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Scrap Steel Recycling: A Carbon Emission Reduction Index for China

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Abstract: Accurately assessing carbon emissions from recycling scrap steel is essential for reducing emissions in the steel industry, especially in China, the world's largest crude steel producer. In this study, a carbon emission reduction index was introduced to evaluate the effectiveness of recycling scrap steel in reducing emissions. The index considers the three processes used in scrap steel recycling: blast furnace ironmaking, converter steelmaking, and electric arc furnace steelmaking. This study developed an evaluation model using fuzzy analytic hierarchy process and iterative cluster analysis to determine the reduction of carbon emission. From a life cycle perspective, this study identified primary factors contributing to emissions, including fuel, raw materials, electric energy, and auxiliary materials. Then, the carbon emission reduction index for scrap recycling was developed by examining the production of one ton of steel and each additional ton of scrap steel, which can provide valuable insights into the environmental impact of scrap recycling. Finally, the study forecasts the future Carbon Emission Reduction Index for steel scrap recycling. The study indicates an increase in the carbon emission reduction index for scrap recycling prior to 2017, followed by a decrease about 11.8% from 2017 to 2018 and increases from 2018 to 2021. Finally, it dropped by 8.7% per cent in 2022. Similarly, the carbon emission reduction index for electric furnace steelmaking increased prior to 2019, then subsequently decreased. It is changing by ten per cent a year. Additionally, the scrap recycling index experienced a significant decrease of 90% in 2015, followed by a gradual increase until 2017 and then a consistent decrease every year thereafter. The index suddenly rose in 2021 and then decreased change for policy reasons. The forecast results suggest a gradual increase in the carbon emission reduction index per ton of steel scrap in the future. In conclusion, the practicable modeling methodology has the ability to assist government organizations and private enterprises in devising efficient green and low-carbon development tactics.

Keywords: carbon emission; reduction; steel industry; scrap steel; recycling; index

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1. Introduction

In light of the Paris agreement goals [1] for global temperature control, countries around the world need to take all achievable actions to reduce greenhouse gas emissions (GHG) from every sector [2]. Many countries have set timetables for peaking carbon emissions and have adopted broader policies and practical measures. Additionally, countries are under considerable pressure to improve their air quality as they develop green, low-carbon economies and energy systems. Although the prevention and control of air pollutants has been somewhat successful [3], controlling total societal pollution remains a long-term task [4]. As typical energy-intensive industries, the iron and steel industries are under great pressure to reduce its emissions [5].

In developing countries, especially in China, the pattern of energy use favors a raw approach. Specifically, China has a rather typical steel industry, with steel production having expanded over the past decade and its share of crude steel production having increased from 15% to 56%. It has become the world's largest steel producer [6]; consequently, the associated increases in energy consumption and pollution emissions have become a serious problem [7]. In China, 90% of steel production is based on the blast furnace–alkaline oxygen furnace (BF–BOF) process, which involves the use of iron ore. Unlike iron ore, which is a limited natural resource, scrap is a renewable and recyclable resource. Improving scrap recycling saves resources and makes production more sustainable, while the use of scrap in crude steel smelting results in much lower CO_2 emissions than those when using iron ore. The scrap-based electric arc furnace (EAF) process accounts for 10% of the steel production capacity [8]. Because the EAF process produces 50% less carbon emissions than those produced by the BF–BOF process [9], the promotion of the EAF process is widely considered an important measure for achieving emission reductions in the steel industry. Rational modelling is needed to assess the carbon reduction benefits of steel scrap recycling.

In recent years, carbon emissions have attracted the attention of many researchers. To reduce carbon emissions, the steel industry can impose direct restrictions on steel production; however, these come at the expense of socioeconomic development. Researchers have analyzed CO_2 reduction options for the steel industry. For example, research has been conducted on low-carbon processes and the use of energy sources (e.g., fuels) with low CO_2 emissions [10–12]. The first topic involves reducing carbon along the 14 process steps of steel smelting [13], increasing the smelting temperature to reduce CO_2 emissions from the pellet ore in the blast furnace, or developing slag-free, low-energy-consumption pellet bonding technologies. The second topic involves developing large coking reactors and non-recycling furnaces to improve the coking efficiency [14]. There are also technologies that use carbon-neutral materials, such as recycled waste plastics and biomass, as reducing agents in kilns to reduce the use of fuel and coke, thereby allowing waste to be recycled and reducing resource consumption and greenhouse gas emissions [15]. There is also a category of technologies that use carbon capture and sequestration technologies [10].

Nevertheless, the development and deployment of efficient carbon abatement technologies is expected to take decades, and alternative pathways to carbon abatement in the steel industry are necessary for the short to medium term [16]. Existing studies on the production structure suggest that future carbon reduction in the steel industry will largely depend on the coverage of electric arc furnaces (EAFs) [16]. Xuan (2017) emphasized that increasing the proportion of the EAF route in production can contribute to the sustainable performance of the steel industry in many ways, while saving iron ore and other energy sources [17]. However, the use of EAFs is inseparable from scrap, and researchers have focused on the integral role of scrap recycling in promoting the management of pollutant emissions in the steel industry [18]. The recycling of waste resources is an important way forward for the green development of society, and many scholars are exploring methods of waste resource utilization [19,20], with some scholars exploring policy support for the rational use of waste resources [21,22]. The recycling value of steel scrap is even greater, and many studies have focused on predicting scrap inventory demand and recycling. For example, Zhang (2015) used econometric analysis to analyze future scrap trends by forecasting steel demand in terms of gross domestic product (GDP) and GDP per capita [23]. Based on an input–output model, Xuan (2017) indicated that China can still achieve great improvements regarding its scrap ratio compared to those that the United States or many European countries can achieve [17]. Ryan (2020) used a dynamic material flow model to determine the range of steel inventories and available scrap based on changes in per capita steel inventories and recycling rates in the United States [24]. To further investigate scrap recycling, Sahoo (2019) developed an Life Cycle Assessment (LCA) model-based approach to evaluate the optimal utilization scenario for scrap steel [25]. Numerous other studies have investigated the technical processes of scrap melting in EAFs in different ways [26–30].

The manner in which scrap is recycled in China does not differ from those in developed countries. Many steel mills in China commonly use a method involving iron plus scrap combinations. This method is very different from the all-scrap EAF melting method used in developed countries and is known as the Chinese-style short-process steelmaking method [31–33]. The use of iron plus scrap in China is mainly motivated by the economy rather than carbon emission reductions [34]. There is also a direct correlation between the slow establishment of EAFs in the steel industry and high scrap prices [35]. Many studies have analyzed the economic benefits and environmental indicators of using iron plus scrap based on economic cost considerations for specific situations. For example, Duan (2009) showed that increasing the amount of iron in an electric furnace leads to decreased electricity consumption and increased oxygen and lime consumptions [35]. Conversely, the emission reduction benefits of electric furnace production are also outstanding. Burchart-Korol (2013) compared the life-cycle greenhouse gas (GHG) emissions of the Polish blast furnace-converter and scrap-based electric furnace routes [36]. The results showed that the GHG emissions of one ton of steel produced in an EAF were 913 kg CO_2, i.e., much lower than the 2459 kg CO_2 produced in a blast furnace. Ryberg (2018) studied the GHG emissions of three typical steelmaking processes: the sinter-converter, roasting-electric furnace, and scrap-electric furnace routes [37]. The results showed that the scrap-electric furnace route results in an emission reduction of 1 kg per 1 kg of finished steel produced. However, these carbon emission studies do not provide good assessments of the melting patterns of ferrous scrap in China.

The Chinese-style, short-process steelmaking method is based on the social reality. Developing countries have insufficient scrap resources and high steel smelting costs; therefore, they use a combination of small amounts of scrap and large amounts of iron to reduce costs and remove impurities. Developing countries cannot achieve the all-scrap smelting patterns of developed countries [38–40]. China's short-process steelmaking model is of interest to developing countries, with countries such as Brazil and India having adopted this model to smelt steel [31]. However, the large amount of iron used will inevitably result in carbon emissions and will not allow the carbon reduction effect of scrap steel to be realized. Therefore, there is a need to establish a carbon emission reduction index to assess the impact of scrap recycling on carbon emissions in developing countries.

This study builds on the above literature by first defining the system boundary and calculation method of CO_2 emissions in scrap steel recycling. By selecting the typical iron and steel melting processes in China, this study calculates and analyzes the carbon emissions of the "Chinese-style" long- and short-process steelmaking. Many factors of scrap recycling were combined to calculate carbon emissions, design an evaluation method for the carbon emission reduction index of scrap recycling, and establish a carbon emission reduction index model. Furthermore, the carbon emission reduction effect of scrap recycling was evaluated in China in recent years; this study analyzes and compares the current role of scrap steel in carbon emission reduction in the iron and steel industry, and offers realistic suggestions.

This study helps to enrich the theoretical system of carbon emission calculation in the steel production process. It also provides theoretical references for determining the boundary and content of carbon emission reduction, accounting for the recycling of steel scrap. By studying the composition of actual carbon emissions under different smelting modes of iron and steel enterprises, it provides reference significance for the government and enterprises to explore the low-carbon transition path. This study innovatively applies an index to demonstrate the carbon emission reduction effect of steel scrap, providing a new way of expressing carbon emission reduction in the iron and steel industry.

2. Materials and Methods

2.1. System Boundary and Measured Indicators

The determination of carbon accounting boundaries is scientifically sound. This study firstly determines the carbon emission boundary of scrap steel recycling by reviewing the information of *ISO 14064* [41] and *China's greenhouse gas emission guideline*, then discusses the reasonableness of the boundary setting with industry experts, and finally determines the carbon accounting boundary of scrap steel recycling. The reliability of the carbon accounting boundary is ensured by combining literature and expert interviews.

This study analyzed the carbon emission reduction of scrap recycling only at the manufacturing stage. This paper does not consider the carbon emissions generated during the recycling process of steel scrap, nor does it consider the carbon emissions of other materials affected by the recycling of steel scrap, and the accounting boundary is limited to the remanufacturing process of steel scrap.

This study does not make an additional distinction between carbon emissions from other by-products, which are included in the necessary carbon emissions from steel production. The sources of emissions from the smelting process are direct carbon emissions, except for carbon emissions from electricity, which are indirect. A boundary diagram of the carbon-reduction calculation system for the steel manufacturing process is shown in Figure 1. This study measured the carbon emissions from the use of raw materials, energy sources, fuels, and auxiliary materials during the manufacturing process, excluding those from raw material sourcing, transport, and use. By combining the life-cycle analysis approach, this study first broke down the various manufacturing process steps, from the input of different raw materials into the blast furnace to the final formation of steel in the converter (or EAF), and then calculated the carbon emissions of each step.

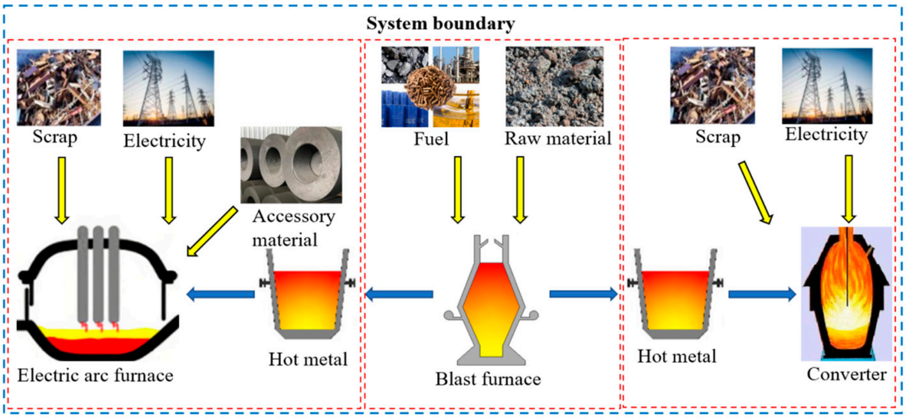

Figure 1. System boundary of the carbon reduction calculation for the steelmaking process.

Scrap steel melting can be either long- or short-process steelmaking. Long-process steelmaking begins with iron ore, which is refined in a blast furnace and then poured into a converter, where impurities are further removed to produce crude steel. Short-process steelmaking begins with scrap steel, which is fed into an EAF for melting.

The raw materials of traditional steel melting, whether it is long- or short-process steelmaking, are mixed with iron and steel scrap; therefore, it is difficult to calculate the CO_2 emission reduction. For comprehensiveness, this study focuses specifically on calculating the emission reduction value as well as assessing the overall emission reduction effect caused by the use of scrap steel. The scope of the assessment includes changes in the amount of scrap steel in society as well as in the effect exerted by changes in domestic and foreign imports and exports. The index system was developed by combining literature and an expert assessment, as shown below (Table 1).

The three indices developed in Table 1 are further generalized from the definition of carbon accounting boundaries. Through data analysis and expert research, it was found that the process of steel scrap recycling can be divided into converter steelmaking and electric steelmaking, which are also the main emission processes. However, there is a lack of indicators that can be strongly correlated with the use of scrap, so a sub-index for scrap recycling was created on the suggestion of experts. The assessment indicator system for the carbon emission reductions consists mainly of three secondary indicators: the emission reduction index of converter steelmaking, emission reduction index of electric furnace steelmaking, and scrap recycling index. These secondary indicators are further subdivided into 11 tertiary indicators, as listed in Table 1.

Table 1. Assessment indicators for the emission reduction index.

Destination Layer	Criterion Layer	Index Layer
Carbon emission reduction index of scrap recycling (Q)	Emission reduction index of converter steelmaking (q_1)	Combustion carbon reduction (r_1)
		Energy carrier carbon reduction (r_2)
		Raw material carbon reduction (r_3)
	Emission reduction index of electric furnace steelmaking (q_2)	Combustion carbon reduction (r_4)
		Accessory material carbon reduction (r_5)
		Energy carrier carbon reduction (r_6)
		raw material carbon reduction (r_7)
	Scrap recycling index (q_3)	Change in the amount of scrap recovered (r_8)
		Scrap import volume change (r_9)
		Scrap long-process use ratio (r_{10})
		Scrap short-process use ratio (r_{11})

2.2. Comprehensive Evaluation Method

The weights of the indicators were calculated using hierarchical analysis according to the scoring tables of experts for the indicators. The emission reductions for each year were subsequently multiplied by the weights to obtain specific scores.

$$q_1 = \sum_{i=1}^{3} w_i \cdot r_i, \tag{1}$$

$$q_2 = \sum_{i=4}^{7} w_i \cdot r_i, \tag{2}$$

$$q_3 = \sum_{i=8}^{11} w_i \cdot r_i, \tag{3}$$

$$Q = \sum_{j=1}^{3} w_j \cdot q_j, \tag{4}$$

where q is a secondary sub-index, w_i is the weight value of the i-th tertiary indicator, r_i is the reduction value of the i-th corresponding indicator, and q_j is the j-th sub-index. Sub-index q_1 is the converter steelmaking carbon reduction index, reflecting mainly carbon emissions from the consumption of different types of products in the converter steelmaking process. Sub-index q_2 is the electric furnace steelmaking carbon reduction sub-index, reflecting mainly carbon emissions from the consumptions of electricity, auxiliary materials, raw materials, and other products during the electric furnace steelmaking process. Q is the total carbon reduction index.

In this model, the weight of each indicator is determined using the Fuzzy Analytic Hierarchy Process (FAHP) and iterative cluster analysis. The method can effectively deal with the fuzzy information and uncertainty present in the decision problem, making decision-making more flexible. It is also able to consider the interrelationships between elements within and between different levels, reflecting the complexity of the problem more fully [42,43].

The chosen systematic cluster analysis method, i.e., cohesive spectral clustering (hierarchical clustering), is the most widely used. The basic logic is that each case (or variable) is first considered a class, then grouped into smaller classes according to the distance or similarity between cases (or variables), and finally gradually grouped upward according to the distance or similarity between classes until all cases are aggregated into one large class. When constructing the judgement matrix for the two-by-two comparison, the Analytic Hierarchy Process (AHP) does not consider the fuzziness of human judgement but only polarizes human judgement into "yes" or "no", despite the judgement of some real-life problems being uncertain. For this reason, the FAHP is used to replace the deterministic values in the judgement matrix with triangular fuzzy numbers to effectively address the judgement uncertainty problem. The combination of the two methods can solve the weights accurately.

2.3. Calculation of Carbon Emission Reduction for Converter and Electric Arc Furnace

This study mainly calculated the carbon emissions of the three levels of indicators in the carbon emission reduction index system in different years; their comparison revealed that the carbon emission reduction of most indicators gradually decreased.

$$E_{tpi} = \frac{e_{2013} - e_i}{S_i} \cdot 1000, \quad (5)$$

where E_{tpi} is the CO_2 emission reduction per ton of scrap steel in a fixed year, e_i is the carbon emissions per ton of steel in year i, e_{2013} is the CO_2 emissions per ton of scrap in 2013 (i.e., fixed reference year), and S_i is the amount of scrap used to smelt one ton of steel in year i (kg).

2.4. Measurement of Carbon Emission Reduction

There are three methods commonly used for calculating CO_2 emissions from steelmaking. In this study, this study adopted the LCA method. The first method follows the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [44]. The GHG emission factors and energy consumption data of existing steel mills in China were used in the IPCC methodology. The second method involves localization of the Ecoinvent database, namely Life Cycle Impact Assessment (LCIL), which calculates the GHG emissions of each sub-process of energy-related steel production based on the implied GHG emission factors of each energy source (i.e., coal, coke, electricity, and natural gas). The third method calculates GHG emissions from iron and steel production in accordance with the Comprehensive Energy Consumption (CEC) method, which uses the proportional distribution of energy consumption for iron and steel production in China as well as the GHG emission factors for each type of stationary GHG combustion [45]. Each method has advantages and limitations. The carbon emission calculation methodology in this paper combines "Guidelines for Accounting Methods and Reporting of Greenhouse Gas Emissions of Chinese Steel Producers (for Trial Implementation)", as it includes more specific emission segments in its calculation methodology.

2.4.1. Calculation of Carbon Emissions

(1) Carbon emissions from fuel combustion

CO_2 emissions from the net consumption of fossil fuel combustion, including emissions from stationary sources within steelmaking plants, such as coke ovens, sinter plants, blast furnaces, industrial boilers, and other stationary combustion equipment, are calculated as follows:

$$E_{CO} = \sum_{i=1}^{n} AD_i \times EF_i, \quad (6)$$

where E_{CO} is CO_2 emissions from the net consumption of fossil fuel combustion during the accounting and reporting periods (tCO_2), AD_i is the activity level of fossil fuel i (GJ) for the accounting and reporting periods, and EF_i is the CO_2 emission factor of fossil fuel i (tCO_2/GJ).

(2) Energy carrier carbon emissions

The net purchased electricity for production implicitly generates CO_2 emissions is calculated as follows:

$$E_{ec} = AD_p \times EF_p, \quad (7)$$

where E_{ec} is the implied CO_2 emissions generated by the net purchased electricity for production, AD_p is the net purchased power of the accounting and reporting period (MWh), and EF_p is the CO_2 emission factor of electricity.

(3) Carbon emissions from auxiliary materials

The calculation of carbon emissions from auxiliary materials mainly includes carbon emissions from electrodes in the electric furnace steelmaking process.

$$E_{am} = P_e \times EF_e, \tag{8}$$

where E_{am} is the CO_2 emissions from the electrode consumption (tCO_2), P_e is the number of electrodes consumed (t) during the accounting and reporting periods for the electric furnace steelmaking and refining furnaces, and EF_e is the CO_2 emission factor (tCO_2/(t electrodes)) for electrodes consumed in electric furnace steelmaking and refining furnaces.

(4) Carbon emissions from iron-containing materials

CO_2 emissions from consumption of carbon-containing raw materials are calculated as follows:

$$E_{rm} = \sum_{i=1}^{n} M_i \times EF_i, \tag{9}$$

where E_{rm} is the CO_2 emissions from the consumption of other carbon-containing raw materials, including purchased pig iron, ferroalloys, and directly reduced iron (tCO_2), M_i is the amount of carbon-containing raw materials i (t) during the accounting and reporting periods, and EF_i is the CO_2 emission factor of the purchased carbon-containing raw material i (tCO_2/(t raw material)), and the types of carbon-containing material include pig iron, ferroalloys, and direct reduced iron.

Summing the above four parts gives the total carbon emissions for steel smelting.

$$E_{total} = E_{co} + E_{ec} + E_{ac} + E_{rm} \tag{10}$$

2.4.2. Calculation of Carbon Emissions from Blast Furnace Ironmaking

(1) Calculation of carbon emissions from blast furnace ironmaking fuel

Blast furnace ironmaking data were obtained from the China Iron and Steel Statistical Yearbook, which converts all fuels, such as coal spray and heavy oil, to coke ratio, which is the amount of coke used to melt one ton of pig iron. The low-level heat content of coke is 28.447 MJ/t, the carbon content per unit calorific value is 29.50 tons of carbon/million kJ, and the carbon oxidation rate is 93%, according to the China Greenhouse Gas Inventory Study. The emission factor EF_i of coke was calculated to be 0.101 tCO_2/GJ using the following equation:

(2) Calculation of carbon emissions from the electricity of blast furnace ironmaking

The calculation of the CO_2 consumption of blast furnace electricity is based on the latest national "Corporate Greenhouse Gas Emissions Accounting Methodology and Reporting Guide Power Generation Facilities (Revised Version 2021)", in which the power system CO_2 emission factor of the power system is 0.5839 tCO_2/MWh. The carbon emissions of blast furnace electricity were calculated by multiplying the electricity consumption by the CO_2 emission factor of one ton of iron. Iron electricity consumption data in tons for blast furnace ironmaking were retrieved from the China Iron and Steel Yearbook.

(3) Calculation of carbon emissions from raw materials

Carbon emissions from raw materials include sintered, pelleted, and natural ores; however, these are not used in the same proportions. Pellet ore accounts for 80% of the total, whereas sintered and natural ores account for 10% each. The carbon emission factors for pellet, sintered, and natural ores from ISO (14064) [41] are 0.137, 0.262, and 0.073 tCO_2/t, respectively.

2.4.3. Calculation of Carbon Emissions from Converter Steelmaking

The current mainstream steelmaking process involves the production of iron in a blast furnace, followed by the use of either a converter or an EAF for steelmaking. The raw material used for steelmaking is a combination of iron and scrap; however, different proportions are used in converters and EAFs. The calculation in this study is based on the assumption that it would take 1.1 tons of iron to melt one ton of steel in the converter in 2013; then, the carbon emissions from the converter steelmaking raw material would be the carbon emissions from 1.1 tons of iron plus the carbon emissions from the energy source, which in this case would be the carbon emissions from electricity. The final result represents the carbon emissions from the entire steelmaking process in the converter.

2.4.4. Calculation of Carbon Emissions from Electric Arc Furnace Steelmaking

The proportion of scrap steel is higher during the EAF steelmaking process. The calculation of the iron used in EAF steelmaking is the same as that in converter steelmaking (see previous section), which includes the carbon emissions proportionally. The calculation also accounted for auxiliary materials. Data on auxiliary materials were retrieved from the China Iron and Steel Industry Yearbook. Materials used in particularly small quantities were ignored, and only carbon emissions from the use of electrodes were considered. The CO_2 emission factor of the electrodes in EAF steelmaking is 3.663 tCO_2/t. Electricity consumption is relatively high in electric furnace steelmaking, and the method for calculating carbon emissions from electricity is the same as that described previously.

2.4.5. Calculation of the Scrap Recycling Index

In this paper, the formula for calculating the Carbon Emission Reduction Index is constructed with reference to the one-factor exponential model and the marginal effect function in economics.

The calculation of the scrap quantity index is as follows:

$$R_{gi} = \frac{r_{gi}}{r_{zi-1}}, \tag{11}$$

where R_{gi} is the ratio of change of domestic recycling in China in year i, r_{gi} is the change in the amount of domestic recycling in China in year i, and r_{zi-1} is the total annual recovery in year $i-1$.

$$R_{ii} = \frac{r_{ii}}{r_{zi-1}}, \tag{12}$$

where R_{ii} is the proportion change in the amount of the recycling volume of imported scrap in year i, r_{ii} is the change in the amount of scrap steel imported in year i, and r_{zi-1} is the total annual recovery in year $i-1$.

$$U_{li} = \frac{r_{ci}}{r_{ci} + u_{ci}}, \tag{13}$$

where U_{li} is the ratio of scrap use to the sum of pig iron and scrap use for long-process steelmaking in year i, r_{ci} is the amount of scrap used for long-process steelmaking in year i, and u_{ci} is the amount of pig iron used in long-process steelmaking in year i.

$$U_{si} = \frac{r_{ei}}{r_{ei} + u_{ei}}, \tag{14}$$

where U_{si} is the ratio of scrap use to the sum of pig iron and scrap use for short-process steelmaking in year i, r_{ei} is the amount of scrap used for short-process steelmaking in year i, and u_{ei} is the amount of pig iron used in short-process steelmaking in year i.

3. Data Specification and Results

3.1. Data Specification

Twenty industry experts from the steelmaking, scrap reuse, and carbon research industries were selected for this study. They possess considerable experience in their respective fields. After providing an overview of the content and requirements of the indicators to the experts, we engaged in group discussions regarding the questionnaire and subsequently completed the questionnaire evaluation sheet. The weight values of the different indicators were obtained by conducting a questionnaire survey with experts, which was developed based on the evaluation system. The respondents were senior experts in the steel industry and had the most relevant professional experience, guaranteeing the reliability of the data sources. The data used in this study are from *China Steel Industry Yearbook* and *China Recycling Industry Development Report*.

3.2. Weight of the Indicators

Expert opinions were first categorized with the cluster analysis method. Subsequently, the classified results were analyzed by FAHP to solve the final weights for the indicators. The number of clusters was set to two, three, and four for the cluster analysis, as shown in Table 2.

Table 2. Iteration records.

Iteration	Changes in Clustering Centers								
	Two		Three			Four			
	1	2	1	2	3	1	2	3	4
1	5.385	7.583	0	5.099	4.422	0	0	4.422	1.000
2	0	0	0	0	0	0	0	0	0

The iterative cluster analysis showed that when the clusters were divided into three or four classes, the optimal result was still divided into two classes, and the final results converged.

Figure 2 shows a genealogy chart of the clustering results. The clustering results were divided into two categories. The next step of the FAHP method was performed for each of the two categories. Table 3 presents the overall results.

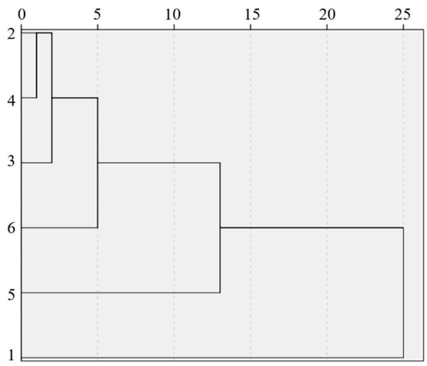

Figure 2. Cluster dendrogram.

Table 3. Weighting table for comprehensive indicators in scrap steel smelting for the carbon emission reduction index.

Criterion Layer	Weight of the Secondary Indicator w_j	Index Layer	Weight of the Three-Level Indicator w_i
Emission reduction index of converter steelmaking	0.592	Combustion carbon reduction	0.2832
		Energy carrier carbon reduction	0.098
		Raw material carbon reduction	0.1336

Table 3. *Cont.*

Criterion Layer	Weight of the Secondary Indicator w_j	Index Layer	Weight of the Three-Level Indicator w_i
Emission reduction index of electric furnace steelmaking	0.251	Combustion carbon reduction	0.0996
		Accessory material carbon reduction	0.0408
		Energy carrier carbon reduction	0.0776
		Raw material carbon reduction	0.1186
Scrap recycling index	0.157	Amount of scrap recovered	0.0562
		Imported scrap volume	0.0222
		Scrap long-process use ratio	0.0394
		Scrap short-process use ratio	0.0309

3.3. Carbon Emission Reduction

Combining the weights of the indicators and the equations in Section 3, Table 4 presents the corresponding carbon reduction calculations under the carbon reduction sub-index for converter and EAF steelmaking, including carbon reductions for fuels, energy carriers, auxiliary materials, and raw materials from 2014 to 2022. Table 5 shows the results of the calculation of the tertiary indicators corresponding to the recycling indicator of scrap steel under secondary indicators from 2014 to 2022.

Table 4. Carbon emission reduction per ton of scrap steel in fixed years (2014–2022).

Index Level	2014	2015	2016	2017	2018	2019	2020	2021	2022
Combustion carbon reduction	0.047	0.452	1.007	0.932	0.806	0.897	0.970	1.060	1.051
Energy carrier carbon reduction	0.000	−0.028	0.036	0.047	0.015	0.033	0.042	0.024	1.000
Raw material carbon reduction	−0.150	−0.582	−0.300	−0.197	−0.130	−0.136	−0.118	−0.057	−0.111
Combustion carbon reduction	−0.052	−0.032	0.080	0.296	0.301	0.415	0.366	0.340	0.352
Accessory material carbon reduction	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.004	0.004
Energy carrier carbon reduction	−0.085	−0.036	−0.122	−0.119	−0.115	−0.065	−0.051	−0.057	−0.069
Raw material carbon reduction	−0.023	−0.069	−0.029	−0.002	0.008	0.033	0.020	0.020	0.019

Table 5. Data on indicators related to scrap recycling from 2014 to 2022.

Criterion Layer	Index Level	2014	2015	2016	2017	2018	2019	2020	2021	2022
Scrap recycling index	Change in the amount of scrap recovered	0.777	−0.056	0.052	0.149	0.223	0.133	0.069	−0.029	−0.038
	Scrap import volume change	−0.326	−0.090	−0.073	0.074	−0.421	−0.863	−0.853	19.4	0.013
	Scrap long-process use ratio	0.06	0.05	0.06	0.1	0.12	0.13	0.13	0.15	0.013
	Scrap short-process use ratio	0.37	0.36	0.41	0.45	0.49	0.57	0.56	0.57	0.57

According to the data from the China Iron and Steel Industry Yearbook, first, the different index quantities of the carbon emission reduction sub-index of scrap recycling were calculated. Then, according to the weight values of different index, the carbon emission reduction index were calculated, as shown in Table 6. Discussion and analysis of the calculation results are presented in the following section.

Table 6. Carbon emission reduction index per ton of scrap steel for fixed years from 2014 to 2022.

Index Level	2014	2015	2016	2017	2018	2019	2020	2021	2022
Carbon emission reduction index of converter steelmaking	−0.007	0.047	0.249	0.242	0.212	0.239	0.263	0.295	0.381
Carbon emission reduction index of electric furnace steelmaking	−0.014	−0.014	−0.005	0.020	0.022	0.040	0.035	0.032	0.032
Scrap recycling index	0.050	0.008	0.016	0.028	0.023	0.011	0.007	0.453	0.021
Carbon emission reduction index of scrap recycling	−0.001	0.021	0.129	0.136	0.120	0.138	0.148	0.230	0.210

4. Discussion

4.1. Carbon Emission Reduction Index

4.1.1. Analysis of the Carbon Emission Reduction Index per Ton of Scrap Used

In this study, the carbon emission reduction index of scrap recycling was to use 2013 as a fixed reference year, compare each subsequent year with 2013, and calculate the carbon emission reduction index from 2014 to 2022, as shown in Figure 3. According to Figure 3, this study has several observations.

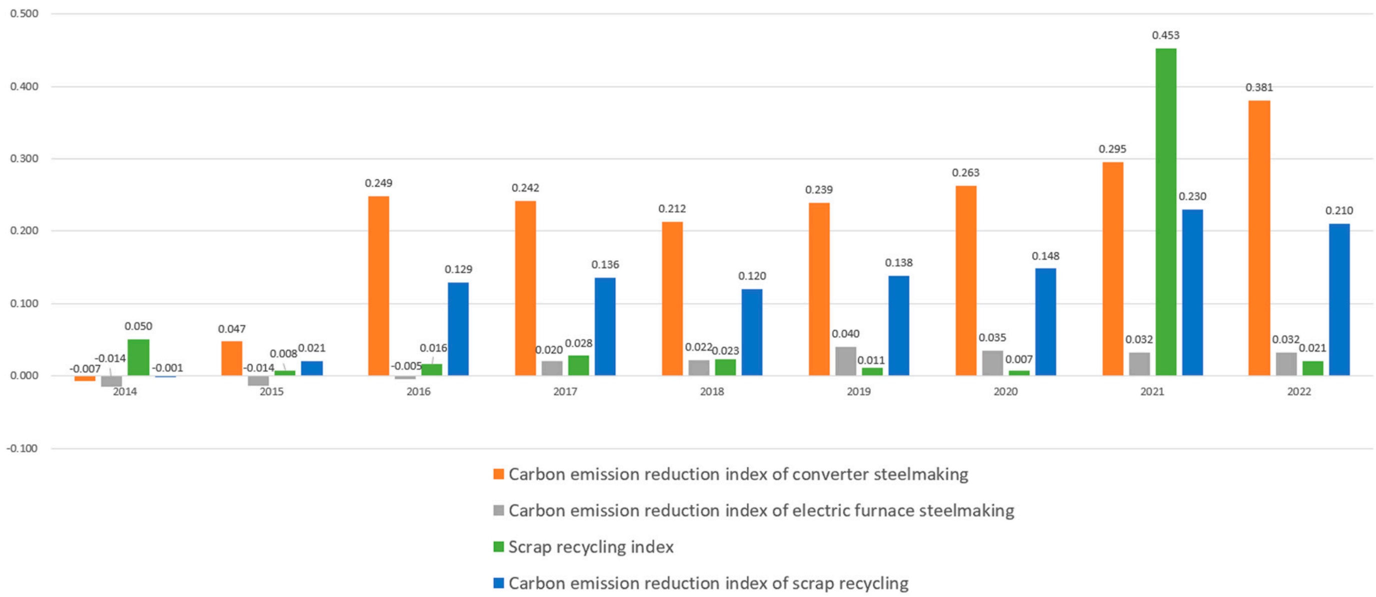

Figure 3. Carbon emission reduction index per ton of scrap steel for fixed years from 2014 to 2022.

Observation 1. From 2014 to 2022, the carbon emission reduction index of scrap recycling increased by 10 times. The carbon emission reduction index of scrap recycling increased before 2017, then decreased by 11.8% from 2017 to 2018, and increased from 2018 to 2021. Finally, it dropped by 8.7% per cent in 2022.

According to the blue bars in Figure 3, the lowest carbon emission reduction index was seen in 2014, whereas the highest index value was in 2022. This phenomenon can be explained as follows. In 2014, the General Office of the State Council of China issued the action program of "2014–2015 Action Program on Energy Conservation, Emission Reduction and Low-Carbon Development", which proposed that the iron and steel industry strengthen its energy conservation and emission reduction efforts. The implementation of action program contributed to an increase in the carbon emission reduction index in 2014–2016. In 2016, the Ministry of Industry and Information Technology of China issued the plan of "Steel Industry Adjustment and Upgrading Plan (2016–2022)". The plan stated that the steel industry should decrease production capacity, restructure the industry, and commit to environmentally friendly development. Historical data from "the China Iron and Steel Industry Yearbook" demonstrates an increase in the recycling of scrap steel in the production of each ton of steel from 2016 to 2018, which increased 100% during this period. On the contrary, fuel usage did not decrease significantly during this period, resulting in a reduction in the proportion of carbon emissions to scrap steel usage. This led to the lowest carbon reduction index in 2018. Moreover, during 2018–2022, the implementation of environmentally friendly production in the steel industry proved effective in reducing carbon emissions from fuel and other sources, which led to a gradual increase in the carbon reduction index.

Observation 2. The carbon emission reduction index for electric furnace steelmaking increased before 2019 and then decreased. It is changing by ten per cent a year.

From 2014 to 2019, the carbon emission reduction index for electric furnace steelmaking increased, but from 2020 to 2022, it decreased. Analysis of data from the China Iron and Steel Industry Yearbook revealed that the increase in the proportion of iron used in electric furnace steelmaking by 10% from 2019 to 2022 is the primary factor for increased carbon emissions and the subsequent reduction in the carbon emission reduction index.

4.1.2. Analysis of Scrap Recycling Index

In this subsection, the scrap recycling index is focused on changes in the amount of recycled scrap steel.

Observation 3. From 2014 to 2022, the scrap recycling index decreased by 90% significantly in 2015, increased slowly until 2017, and then decreased each year. The index suddenly rose in 2021 and then decreased (Figure 4).

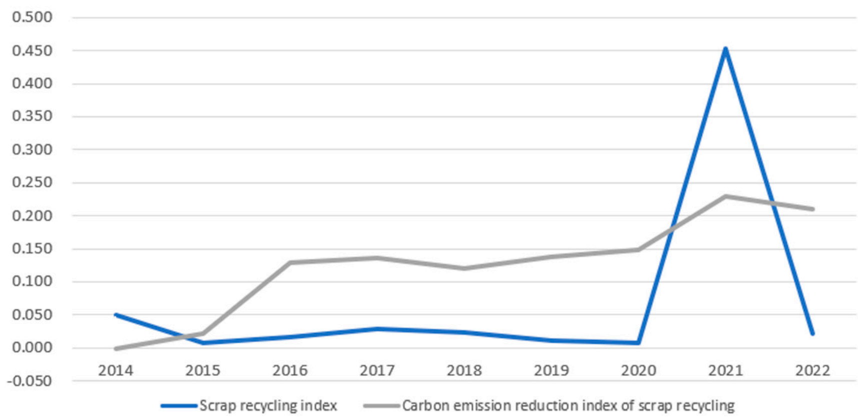

Figure 4. Carbon emission reduction index for scrap recycling from 2014 to 2022.

In recent years, China has reduced the import of foreign scrap resources to address environmental concerns, to improve resource recycling, and to promote domestic industrial upgrading. In 2017, the Ministry of Environmental Protection issued the Imported Waste Management Catalog, which limits the amount of solid waste materials including steel scrap. Starting in January 2020, the import of steel scrap will be completely banned. The scrap recycling index for 2020 is particularly low. However, in 2021, the policy on imported scrap changed. In 2021, China's new import policy broadened the import criteria for ferrous scrap to include recycled steel raw materials that can be fed directly into steelmaking furnaces. Scrap is therefore no longer a prohibited product. As a result, scrap imports increased significantly in 2021 compared to 2020. The scrap recycling index for 2021 rose sharply. Steel scrap recycling is still constrained by an imperfect scrap recycling system. Specifically, in the automotive manufacturing industry, a significant number of end-of-life vehicles are sold to illegal operators who repair and sell them for reuse, thereby limiting the number of vehicles that can be officially processed. In addition, recycling efficiency and scrap production are reduced by a significant amount of illegal, small-scale processing under inadequate processing conditions. As a result, the cost of formal scrap recovery and recycling is high, which reduces the willingness of China's domestic steel companies to carry out scrap recycling.

4.2. Predicting the Future Carbon Emission Reduction Index

In this section, the future development of the carbon emission reduction index can be predicted by analyzing the recycling and development trend of scrap steel. This information can serve as a valuable reference for future decisions regarding scrap recycling modes. Numerous techniques exist for time-series prediction [46], including regression fitting prediction, which is known for its low accuracy; exponential smoothing and neural network prediction, both of which require large amounts of sample data [47,48]; and grey prediction, which requires small amounts of data yet provides relatively high accuracy in prediction [49].

In this study, the gray prediction model was used to predict the carbon emission reduction index of the scrap steel industry in the coming years. It requires five to eight premium datasets for reliable results [50]. The first step involved creating a time-series prediction model for the carbon emission reduction index of scrap recycling, using known data from 2014 to 2022 and predicting values for 2023 to 2030. The graph in Figure 5 displays the predicted fit.

Observation 4. The index for reducing carbon emissions per ton of recycled scrap steel increases steadily over fixed years.

This increase is due to the rise in the stock of scrap steel and advancements in smelting technology in China [23]. As these factors progress, the carbon emission reduction index will continue to rise, resulting in the ultimate maximum value of carbon emission reduction. By predicting the carbon reduction index, it is possible to verify that the current scrap reuse policy is contributing to the reduction of carbon emissions, and the prediction method can assist other carbon emission-related prediction studies.

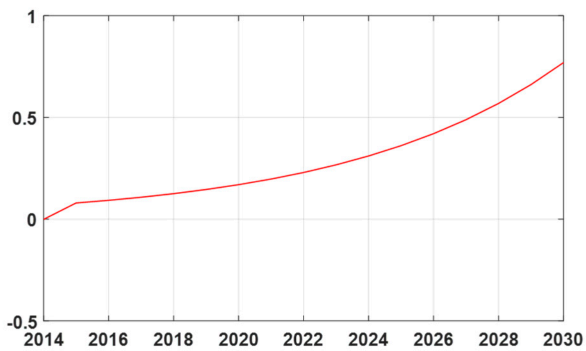

Figure 5. Projected carbon emission reduction index per ton of scrap steel for fixed years from 2014 to 2030.

4.3. Management Insights

This paper makes the following suggestions for the future development of the steel industry:

Firstly, coal is the main fuel used in long-process steelmaking and is associated with high carbon emissions. With the increase in crude steel production, the consumption of coal and other fuels has rapidly increased, resulting in increased emissions. It is recommended that steel enterprises increase their use of clean energy to reduce pollutant emissions.

Secondly, in short-process EAF steelmaking, a significant proportion of hot metal is produced by the EAF process, which cannot save energy or reduce emissions. Unfortunately, this situation is common in China, where some enterprises have a hot-metal ratio of more than 80% [51]. Steel companies should reduce the use of hot metal and increase the proportion of scrap steel to reduce CO_2 emissions. Unnecessary steps in hot metal transfer can be eliminated by maintaining a high temperature of the hot metal and preheating the scrap steel. This approach can shorten the melting time, save energy, and reduce emissions.

Thirdly, comprehensive scrap processing optimization—from raw material preparation, melting, and cooling to finished product processing—should lead to innovative ways of reducing carbon emissions. Examples include measures for improving the selection and pretreatment of scrap charges, optimizing melting temperatures and times, and effectively controlling the scrap and byproducts generated during scrap processing.

Finally, government should formulate appropriate industrial policies to promote the development of the scrap recycling industry and establish partnerships with related industries to promote the research, development, and application of scrap recycling technologies. Establishing a scrap resource integration platform to promote the exchange and sharing of scrap resources across different regions should also be a priority. This will help reduce carbon emissions from long-distance transportation while improving the efficiency of scrap recycling. Promoting the green design of scrap steel and considering its recycling at the product design stage will be beneficial. Lastly, minimizing resource waste and reducing CO_2 emissions should be executed by designing products that are easier to disassemble and recycle.

5. Conclusions

This study established a model for evaluating the CO_2 emission reduction effect of scrap recycling. The construction of the emission reduction evaluation model focused on the calculation of carbon emissions from iron and steel smelting processes. Based on the dynamic changes in the values of raw materials, scrap ratios, and fuels in different years, we calculated and analyzed the changes in the carbon emission reduction index of the iron and steel industry under the influence of scrap recycling. The carbon reduction index for scrap recycling established in this paper is suitable for steel enterprises to assess the carbon emissions in the process of scrap utilization and adjust the related material usage. It can also help government departments to assess the carbon emission situation of the steel industry at different moments and formulate relevant policies in a timely manner. The limitation lies in the fact that the data collected are too short to assess the changes of the index from a long-term historical perspective.

In this study, the use of steel scrap is divided into two main categories, namely long process steelmaking and short process steelmaking. Both types require iron to be melted in a blast furnace. Smelting iron in a blast furnace requires various fuels, electricity and raw materials. The highest carbon emissions are from fuels, which emit 1.42 tonnes of carbon dioxide per tonne of iron, electricity, which emits 0.038 tonnes of carbon dioxide, and raw materials, which emit 0.22 tonnes of carbon dioxide. The molten iron is used to make steel in either a converter or an electric arc furnace. The carbon dioxide emissions per tonne of steel in converter mode are 1.58 tonnes (based on 2022 figures) and 0.996 tonnes per tonne of steel in electric arc furnace mode (based on 2022 figures). This is close to what Sahoo calculated, but a little lower [25]. The result is also lower than the 2.15 tonnes of CO_2 mentioned by Hasanbeigi [52]. Emissions vary from year to year due to the different proportions of materials used.

The results showed that the carbon emission reduction index per ton of steel has increased in recent years, considering a fixed reference year. This finding confirms from an academic research perspective that the existing smelting processes can effectively reduce carbon emissions by increasing the use of scrap steel. In recent years, only 20% of scrap has been used. Xuan and Yue (2016) believe that full utilization of scrap can only be achieved when the scrap ratio reaches 36.6% [53]. By covering scrap steel with molten iron during the smelting process, the purity of the steel can be improved while maintaining cost efficiency. However, because of the consistent use of a low fixed proportion of scrap steel over the years, this method has resulted in relatively high carbon emissions from smelting, resulting in a weak carbon emission reduction effect.

The results calculated from the model show that the years with the highest fluctuations in the carbon emission reduction index for scrap recycling, with 2013 as the base year, were 2015 and 2016. However, in the subsequent years, the index showed minimal changes. Furthermore, the pattern of change in the scrap recycling rate was very similar to the index fluctuations, indicating a significant emission reduction effect of scrap recycling. Similarly, calculations have shown that the EAF mode with pure scrap steel can achieve an emission reduction of up to 80% compared with the traditional mode. The same Sirintip study calculated that increasing the use of steel scrap could reduce carbon emissions by more than 60 percent [54]. Given the current situation in China, although the Chinese-style short-cycle steelmaking can produce high-quality steel at a low cost, it cannot effectively and sustainably reduce carbon emissions from the steel industry and has failed to meet the emission reduction targets on time. To address this issue, companies must shift their focus from cost considerations to carbon reduction. Increasing the use of scrap steel is key for meeting the environmental targets of the steel industry.

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