62%. Optimizing the utilization of scrap steel and molten iron resources and improving the efficiency of resource and energy utilization will help reduce environmental hazards in the steelmaking system.*

Keywords: Environment, Cost, Steel, Life cycle assessment

1. Introduction.

The steel industry is one of the major industries in China that emit industrial fumes, consume resources, and generate solid waste. According to China's "Announcement on the Second National Pollution Source Census Bulletin" (Announcement No. 33 of 2020), data show that in 2017, the ferrous metal smelting and rolling processing industry emitted 823,100 tons of sulfur dioxide and 1,434,200 tons of nitrogen oxides, particulate matter emissions of 1.3112 million tons, accounting for 15.56%, 22.20%, and 10.32% of the total emissions of industrial air pollutants [1]. China, a major producer of crude steel, aims to achieve green and sustainable development of the iron and steel industry with the aim of reducing pollution and therefore it is necessary to determine the main pollutants and substances that have a large impact on the cost, and conduct a comprehensive analysis of these factors [2,3].

Life cycle assessment (LCA) provides people with a tool to quantify the resource consumption, environmental load and potential environmental impact of steel products. Life

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cycle cost analysis is a powerful cost analysis method, and the combination of the two achieves the goal of quantifying the environmental impact and expenditure of steel companies. Some scholars and companies around the world have explored this [4-6]. India's Tata Steel Company has carried out life cycle assessments for 88% of its products in 2008, quantified the environmental performance of the products through life cycle assessments, and issued 40 product environmental declarations to construction steel customers for more than 200 covering system. Nippon Steel uses life cycle assessment to manage its entire production process supply chain to minimize the impact of steel product production on the environment; it evaluates the positive effect of recycling on the life cycle cost and environmental impact of steel products. The International Steel Association selects three typical steel products (section steel, hot-rolled coil and hot-dip galvanized steel) for life cycle assessment. These three products cover the typical environmental impacts of most steel products. Through the analysis of the data results of the life cycle inventory of steel products, the energy consumption and the distribution of the four types of environmental impact (global warming potential, acidification potential, eutrophication potential and photochemical oxidant generation potential) in different life cycle stages are specified [7,8]. Bieda [9] and others successively carried out life cycle assessments on the ironmaking and continuous casting processes of Polish steel plants, and compiled the input and output lists of converters and steel rolling, which included both energy and fuel materials and waste emission data, for subsequent steel life cycle assessment research provide reference and comparison data. [10] mainly carried out LCA evaluation for electric furnace process. He concluded that pig iron is the link that consumes the most fuel and emits the largest greenhouse gas, and iron ore sintering produces the most dust. Improve and replace the ironmaking process or raw materials to achieve the purpose of energy saving and emission reduction. [11] studied the environmental impact of steel in 12 major steel-producing countries, and uses unit GDP production intensity to measure the impact. They pointed out that ecotoxicity is the most important category of impact in the entire industrial chain, and the impact is significantly higher than carbon emissions. And countries that benefit from the import of non-polluting materials should share the pollution emission targets of trading partner countries.

Life cycle cost (LCC) assessment is an analysis method for comprehensive life cycle costs. Some existing studies focus on internal cost analysis, such as design, production and operation costs [12]. Ye et al. [13] conducted a life cycle cost analysis on the production of ceramic tiles, and found that the cost of ceramic tiles per square meter was 2.77 US dollars, and the raw materials accounted for 39.6% economic costs and 12.9% environmental burdens. [14] studied the life cycle environmental and economic assessment of shale gas, and monetized the cost of human health to obtain the economic cost. Researchers realized that pollutant emission is only one aspect of environmental impact [15]. The ecological damages caused by pollutant emission, human health and other issues are key issues, and how to price this part of the impact and who will pay for it are worth exploring.

Economic and environmental assessment based on the life cycle can provide decision makers with more scientific and comprehensive information. Literature analysis found that there is no LCC research related to converter steelmaking. This article quantifies the environmental impact as an economic cost on the basis of life cycle assessment, combined with traditional economic assessment. In this way, the total cost considering the environmental impact can be obtained more intuitively. The organization of this article is as follows. The next section explains the main LCA and LCC 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.** Steel product life cycle assessment is a technique for evaluating environmental loads and potential environmental impacts associated with steel products, including processes from raw materials (iron ore, etc.), fuels (coal, etc.), auxiliary materials (refractories, etc.) to steel products, as well as downstream product production, use, scrap and recovery [16].

The system boundary selected in this study is that molten iron enters the steelmaking station and is smelted into molten steel in the converter [17]. Steelmaking needs to add scrap steel first, then molten iron, and add appropriate auxiliary materials in proportion. Finally, insert an oxygen spray gun from the top of the furnace and blow in oxygen. Oxygen reacts with molten iron to remove impurities to obtain molten steel. The raw material fuels and emissions involved in this process are taken into account. Choose one ton of crude steel as the research unit to determine the life cycle list.

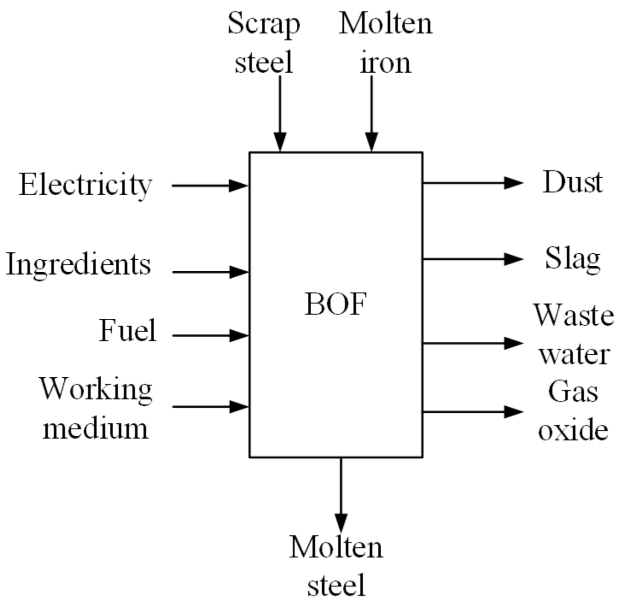

Figure 1. Simplified scheme of iron and steel production routes, processes

2.2. **Data source and life cycle inventory.** In order to construct the life cycle items of the steelmaking system, this paper collects, sorts out and studies the actual production data of a group company in Shandong Province, and obtains data on raw materials, fuels, emissions and waste disposal in the steelmaking process. Price information comes from actual expenses. Part of the data comes from literature data [18,19] and cleaner production secondary indicators (HJ/T294-2006, HJ/T426-2008, HJ/T 1262003, HJ/T 427-2008, HJ/T 428-2008, HJ/T 318-2006) [20]. The life cycle list of molten steel products is shown in Table 1.

2.3. **Life cycle impact assessment method.** The recipe midpoint method is used to quantify the life cycle environmental impact results [21]. The method includes 18 midpoint categories [14]. The 18 midpoint categories are divided into three endpoint categories. In this way, you can see both the impact value of the midpoint category and the final environmental impact. This article uses simapro software to calculate.

Based on the research of Hong et al. [14], they combined LCC and LCA to analyze environmental impact and costs. Usually life cycle inventory (LCI) is combined with cost

TABLE 1. Life cycle inventories of molten steel. Values are presented per ton.

Inputs and outputs	Value	Unit
Inputs		
Molten iron	900	kg
Scrap steel	80	kg
Electricity	76	kWh
Quicklime	39	kg
Dolomite	7.8	kg
BOF gas	12.15	m^3
Oxygen	37.28	m^3
Pure water	3.6	m^3
Outputs		
CO_2	26.86	kg
SO_2	5.46	g
NO_2	3.64	g
CO	4.37	kg
Waste water	1.02	m^3
Dust	128	kg
Cd	47	mg
Cr	114	mg
Cu	2935	mg
Ni	266	mg
Pb	883	mg
Zn	7125	mg

information, and then combined with the environmental impact quantified by the recipe method. Table 1 shows the LCI and cost of the functional unit. Based on this, this paper conducts the calculation and analysis of the internal cost of the steelmaking system.

$$C_n = \sum C_i M_i + C_r \tag{1}$$

where C_i represents the unit cost of substance i, M_i represents the amount of substance i, and C_r represents the labor cost.

Most environmental impacts can be quantified through environmental taxes and sewage charges. Part of the environmental impact on human health is quantified by willingness to pay theory (WTP). WTP refers to the amount that consumers are willing to pay for accepting a certain number of consumer goods or services. In terms of environmental impact, it refers to the cost that is willing to reduce environmental impact. Through the above theory, the environmental impact is converted into economic value. The environmental monetization factors are shown in Table 2 [22]. The external cost of system is obtained by Formula (2).

$$C_w = \sum C_j M_j \tag{2}$$

where C_j represents the unit cost of the j-th pollution category, and M_j represents the value of the characteristic unit of the j-th pollution category.

3. Results and Discussion.

3.1. LCA result. Table 3 lists the LCIA midpoint results based on functional units. According to climate change, the median LCIA for 1 ton of molten steel production is

Table 2. Monetization factor of environmental impact in steelmaking process

Categories	Unit	Monetary factory/CNY	Source
Climate change	Kg CO_2 eq	0.22	China Climate Change Country Study Group, 2000
Terrestrial acidification	Kg SO_2 eq	6.32	State Council of China, 2017
Freshwater eutrophication	Kg P eq	28	State Council of China, 2017
Marine eutrophication	Kg N eq	8.75	State Council of China, 2017
Terrestrial ecotoxicity	Kg 1, 4-DB eq	280	State Council of China, 2017
Freshwater ecotoxicity	Kg 1, 4-DB eq	280	State Council of China, 2017
Marine ecotoxicity	Kg 1, 4-DB eq	280	State Council of China, 2017
Agricultural land occupation	m^2	22.5	State Taxation Administration, 2018
Urban land occupation	m^2	11.025	The People's Government of Hebei Province, 2013
Natural land transformation	m^2	22.5	State Taxation Administration, 2018
Water depletion	m^3	0.4	The People's Government of Hebei Province, 2016
Metal depletion	Kg Fe eq	0.0171	State Taxation Administration, 2011
Fossil depletion	Kg oil eq	0.27	State Taxation Administration, 2011
Ozone depletion	DALY	61,605a	National Bureau of Statistics of China, 2019; World Health Organization, 2012
Photochemical oxidant formation	DALY		
Particulate matter formation	DALY		
Human toxicity	DALY		
Ionising radiation	DALY		

*Note: Some characteristic units are DALY (disability-adjusted life years), which refers to all healthy life years lost from illness to death. Therefore, it can be characterized by WTP. The death rate and disease burden are calculated by the WHO, and then divided by the annual medical expenditure in China to get a.

158.5291 kg CO_2 equivalent, for aquatic acidification is 1.96 kg SO_2 for aquatic acidification, and 0.42 kg PM2.5 eq for respiratory inorganics, a total of 18 intermediate points. The detailed values are shown in Table 3.

In order to compare the different impact categories of each intermediate point and analyze the impact of each intermediate point type on the overall situation, this study conducted a normalized analysis. The normalized midpoint results of each functional unit are shown in Figure 2. The most affected categories are freshwater eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity and natural land transformation.

Figure 3 shows the standardization results of the life cycle assessment of each substance in the steelmaking system. The results are weighed by all intermediate damage types and their values. It can be seen from the figure that oxygen, electricity and scrap steel have a greater impact on the environment. Among them, the environmental load of oxygen is 0.42, the environmental loads of electricity and scrap are 0.32 and 0.19 respectively, and the environmental contribution of refractories is 0.11, ranking the fourth.

3.2. **Life cycle cost analysis.** The internal cost is calculated by the method described above. The internal cost ratio of each process is shown in Figure 4. The internal cost of molten iron is 1730 CNY, accounting for 85%, followed by the cost of scrap steel, which is 165 CNY, accounting for 8%. These two items account for more than 90% of the total internal cost. The contribution of auxiliary materials and fuels to internal costs is relatively small.

The external cost is obtained from the environmental characterization value obtained by LCA and the environmental impact economic value. As shown in Figure 5, the external

TABLE 3. Life cycle assessment midpoint results of molten steel

Impact category	Unit	Value
Climate change	kg CO_2 eq	158.5291
Ozone depletion	kg CFC-11 eq	1.51E-05
Terrestrial acidification	kg SO_2 eq	0.366888
Freshwater eutrophication	kg P eq	0.055057
Marine eutrophication	kg N eq	0.024171
Human toxicity	kg 1, 4-DB eq	47.39403
Photochemical oxidant formation	kg NMVOC	0.283769
Particulate matter formation	kg PM10 eq	0.175358
Terrestrial ecotoxicity	kg 1, 4-DB eq	0.006074
Freshwater ecotoxicity	kg 1, 4-DB eq	3.485514
Marine ecotoxicity	kg 1, 4-DB eq	3.098799
Ionising radiation	kBq U235 eq	28.60816
Agricultural land occupation	m^2a	6.899748
Urban land occupation	m^2a	0.621144
Natural land transformation	m^2	0.025889
Water depletion	m^3	6.050261
Metal depletion	kg Fe eq	14.28867
Fossil depletion	kg oil eq	48.5991

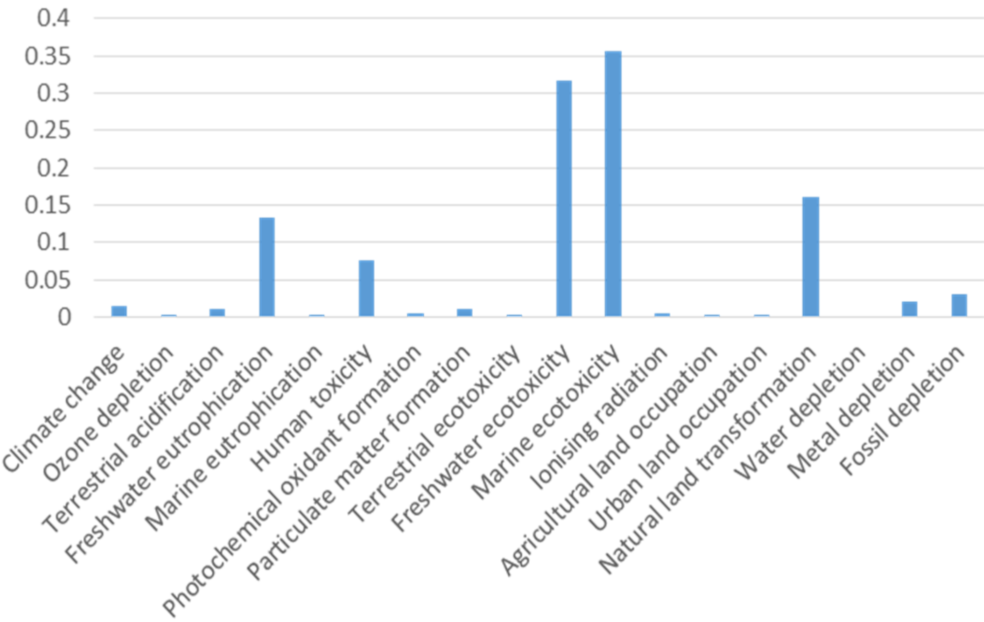

FIGURE 2. Normalized midpoint results

cost of oxygen is 347 CNY, which contributes 45%, followed by electricity and scrap steel costs of 183 CNY and 125 CNY, which contribute 24% and 16% respectively. These three items account for 85%, and other materials such as limestone contribute little to external costs.

The total cost of the steelmaking system is the addition of internal costs and external costs. Figure 6 shows that the total cost of the steelmaking system is 2804 CNY, of which the cost of molten iron is 1730 CNY, accounting for 62%, and the total costs of scrap and oxygen are 290 CNY and 369 CNY, respectively, accounting for 10% and 13% of the

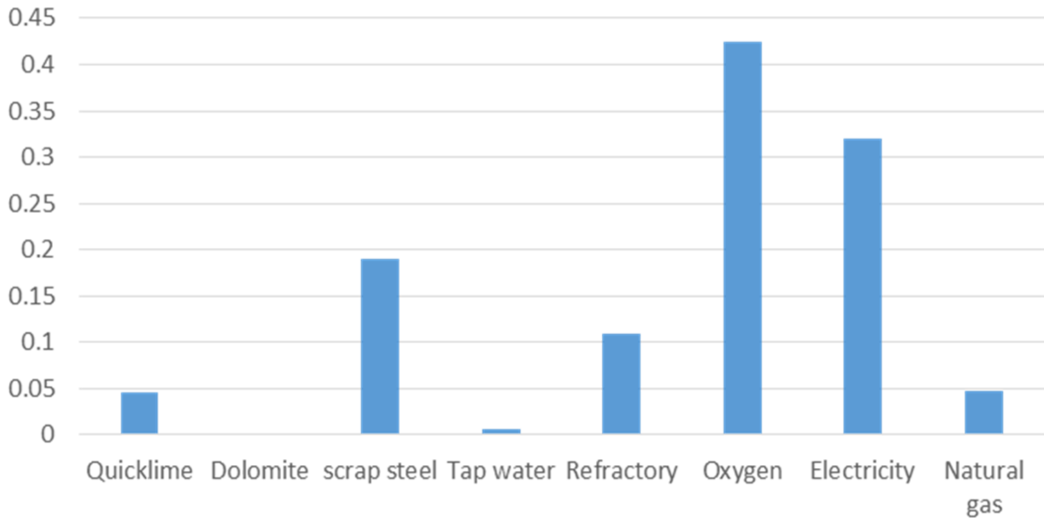

FIGURE 3. Standardization results of the environmental impact of each substance

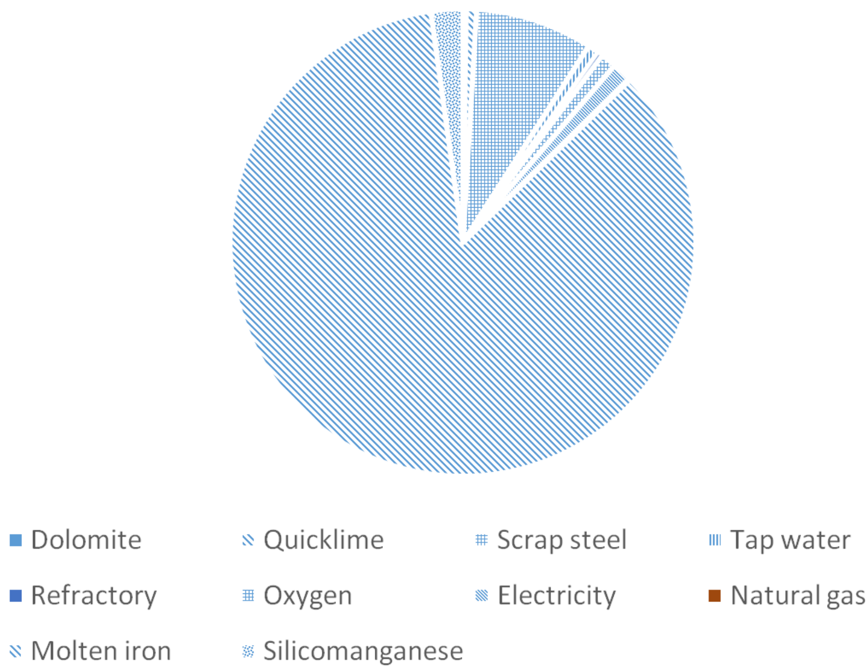

FIGURE 4. Internal cost ratio of steelmaking process

total cost. The total cost of auxiliary materials and labor is relatively small, accounting for 15% of the total cost of the steelmaking system.

3.3. **Main process.** According to the results of standardized evaluation, the most important potential environmental impacts in the entire life cycle of molten steel products are marine toxicity, water toxicity, water eutrophication, land occupation and human health. Therefore, it is necessary to identify and analyze the key processes that cause the above-mentioned environmental impact, so as to make relevant recommendations. Based on the evaluation results in the middle of the life cycle, the key process identification is performed, and the results are shown in Figure 7. It can be seen from Figure 7 that oxygen and electricity are the most important environmental contributors to the above-mentioned impact categories, and their impact on most environmental categories accounts

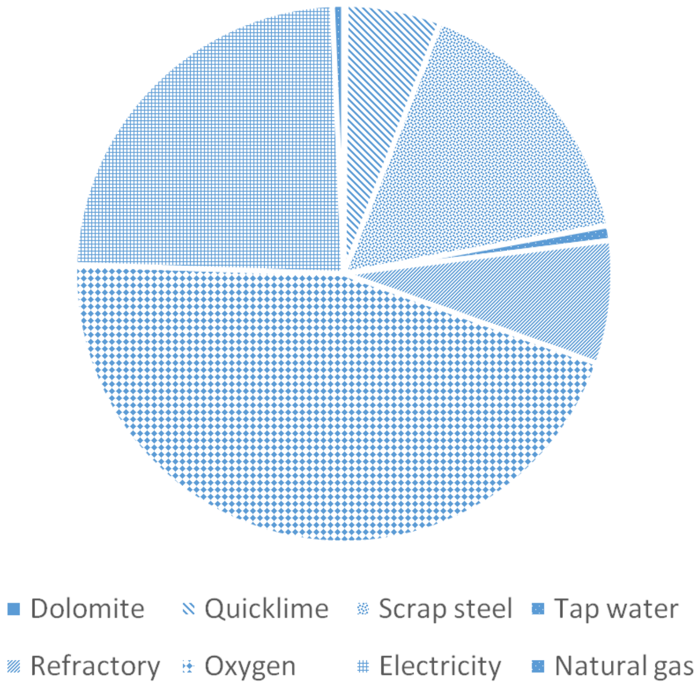

FIGURE 5. External cost ratio of steelmaking process

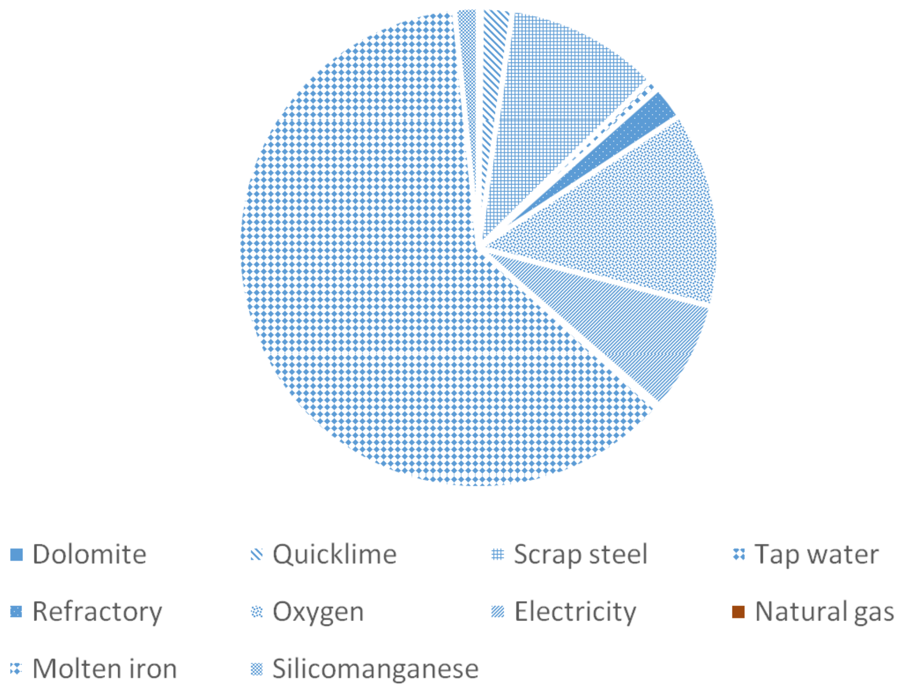

FIGURE 6. Total cost ratio of steelmaking process

for more than 50%. Scrap steel is particularly toxic to water and oceans, and it also has a significant impact on human health and water eutrophication. At the same time, the contribution of natural gas to land occupation cannot be ignored.

3.4. **Sensitivity analysis.** Through sensitivity analysis, the sensitivity of the input data can be verified, and the key environmental impact categories and the sensitivity to the overall economic and environmental impact can be obtained [14]. Test based on the input

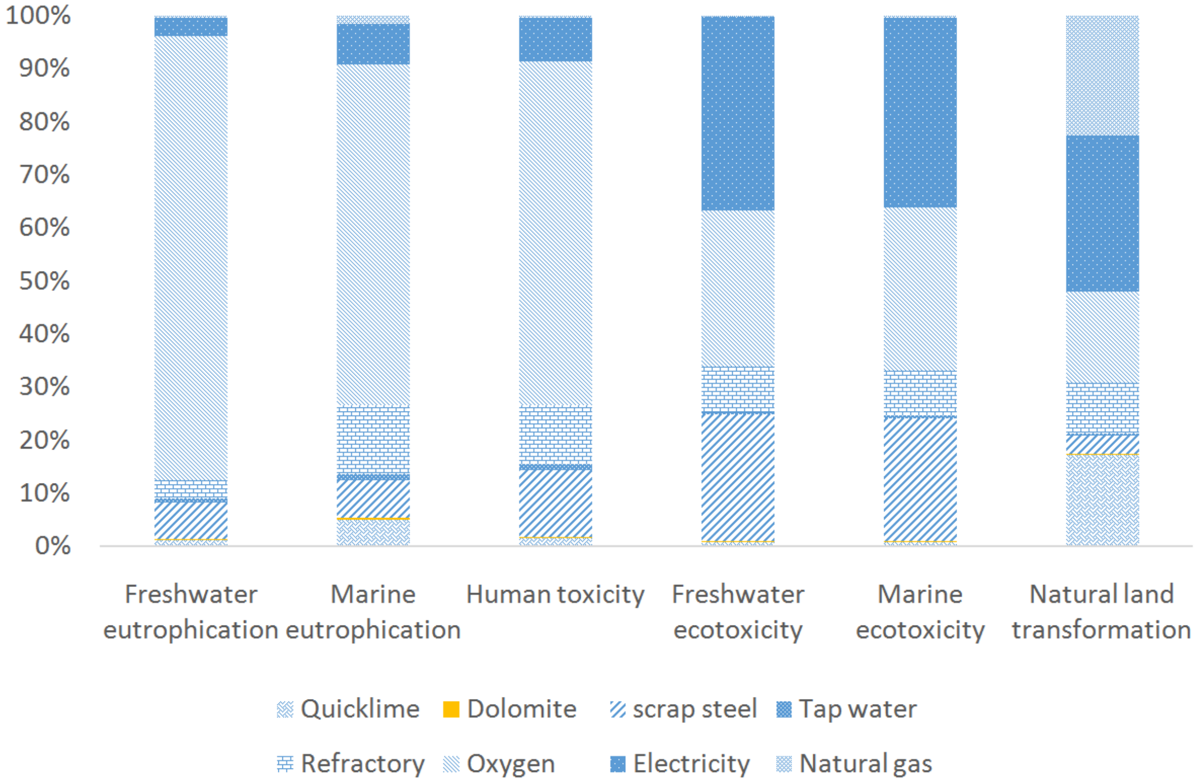

Figure 7. Main process that contributes to significantly affected categories

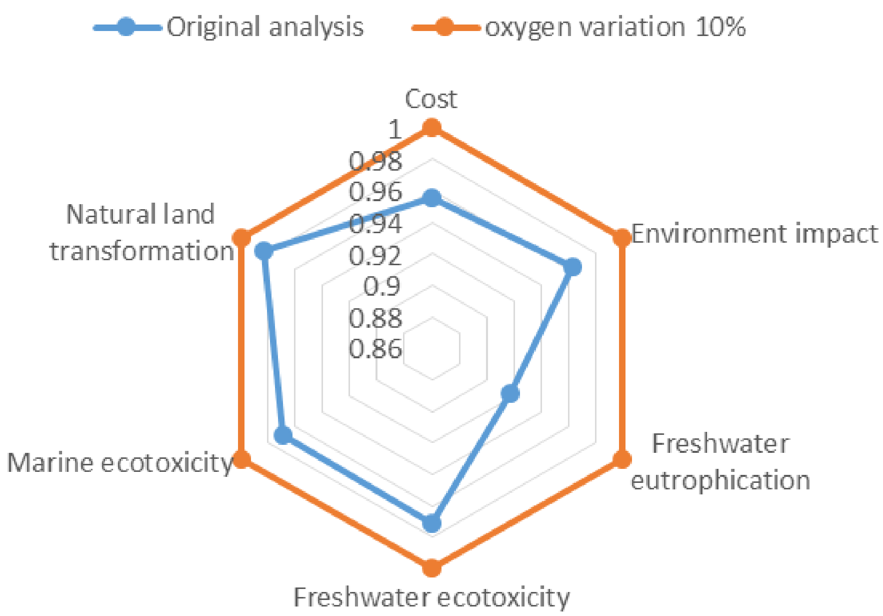

Figure 8. Sensitivity analysis

parameter percentage adjustment rule [23]. By reducing the oxygen input by 10%, the results are shown in the figure. The total environmental impact is reduced by 4%, the economic cost is reduced by 5%, and the freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and natural land transformation in the key environmental impact categories are 9%, 3%, 3%, and 2%.

4. **Conclusions.** This article uses LCA and LCC to quantitatively analyze the environmental and economic impact of the steelmaking system. Through analysis, it is found that the main categories of environmental impact are freshwater eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity, and natural land transformation. The key substances that cause this environmental impact are scrap steel, refractory oxygen and electricity. The key substances in marine ecotoxicity are scrap steel, oxygen, and electricity, which account for the same proportion. The key substances in freshwater ecotoxicity are similar to marine toxicity. However, in the water eutrophication category, the key substance oxygen accounts for about 90%.

The total economic cost per ton of steel is 2804 CNY, of which the internal cost is 2034 CNY and the external cost is 770 CNY. The total cost of hot metal and scrap oxygen accounted for 62%, 13%, and 10% respectively. The major influences on internal costs are molten iron and steel scrap, accounting for 85% and 8% respectively. Oxygen, electricity, and steel scrap have a greater impact on external costs, accounting for 45%, 24%, and 16% respectively. According to sensitivity analysis, oxygen input is reduced by 10%, and expenditure and environmental costs are reduced by 5% and 4% respectively. The key to reducing economic and environmental impact is to optimize the production structure and reduce the use of molten iron. Now that new energy sources are developing rapidly, upgrading the power structure can be considered.

In the context of overcapacity in the steel industry, increasingly fierce competition, and severe environmental protection, building a green product manufacturing system based on life cycle assessment methods and establishing a green industrial chain are the direction of future development. It is suggested that iron and steel enterprises should gradually carry out environmental and economic evaluation research on the life cycle of iron and steel products.

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