Environmental Science and Pollution Research (2023) 30:124010–124027
https://doi.org/10.1007/s11356-023-30830-z

RESEARCH ARTICLE

CO_2 emission accounting and emission reduction analysis of the steel production process based on the material-energy-carbon correlation effect

Yueqing Gu[1] · **Chongchao Pan**[1,2] · **Yunren Sui**[2] · **Bowen Wang**[1] · **Zeyi Jiang**[1] · **Cunhai Wang**[1] · **Yusong Liu**[1]

Received: 15 April 2023 / Accepted: 29 October 2023 / Published online: 23 November 2023

Abstract
This paper develops a process-level carbon emission calculation model for iron and steel enterprises through the carbon emission mechanism of the whole production process. The relationship between material, energy and carbon flows is considered and combined. The carbon emissions of enterprises are divided into industrial emissions and combustion emissions, and the indirect emissions of purchased intermediate products and electricity purchased from the grid are also considered. Carbon emission targets and corresponding emission reduction strategies are formulated at the enterprise and process levels. For example, consider an iron and steel enterprise. The different types of carbon emissions are accounted for, with their reduction potential analysed based on the carbon material flow analysis method. The results show that the carbon emission of this enterprise is 1930.87 $kgCO_2/t$ (CS), and the combustion emission caused by energy flow is the main contributor to the enterprise's carbon emission, accounting for 57.02% of the total emission. The carbon emission during iron-making accounts for 69.06% of the entire process and is critical in any carbon emission reduction of the enterprise. Among them, process emissions from the blast furnace process account for 81.79% of industrial emissions of the whole process, which is 356.51 $kgCO_2/t$ (CS), and is the main challenge of low carbon transformation in this extensive process. This study highlights that increasing the integrated steel-making scrap ratio and electric furnace steel production can break through the existing emission reduction limits. A 65.02% carbon emission reduction can be achieved, and using green electricity can reduce emissions by 24.15%. Reasonably determining the amount of purchased coke and paying attention to the high-value recycling of byproduct gas resources in the plant are essential to achieve low-carbon economic development of steel.

Keywords Material-energy-carbon flow · Correlation effect · Carbon emission calculation model · Emission reduction strategy

Introduction

Along with global warming caused by fossil fuel depletion and excessive greenhouse gas emissions, the world has reached a consensus. The Paris Agreement proposes to control global warming levels to within 2°C above pre-industrial levels and achieve net zero greenhouse gas emissions by around 2050 (Yu and Tan 2022). The Chinese government has also committed to achieving carbon peaking by 2030 and work towards carbon neutrality by 2060 (Shao et al. 2022). As a resource and energy-intensive industry, the steel industry consumes large amounts of fossil fuels as reducers and fuels. As the world's largest producer and consumer of steel, China will produce 1.033 billion tons of crude steel in 2021, accounting for more than half of global crude steel production and about 15% of the total domestic CO_2 emissions (Zhang et al. 2023). In the wake of accelerated growth within China's iron and steel industry, the swift surge in crude steel production has posed significant challenges to the effective control of the industry's carbon emissions (Zhang et al. 2022b). Concurrently, evolving from the 11th through the 13th Five-Year Plans, China has officially introduced a

Responsible Editor: V.V.S.S. Sarma

✉ Chongchao Pan
panchch@ustb.edu.cn

[1] School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China

[2] School of Energy and Environment, City University of Hongkong, Hongkong 999077, China

dual control strategy for both overall energy consumption and intensity in its 14th Five-Year Plan (Jia et al. 2022; Tong et al. 2023). Consequently, within the iron and steel sector, research emphasis has progressively shifted from total energy consumption control towards optimising energy efficiency and limiting carbon emissions during the smelting process. This shift aims to foster high-quality development within the iron and steel industry. Under the pressure of "Double Control" of energy consumption and the "Double Carbon" target, the low-carbon transformation of China's iron and steel industry is imminent.

As a typical process industry with multiple physical processes and complex energy-using systems, accurate analysis and quantification of CO_2 emissions from the steel production process is a prerequisite for investigating its emission reduction potential. Currently, there are many carbon emission accounting methods and accounting standards for the steel industry. The variability of accounting boundaries and scope has led to a unified accounting system, which can be mainly summarised into calculation methods based on the average emission factor per ton of steel, calculation methods based on the calorific value and carbon content of the consumed carbon sources, and calculation methods based on carbon balance (Liu et al. 2022). Substance flow analysis (SFA) is an effective tool for studying the industrial metabolism of specific substances and is commonly used to analyse the carbon reduction potential of steel production processes (Xu et al. 2016). Zhang et al. (2018) used carbon substance flow analysis (C-SFA) for two typical steel-making case companies to study CO_2 reduction at the enterprise level. Tian et al. (2022) studied the direct and indirect carbon emissions and carbon reduction potential of iron and steel enterprises based on the SFA around the metabolic form of byproduct gases in the steel production process. Carbon emissions from steel production depend on the coordinated and coupled operation of material and energy flows, and a quantitative study of the coupling characteristic law between material flow, energy flow and carbon emissions has important emission reduction potential mining value (Chen et al. 2022; Sun et al. 2020). Yuan et al. (2023) proposed a single-objective and multi-objective optimisation model for material and energy scheduling and utilisation and discussed the influence of material and energy flows on multi-objective variation. Zhang et al. (2022a, b) comprehensively considered the coupling relationship between material flow, energy flow and carbon flow in steel production. They established a material-energy-carbon hub model to study the influence of material, and energy flows on carbon flow within the process.

There is a synergistic effect between energy efficiency and CO_2 emissions (Wang et al. 2022b), while the current steel-making process is close to the theoretical thermodynamic limit. Metallurgical coal is challenging to replace completely as a key material, making the low-carbon transition route of the Chinese steel industry, which is mainly based on the blast furnace-converter process, difficult and complex. Therefore, many studies have developed comprehensive models to examine the CO_2 reduction paths in the iron and steel industry from different perspectives. Pan et al. (2022) used the two-stage logarithmic mean divisia index (LMDI) to establish the STIRPAT (stochastic impacts by regression on affluence, population and technology) model, which showed that the inhibiting factors in the carbon peaking pathway of the Chinese steel industry are scale factor and energy intensity, respectively. Duan et al. (2022) established an integrated life-cycle-based long-range energy alternatives planning system (LEAP) model to discuss the reduction of energy-related carbon emissions under different low-carbon scenarios. They deduced that the future decarbonisation of steel production relies primarily on increasing the share of electric arc furnace routes and applying hydrogen reduction iron-making technology. Tan et al. (2019) further analysed the emission reduction potential of energy-saving technology applications in the Chinese steel industry in the context of implementing energy substitution policies around the carbonisation of the energy structure of the steel industry. On this basis, Ren et al. (2021), based on a comprehensive analytical framework of life-cycle analysis, pointed out that achieving low-carbon development in the Chinese steel industry requires technological improvements to the blast furnace-converter process, enhanced scrap resource recovery and increased electric arc furnace capacity in the short term. They also identified the importance of ultra-low carbon technologies, such as hydrogen-based direct iron reduction and carbon capture, utilisation and storage (CCUS), in the long-term development. Therefore, to achieve deep decarbonisation in the steel industry, it is urgent to transform the traditional production structure and focus on the application and promotion of breakthrough technologies such as non-blast furnace iron-making, direct reduction (Ren et al. 2023) and CCUS (Yang et al. 2022; Feng et al. 2022). Finally, increasing the proportion of non-fossil energy consumption and electric arc furnace capacity on the existing basis augments the recycling and reuse of steel waste, enhances the symbiotic ecology of the steel industry and expands the multi-industry synergistic low-carbon development model under the carbon trading market need to be considered and implemented.

In summary, the focus of steel low-carbon research has gradually shifted from the industry to the enterprise and specific process levels. In contrast, the complexity of the carbon emission mechanism for the steel production process and the variability of different production processes lead to the complexity of carbon accounting for the steel manufacturing process, and the challenge of effective and accurate emission reduction. Therefore, considering the standard carbon emission calculation and evaluation methods at home and abroad, this paper establishes a carbon emission calculation model for Chinese iron and steel enterprises based on carbon material flow analysis, by combining the inner operation mechanism of material flow, energy flow and carbon flow of iron and steel production. It also illustrates the factors influencing different types of carbon emissions and the corresponding means of emission reduction with case steel enterprises, which will provide theoretical support for enterprises to carry out carbon accounting and low carbon development.

Methods

Common carbon emission calculation methods and analysis for the steel enterprise

Currently, the fundamental methods surrounding CO_2 emission accounting for steel enterprises are all based on C-SFA, which can be methodologically divided into two types of statistical methods, based on life cycle and input–output. Table 1 shows the typical CO_2 accounting methods at home and abroad, internationally primarily including the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006), the Life Cycle Assessment method (LCA) (ISO 2006), the World Steel Association (WSA 2023) and World Resources Institute and World Business Council for Sustainable Development (WRI and WBCSD 2008). In China, mainly the "GHG Emissions Accounting and Reporting Requirements Part 5: Steel Producers" (National Standard) (Standardization Administration 2015) and the "GHG Emissions Accounting Methodology and Reporting Guidelines for Chinese Steel Producers (Trial)" (Guideline) (National Development and Reform Commission 2013) are considered.

The main difference lies in the system boundary and determination of emission factors. On the system boundary, the accounting method based on the IPCC guidelines only considers direct emissions from fossil fuels, without considering indirect emissions such as carbon emission credits, and purchased electricity and heat, and is commonly used for carbon emission accounting at national or regional levels. The system boundary of other accounting methods gradually covers the whole steel production process and upstream emissions such as raw materials, which improves the accuracy and precision of accounting, but also requires more stringent management and collection of production data. Carbon emission factors are the main reason for the different accounting results. Considering that it is difficult for enterprises to rely entirely on self-testing calculations and that emission factors can change significantly under different technical levels and production conditions, the results can significantly deviate from the actual values. Therefore, iron and steel enterprises should choose suitable emission factors according to their actual situations, and carry out accounting work by combining their self-testing values.

Therefore, to ensure that the CO_2 accounting method applies to Chinese iron and steel enterprises, explore the influence of material flow and energy flow on carbon flow in the iron and steel production process and find carbon reduction measures for iron and steel enterprises, this paper comprehensively considers the system boundaries and emission factors of the LCA, National Standard and WSA. Carbon emission studies of typical iron and steel manufacturing processes based on carbon elemental flow analysis were undertaken.

Carbon emission calculation model

System boundary

Figure 1 shows the system boundary of a typical steel manufacturing process, covering essentially all consumables. It mainly includes steel production, energy conversion and energy storage systems. The steel production system has two main routes, and the first route is the blast furnace-basic oxygen furnace (BF-BOF) route using iron ore and coal as raw materials and energy sources. The second is the electric arc furnace (EAF) route using scrap and electricity as raw

Table 1 Carbon accounting methods for the steel industry

Calculating method	Fossil fuel	Power	Material	Product	Upstream	Indirect emission	Emission credit
IPCC	√	×	×	×	×	×	×
LCA	√	√	Only the carbon carriers	√	√	√	√
WSA	√	√	Only the carbon carriers	√	Only fossil fuel	√	√
WRI/WBCSD	√	√	Only the carbon carriers	√	√	√	√
National Standard	√	√	Only the carbon carriers	√	×	√	√
Guideline	√	√	Only the carbon carriers	√	×	√	√

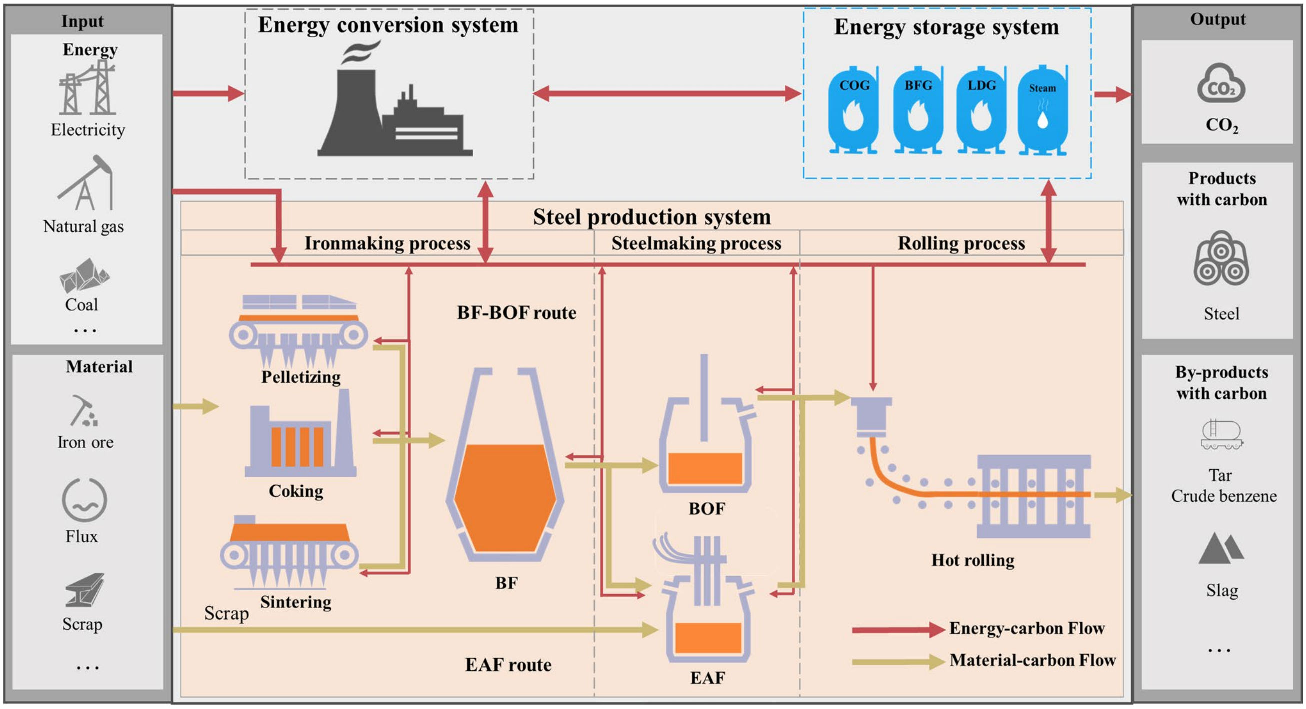


Fig. 1 System boundary of a typical steel manufacturing process

materials and energy sources, which usually also uses part of the iron in the EAF, considering the limitations of the scrap stock. The energy conversion system mainly consumes various byproducts of gas and waste heat and energy recovered from the energy storage system through an onsite power plant (OPP) for enterprise self-generation, supplemented by purchasing electricity and gas from the superior grid and natural gas network.

Elemental carbon in iron and steel enterprises primarily enters in the form of coal and raw materials containing carbon. In the coking process, washed coal is indirectly heated, and dry distilled through the combustion of gaseous fuels (natural gas, coke oven gas, etc.) in the combustion chamber and is converted into secondary energy such as coke and coke oven gas (COG). The sintering and pellet processes use solid fuels (coke powder, anthracite, etc.) and gaseous fuel combustion to provide raw materials for the blast furnace iron-making process. The carbon in the iron-making process mainly comes from coke and blown coal powder, with a small amount coming from, for example, limestone. After complex physical and chemical changes in the blast furnace, the residual carbon in carbon-containing melts, sinter and pellet ores will eventually be converted into CO and CO_2 into the blast furnace gas (BFG). It will also be partly dissolved in the iron water and a small amount into the dust with the BFG to escape from the furnace. In the steel-making process, the iron enters the BOF and EAF after pretreatment to smelt into crude steel. The carbon is mainly from the gas fuel, with a small amount from the carbon-containing melt, iron and scrap. Finally, most of it is converted into CO and CO_2 in the converter gas (LDG), and a small amount is dissolved in the crude steel. The EAF is not usually recycled because of the unstable gas composition in the furnace. The carbon element of the rolling process mainly comes from the gas fuel, which is used to burn the gas fuel for the final metal processing of the crude steel after refining and continuous casting. The byproduct gas recovered throughout the process is used as fuel for major processes such as coke ovens, sintering machines, hot air furnaces, heating furnaces, gas boilers and the combustion of self-built power plants. However, the actual participation of byproduct gas as a carbon energy source is only the H_2, CO and hydrocarbon components in the operation of the energy stream, among which the CO_2 component is mainly affected by the material stream operation. Only a few companies use byproduct gas to synthesise chemical products, effectively avoiding the emission of such CO_2 into the environment.

Studying the relationship between material flow, energy flow and carbon emission is the core issue for steel enterprises to carry out carbon emission reduction work. Considering that steel enterprises' production processes and energy media are diverse and complex in structure, different energy media always accompany the material flow production process and promote production through generation, conversion, storage and consumption. Therefore, the essence of the steel production process is coupling the material and energy flows with each other and constraining each other.

Calculation method

As described above, carbon emissions from each operating unit in a steel company are generated due to physicochemical reactions between carbon energy and carbonaceous substances. Therefore, based on the carbon conservation principle and the carbon accounting method of the International Steel Association, the CO_2 emissions in the system are calculated by balancing the input and output of the carbon streams in the system. As shown in Fig. 2, the carbon flow per share of process i is represented as follows:

(1) $C_{\alpha,i,j}$: Carbonaceous substances (such as washed coal, coke, limestone) are imported into process i from outside as energy or raw materials.
(2) $C_{M,i,j}$: Carbonaceous substances imported into process i from other production system processes as energy or raw materials, including non-conforming products containing carbon that are returned to use as raw materials.
(3) $C_{E,i,j}$: Carbonaceous energy input to process i from energy conversion systems, energy storage systems and external sources as energy or raw materials.
(4) $C_{P,i,j}$: Output of carbon-containing products from process i.
(5) $C_{B,i,j}$: Output of carbon-containing byproducts from process i.
(6) $C_{\beta,i,j}$: The carbon emission of process i.

As a result, the input-output model of the carbon flow of process i is shown in Eq. (1).

$$C_{\alpha,i,j} + C_{M,i,j} + C_{E,i,j} = C_{P,i,j} + C_{B,i,j} + C_{\beta,i,j} \tag{1}$$

The direct CO_2 emission from process i is described in Eq. (2).

$$E_{CO_2,i} = \frac{44}{12} \cdot \sum_{j=1}^{n_i} \left(C_{\alpha,i,j} \cdot \theta_{\alpha,i,j} + C_{M,i,j} \cdot \theta_{M,i,j} + C_{E,i,j} \cdot \theta_{E,i,j} - C_{P,i,j} \cdot \theta_{P,i,j} - C_{B,i,j} \cdot \theta_{B,i,j} \right) \tag{2}$$

where $E_{CO_2,i}$ is the direct carbon emission of process i, C is the consumption factor and θ is the material carbon content factor; $\frac{44}{12}$ is the conversion factor for the conversion of C to CO_2.

By considering the intrinsic operation mechanism between carbonaceous material flow, energy flow and carbon flow, the direct carbon emissions in the actual industrial process can be divided into two categories. Industrial carbon emissions (ICE) are mainly caused by carbonaceous material flow and are directly involved in product production. Secondly, combustion carbon emissions (CCEs) are primarily caused by carbon energy flow and are used to consider indirect heating of various auxiliary equipment. The expressions are shown in Eqs. (3) and (4).

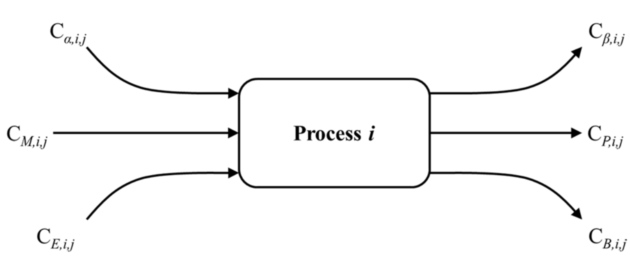


Fig. 2 Schematic diagram of the process carbon balance analysis model

$$ICE_i = \frac{44}{12} \cdot \sum_{j=1}^{n_i} \left(C_{\alpha,i,j} \cdot \theta_{\alpha,i,j} + C_{M,i,j} \cdot \theta_{M,i,j} - C_{P,i,j} \cdot \theta_{P,i,j} - C_{B,i,j} \cdot \theta_{B,i,j} \right) \tag{3}$$

$$CCE_i = \frac{44}{12} \cdot \sum_{j=1}^{n_i} C_{E,i,j} \cdot \theta_{E,i,j} \tag{4}$$

In addition to directly using carbon energy, steel enterprises usually use power media such as electricity, water, oxygen and steam. Table 2 shows the standard coal coefficients of major energy-consuming materials. These power media are generated by electricity consumption. This power media portion can be converted into electricity consumption by energy consumption equivalence, so the indirect emissions of purchased electricity can reflect the level of energy conversion and residual energy recovery of steel enterprises, as shown in Eq. (5). Considering that the responsibility of upstream emissions of purchased intermediate smelting products should be attributed to the steel enterprise, the indirect carbon emissions of purchased coke of the enterprise should be calculated as shown in Eq. (6). Therefore, the carbon emissions of the whole steel enterprise are described by Eq. (7).

$$PECE_i = \sum_{j=1}^{n_i} C_{PE,i,j} \cdot F_{PE} \tag{5}$$

$$PCCE_i = \sum_{j=1}^{n_i} C_{PC,i,j} \cdot F_{PC} \tag{6}$$

Table 2 Conversion coefficient for the energy carriers to the standard coal equivalent

Energy carrier	Coefficient	Unit	Energy carrier	Coefficient	Unit
Cleaned coal[a]	0.8986	kgce/kg	LDG[c]	0.2580	kgce/m^3
Anthracite[a]	0.9110	kgce/kg	Industrial water[b]	0.0414	kgce/kg
Bituminous coal[a]	0.6678	kgce/kg	Steam[b]	0.0939	kgce/kg
Coke[a]	0.9702	kgce/kg	Compressed air[b]	0.0152	kgce/m^3
Purchased coke[a]	0.9702	kgce/kg	Oxygen[b]	0.0802	kgce/m^3
Natural gas[a]	1.328	kgce/m^3	Nitrogen[b]	0.0169	kgce/m^3
COG[c]	0.5883	kgce/m^3	Argon[b]	0.6140	kgce/m^3
BFG[c]	0.1288	kgce/m^3	Electricity[b]	0.1229	kgce/kWh

[a]Data taken from the national standard: Greenhouse Gas Accounting and Reporting Requirements Part 5: Steel Producers (Standardization Administration 2015)

[b]Data taken from the national standard: Guidelines for Energy Efficiency Assessment of Blast Furnace Processes (Standardization Administration 2017)

[c]Data taken from the case company

$$E_{CO_2} = \sum_{i=1}^{n} \frac{ICE_i+CCE_i+PECE_i+PCCE_i}{P_i} \cdot p_i = \sum_{i=1}^{n} e_{CO_2,i} \cdot p_i \quad (7)$$

where E_{CO_2} is the carbon emission per unit product of the steel enterprise, P_i is the output of process i and P_i is the process steel ratio, which is the ratio of process output to crude steel output. The $e_{CO_2,i}$ term is the carbon emission of process i, and $PECE_i$ and $PCCE_i$ denote the indirect carbon emission of purchased electricity and purchased coke of process i, respectively. The $C_{PE,i,j}$ and $C_{PC,i,j}$ are the amount of purchased electricity and purchased coke of process i. The terms F_{PE} and F_{PC} are the corresponding indirect emission factors.

To ensure the accuracy and reliability of the calculation results, some emission factors in this paper refer to the Guidelines issued by China and previous studies (see Table 3). The remaining factors are based on the actual production data of steel enterprises.

CO_2 emission indices of the steel enterprise

This paper establishes various carbon emission indicators at the enterprise and process levels, highlighting the corresponding emission reduction strategies to promote the green and low-carbon development of iron and steel enterprises and to control and reduce carbon emissions. The specific index calculation formula and content are shown in Table 4.

Case study

This study utilises a sizeable ten-million-ton steel complex in East China as the research object. The enterprise produces 90% of the crude steel from the blast furnace-converter process and 10% from the electric arc furnace process. The enterprise has production units such as coking, sintering, pellet, blast furnace, converter, electric arc furnace, continuous casting and rolling. Additionally, auxiliary production

Table 3 Carbon emission factors for the main fuels and materials

Item	Value	Unit	Item	Value	Unit
Cleaned coal[a]	3.164	kgCO_2/kg	BFG[c]	0.538	kgCO_2/m^3
Anthracite[a]	1.924	kgCO_2/kg	LDG[c]	1.157	kgCO_2/m^3
Bituminous coal[a]	1.747	kgCO_2/kg	Hot metal[c]	0.147	kgCO_2/kg
Coke[a]	2.862	kgCO_2/kg	Scrap[c]	0.006	kgCO_2/kg
Purchased coke[b]	3.768	kgCO_2/kg	Crude steel[c]	0.007	kgCO_2/kg
Tar[a]	2.645	kgCO_2/kg	Blast furnace slag[c]	0.183	kgCO_2/kg
Crude benzene[a]	3.411	kgCO_2/kg	Dolomite[a]	0.471	kgCO_2/kg
Natural gas[a]	2.162	kgCO_2/m^3	Limestone[a]	0.440	kgCO_2/kg
COG[c]	0.656	kgCO_2/m^3	Electricity[a]	0.7035	kgCO_2/kWh

[a]Data taken from the national standard: Greenhouse Gas Accounting and Reporting Requirements Part 5: Steel Producers (Standardization Administration 2015)

[b]Data taken from Tian et al. (2022)

[c]Data taken from the case company

Table 4 Carbon emission indices for steel companies

Index		Equation[a,b]	Unit	Emission reduction strategies
Direct emissions	Intensity of ICE	$\frac{\sum_i^n ICE_i}{P_{CS}}$	$kgCO_2/t$ (CS)	Optimise process structure, and apply breakthrough low-carbon technology. Pay attention to process resources and build a circular economy industry chain
	Intensity of CCE	$\frac{\sum_i^n CCE_i}{P_{CS}}$	$kgCO_2/t$ (CS)	Low-carbon energy-saving upgrades to enhance process energy efficiency Optimise the energy network to achieve multi-energy synergy and interaction
Indirect emissions	Intensity of PECE	$\frac{\sum_i^n PECE_i}{P_{CS}}$	$kgCO_2/t$ (CS)	Improve the rate of waste heat and energy self-generation, strengthen the use of rooftop photovoltaic and wind power resources and reduce the amount of electricity enterprises purchase
	Intensity of PCCE	$\frac{\sum_i^n PCCE_i}{P_{CS}}$	$kgCO_2/t$ (CS)	Promote low-carbon production process to reduce coke demand
Carbon emission intensity of the process		$\frac{ICE_i+CCE_i+PECE_i+PCCE_i}{P_{PD}}$	$kgCO_2/t$ (PD)	
Carbon intensity of the total enterprise		$\frac{\sum_i^n (ICE_i+CCE_i+PECE_i+PCCE_i)}{P_{CS}}$	$kgCO_2/t$ (CS)	

[a]P_{CS} is the production of crude steel of the enterprise

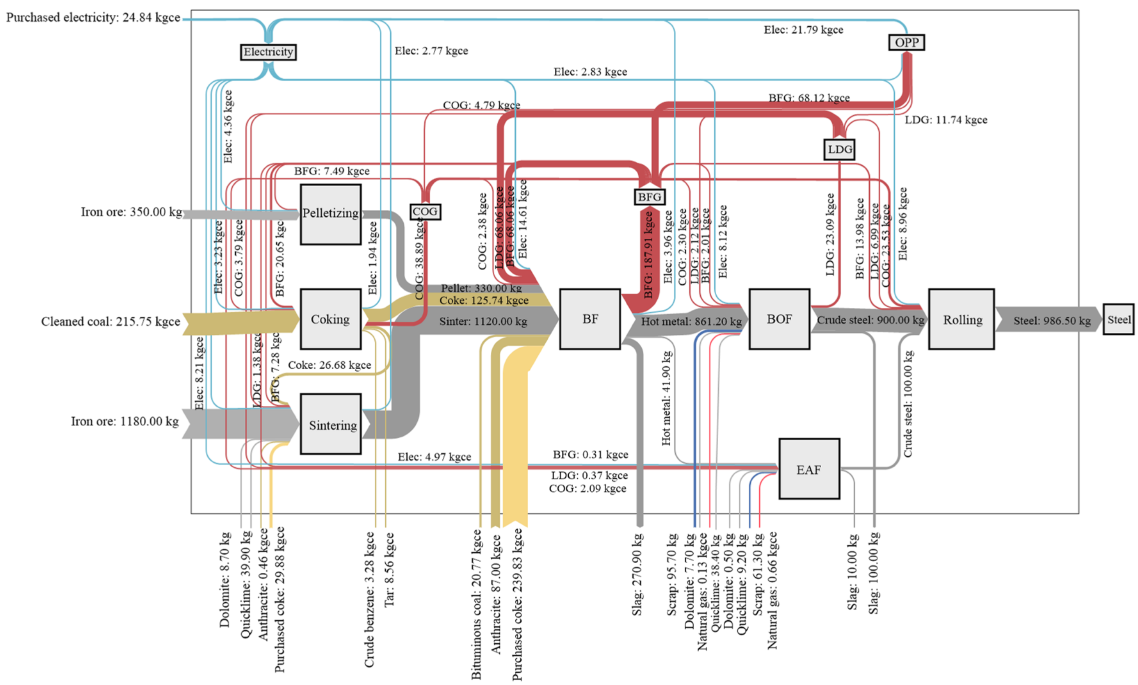
[b]P_{PD} is the production of process products

units such as power generation and conversion have been produced. This study, therefore, adopts the above carbon emission calculation model and selects the final production of hot-rolled steel as an example. This enterprise's material and energy flows are shown in Fig. 3a. Its process structure is 1.12t sintered ore and 0.33t pellet ore to produce 1t crude steel, producing 986.5kg hot rolled steel after continuous casting and hot rolling. Among the purchased products, 60% of the coke needs to be purchased from independent coking plants, and scrap steel accounts for 15% (including converters and electric arc furnaces). The power consumption of the enterprise is 449.9 kWh per ton of steel, of which the proportion of self-generation is 55.2%, including power generation from the self-built power plant, waste heat power generation from coke dry quenching (CDQ), power generation from sintering waste heat (PGSWH) and blast furnace top gas recovery turbine unit (TRT).

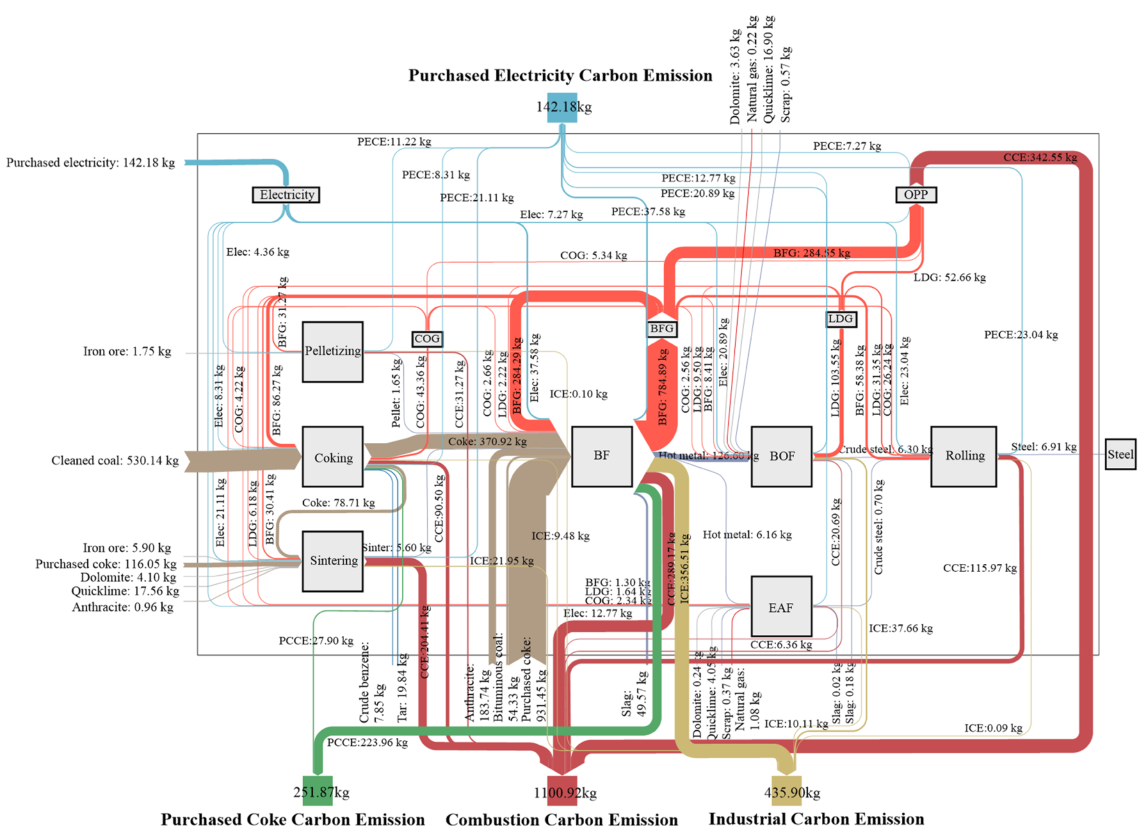
Figure 3b illustrates the carbon stream of the case company, which emits 1930.87 kg of CO_2 per ton of steel. The elemental carbon of this company enters mainly in the form of coal and coke, and upstream emissions carry another part of the implicit carbon from purchased products (such as electricity and coke). Part of this elemental carbon is consumed as fuel and reductant during the steel production process, while the other part is converted into byproduct gas and recycled in the production system. As the subsystem with the largest material and energy flow, the iron-making system emits 1333.47 kg of carbon per ton of steel, accounting for 69.06% of the total emissions. As shown in Fig. 4a, the carbon emission intensity of the blast furnace iron-making process is the highest, followed by the coking process, with process carbon emission intensity of 1004.55 and 689.29 $kgCO_2/t$ (PD), respectively. Therefore, optimisation of the iron-making system is the key to carbon emission reduction in the enterprise.

As shown in Fig. 4b, although the process carbon emission intensity of EAF in the steel-making system is significantly higher than the converter process, the carbon emission per ton of steel for the BF-BOF route is 2002.28 kg considering the upstream emission of iron in the converter. However, although the EAF route can reduce the emission by 36.86%, the carbon emission per ton of steel is still as high as 1264.30 kg because the current electric arc furnace still uses iron as the raw material for steel-making, which is more closely linked to the long process. ICE, CCE and PCCE are reduced by 171.86, 697.76 and 150.02 kg/t (CS), respectively, but because EAF gas is not recovered and the amount of gas recovered in the whole process is reduced, the enterprises' production needs to rely on purchased natural gas and electricity to supply the EAF route. PECE is increased by 281.66 kg/t (CS) instead. Therefore, compared with the traditional long process, the development of high scrap steel by enterprises has a greater value of carbon reduction than the EAF route. The results of carbon emission intensity calculations per ton of steel for iron and steel enterprises are listed in Table 5.

As shown in Fig. 5, CO_2 emissions from the steel production system are closely related to carbonaceous energy



(a)



(b)

Fig. 3 Material flow [kg], energy flow [kgce] (**a**) and carbon flow [kg] (**b**) in the steel enterprise

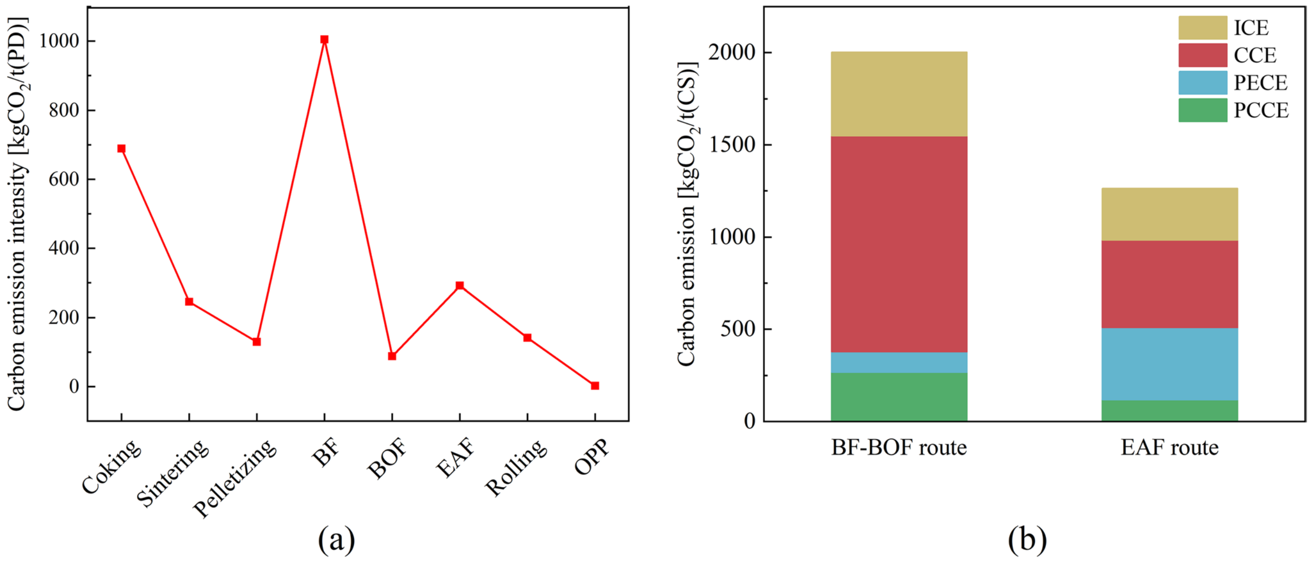


Fig. 4 Carbon emission intensity of each process (**a**) and carbon emission of the BF-BOF and EAF route (**b**)

Table 5 Carbon intensity per ton of steel for iron and steel enterprise

Item	Direct carbon emission intensity /[kgCO$_2$·t (CS)$^{-1}$]		Indirect carbon emission intensity /[kgCO$_2$·t (CS)$^{-1}$]		Carbon intensity of the total enterprise /[kgCO$_2$·t (CS)$^{-1}$]
	Intensity of ICE	Intensity of CCE	Intensity of PECE	Intensity of PCCE	
Coking	9.48	90.50	8.31	0	108.29
Sintering	21.95	204.41	21.11	27.91	275.38
Pelletising	0.10	31.27	11.22	0	42.59
BF	356.51	289.17	37.57	223.96	907.21
BOF	37.66	20.69	20.89	0	79.24
EAF	10.11	6.36	12.77	0	29.24
Rolling	0.09	115.97	23.04	0	139.10
OPP	0	342.55	7.27	0	349.82
Total	435.90	1100.92	142.18	251.87	1930.87

consumption, 1100.86 kg per ton of steel. Blast furnace gas accounts for 71.3% of the carbonaceous energy emission from CCE, mainly providing heat for combustion in the blast furnace, sintering and power plant processes. As blast furnace gas depends on the blast furnace ironmaking process and cannot be stored for a long time due to its large recovery volume, it is difficult to reduce emissions by directly substituting clean energy. Therefore, such emissions are prioritised to optimise the secondary energy network system and improve energy utilisation efficiency to achieve dynamic utilisation of carbon and non-fugitive emissions. At the same time, the carbonaceous material flow accompanying the production of products also influences the carbon emission to some extent, with 435.96 kg per ton of steel and 356.56 kg per ton of steel from the blast furnace as the centre of the carbonaceous material flow. The primary carbon source is coke; however, due to the limitation of coke as the skeleton of the blast furnace, it is difficult to completely replace coke, although it can be replaced by fuels such as pulverised coal, hydrogen, natural gas and coke oven gas. Since the gas in the electric arc furnace is not recovered, all carbon-containing gases are emitted to the environment in the form of CO_2, resulting in significantly higher carbon emission intensities in the electric arc furnace process than in the converter process. The industrial emissions caused by carbon material flow need to optimise the process structure, and adopt advanced process production technology while gradually increasing the electric arc furnace capacity. Therefore, the low carbonisation of the electric power system also impacts carbon emission reduction in steel enterprises. However, relying on intermediate products such as purchased coke does not bring actual emission

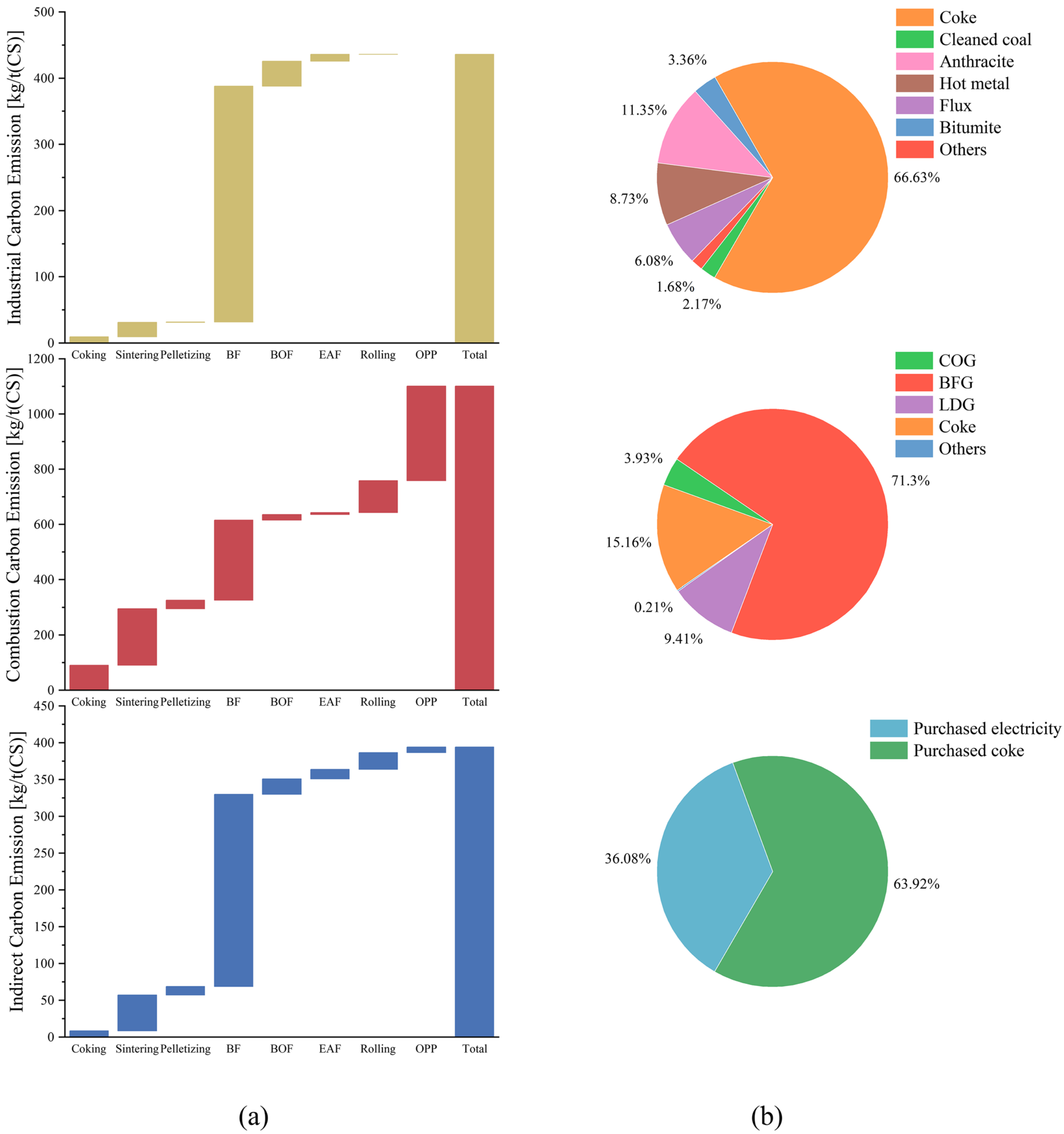


Fig. 5 CO_2 emission structure of different processes (**a**) and various CO_2 emission types (**b**)

reduction benefits for society. It should be improved from the efficiency of secondary energy recovery and utilisation in the enterprise, strengthening the waste heat and energy.

In summary, for the iron and steel enterprise, the focus should be on the impact of material and energy flows in the enterprise on carbon emissions. Priority should be given to optimising production technology, energy structure and adopting cleaner energy sources to reduce molten iron ore, reducing the consumption of carbon fuels such as coking coal and coke. Equally, short-flow steel production processes need to be developed, strengthening the use of internal resources such as byproduct gas and waste heat and energy and reducing the indirect emissions of purchased intermediate products to support the development of low-carbon transformation the steel enterprise.

Discussion

Impact of using scrap

As the only steel-making raw material for the low-carbon transition of steel production, many studies have shown that increasing the scrap utilisation rate in integrated steel-making is a simple and quick measure to reduce carbon emissions in integrated plants (Wang et al. 2022a; Zhang et al. 2019). China has also proposed in the Steel Industry Adjustment Policy and the 14th Five-Year Development Plan for the Scrap Steel Industry that the integrated scrap ratio in Chinese steel-making should reach 30% by 2025 (Wang et al. 2022c). Unfortunately, the availability of scrap and the limitations of high-quality steel grades do not allow a shift to an exclusively scrap-based steel-making process. Therefore, virgin materials such as iron ore will remain dominant in the long run. Kuramochi (2016) also pointed out that increasing the utilisation of scrap in the converter is more cost-effective than developing electric arc furnace steel-making to reduce carbon emissions. Since scrap melting in the converter depends mainly on the heat of the hot iron, the amount of scrap used in the converter is limited. Generally, between 10 and 30% scrap can be added to the converter without adding additional fuel consumption, which can also be increased up to 40% by measures such as adding fuel (Yue et al. 2022; Sun et al. 2020). In contrast, with an increasing scrap ratio in the electric arc furnace steel-making process, the heat supply for the physical and chemical reactions in the furnace is insufficient, and the electrode power supply increases while the energy use efficiency changes (Yang et al. 2017). Therefore, the actual operating status of Chinese steel enterprises infers the upper scrap ratio limit of the converter is 20%, which can smelt all the scrap in the converter, with the remaining scrap smelted entirely in the electric arc furnace.

As shown in Fig. 6a, the carbon emissions of steel enterprises are closely related to the amount of iron produced. When the scrap ratio increases from 0 to 1, the demand for iron is reduced by 298.99 kg/t (CS), and all the emissions from pre-iron processes such as coking, sintering and pellet are proportionally reduced. The total CO_2 emissions of steel enterprises are reduced from 2215.94 to 1688.26 $kgCO_2$/t (CS), with a total emission reduction of 527.68 $kgCO_2$/t (CS). Figure 6b shows the changes in various types of carbon emissions. Among them, combustion emissions have the most considerable emission reduction of 340.21 $kgCO_2$/t (CS), and industrial emissions have the largest reduction rate of 30.43%. Among indirect emissions, indirect emissions from purchased coke decreased by 83.38 $kgCO_2$/t (CS). Indirect emissions from purchased electricity increased by 53.03 $kgCO_2$/t (CS) due to the decrease in the amount of byproduct gas and waste energy recovery, as well as the increase in electricity consumption of electric furnaces and the lack of self-generation by enterprises. Notably, when the scrap ratio is larger than 0.2, the trend of carbon emission reduction slows significantly due to the limitation of the converter scrap ratio and electric arc furnace capacity. The industrial emissions will increase by 6.48 $kgCO_2$/t (CS) and then gradually decrease, because the increase of direct emissions, such as scrap preheating and melt decomposition in electric furnace steel-making, leads to a rise in steel-making process emissions. Therefore, the blind use of low scrap does not necessarily reduce emissions compared to

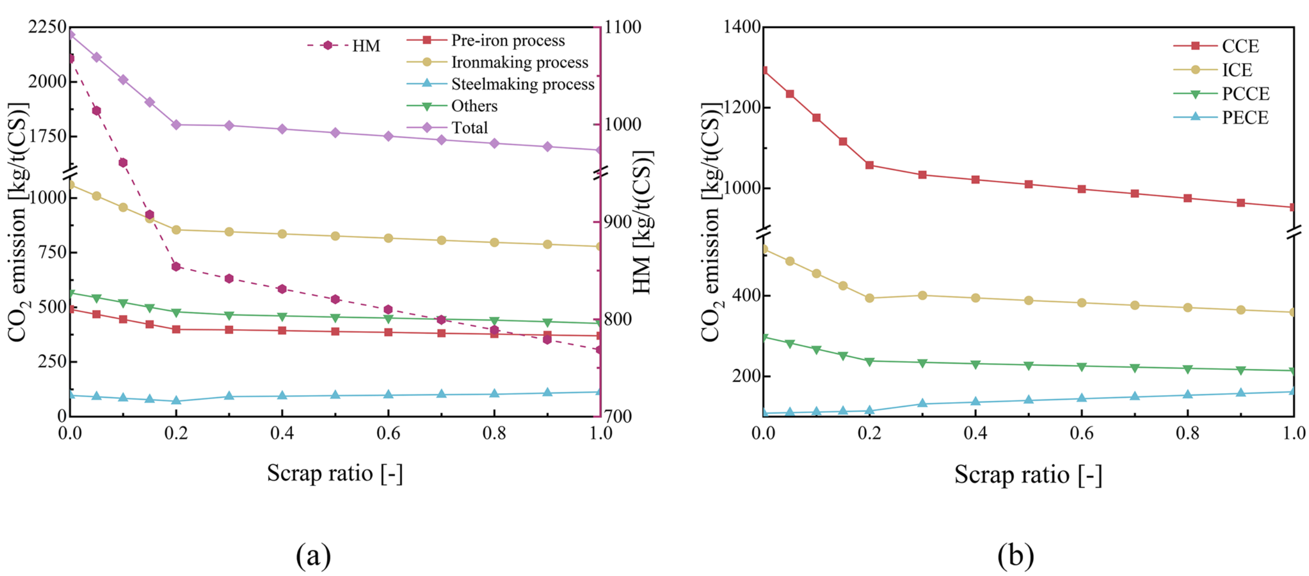


Fig. 6 Impact of the scrap ratio on CO_2 emission from different processes (**a**) and various types (**b**) in the steel enterprise

electric furnace steel-making, and steel companies should further increase the proportion of existing converter scrap.

It can be seen that improving the scrap ratio can directly control the emissions of pre-iron and blast furnace processes, which can effectively reduce the carbon dioxide emissions per ton of steel. Therefore, for enterprises with a low scrap ratio in the converter, it is still the focus of carbon emission reduction to continue to improve the scrap ratio in converter smelting. For enterprises whose converter scrap ratio has reached the advanced level in the industry, the development of an all-scrap electric arc furnace steel-making process can further achieve the emission reduction target.

Impact of increasing the proportion of the short process

The carbon emission per ton of steel will be significantly reduced for the EAF short process compared to the BF-BOF long process. Considering that the electric arc furnace usually also uses part of the iron as raw material, the boundary between the long and short processes is challenging to distinguish completely. The short process for smelting can be divided into electric furnace smelting scrap and non-blast furnace iron-making short processes. As shown in Fig. 7, China's crude steel production in 2021 is 1032.8 Mt, accounting for 53% of the world's crude steel production. However, only 10.6% of the steel is produced via an electric furnace in China, far below the world average. Among other major steel-producing countries, the USA and India have the largest share, reaching 69.2% and 55.2%, respectively (WSA 2022). Li et al. (2023) established a scenario of 20% of electric furnace steel production in 2025, and the scrap demand will reach 380 Mt in 2030, according to the World Steel Association. China's scrap resources can reach 400 Mt by 2030 and 500 to 600 Mt by 2050 (WSA 2021), providing resources to support the large-scale implementation of the electric furnace short process. China's Ministry of Industry and Information Technology, Development and Reform Commission and Ministry of Ecology and Environment also clearly put forward the target that the proportion of electric furnace steel production should not be less than 30% during the 14th Five-Year Plan period, which provides policy support for the promotion of the electric furnace short process.

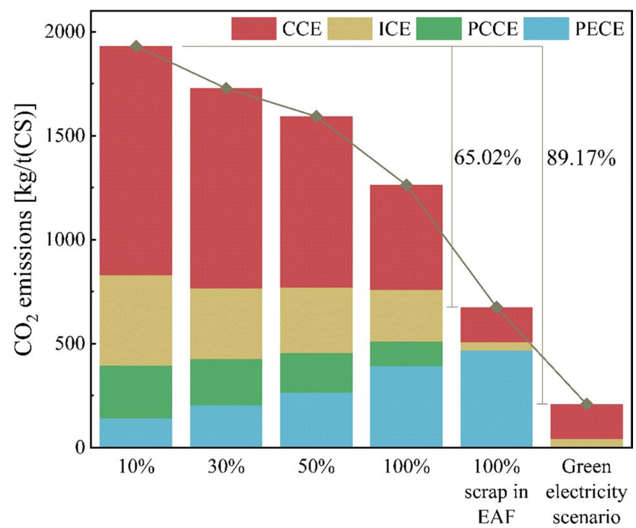


Fig. 8 Impact of the proportion of the electric furnace steel on CO_2 emission in the steel enterprise

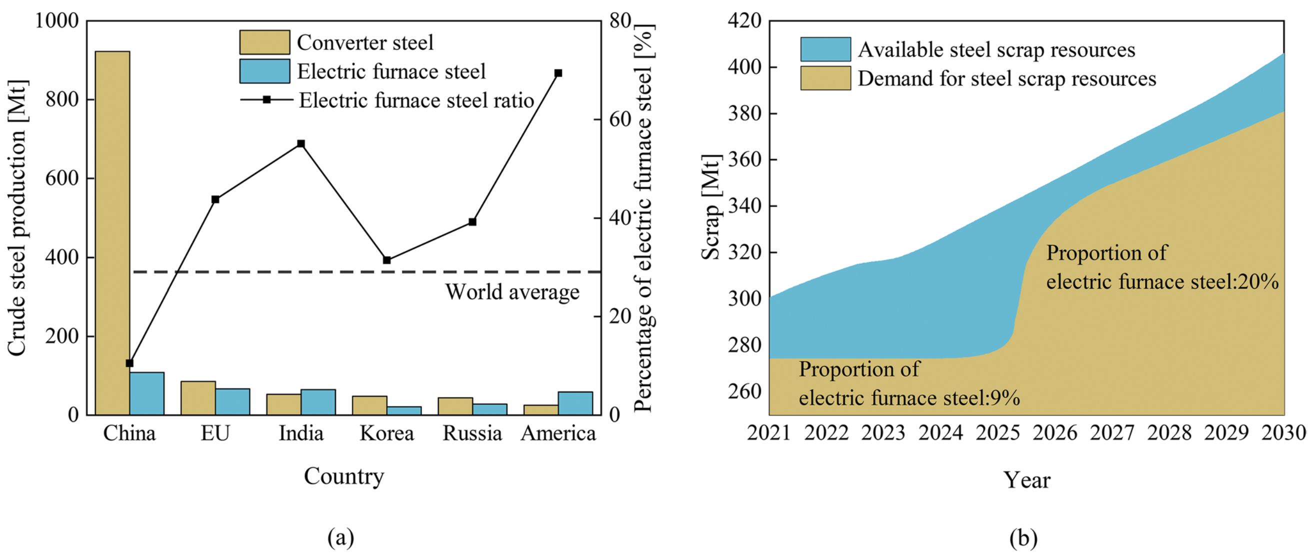


Fig. 7 Steel production and proportion of the converter steel and electric furnace steel in the world's leading steel-producing countries in 2021 (**a**), and development of the availability and demand for scrap resources in China's steel industry (**b**)

The proportion of electric furnace steel production of the enterprise, in this case, is only 10%, which has a limited impact on the carbon emission of the enterprise. For optimising the production process structure, increasing the proportion of electric furnace steel is the key to reducing carbon emissions. For further analysis, this paper establishes three scenarios with 30%, 50% and 100% of electric furnace steel, respectively, and develops an all-scrap smelting scenario based on a 100% share.

As shown in Fig. 8, increasing the proportion of electric furnace steel production breaks through the carbon emission reduction limit of the original production process of the enterprise. Consequently, combustion, process and indirect emissions of the process related to iron-making are further reduced. If the proportion of electric furnace steel is increased to 30% without any process transformations, the carbon emission reduction of the whole process can be achieved at 203.44kg, a reduction of 10.54%. If all-electric furnace steel-making is enabled, the emission reduction can be 667.97kg, a reduction of 34.59%. Notably, the reduction of combustion emissions is lower than the process emissions at first because the amount of recovered gas cannot meet the demand of the enterprise's production, resulting in the need to use cleaner natural gas to supplement. At the same time, when the proportion of electric furnace scrap increases to 100%, the enterprise will not be involved in ironmaking-related processes, and the carbon emissions per ton of steel can be reduced to 675.49kg, achieving 89.17% carbon reduction in the whole process. Therefore, regarding the future carbon tax policy, the steel industry can effectively reduce carbon emissions and improve profitability by increasing the proportion of electric furnace steel production while increasing the input use of scrap, improving gas utilisation efficiency and using cleaner fuel substitution.

When the full scrap electric arc furnace short process smelting, the enterprise tons of steel power indirectly emit 466.36kg/t (CS), accounting for 69.04% of the total emissions. Therefore, the future development of electric furnace short-process smelting cannot be separated from a large amount of electricity as energy support, although the current waste heat and waste energy recovery technology, including blast furnace slag sensible heat recovery, TRT waste pressure power generation, CDQ, sinter ore sensible heat recovery and other technologies and distributed photovoltaic power generation resources, are widely used. However, the gradual reduction in the proportion of long processes eventually leads to enterprise self-generation, which is challenging to meet the development needs, and the connection with the power industry will be closer. Green power, such as photovoltaic, wind power, nuclear power and biomass power generation, will achieve the carbon emission reduction target on energy supply for long-process steel enterprises in the near and medium term and short-process steel enterprises in the long term (Elsheikh and Eveloy 2022). At the same time, because the electric arc furnace electricity demand changes rapidly and the electricity consumption is also larger, increased renewable resources such as photovoltaic and wind power will cause increased uncertainty. The enterprises need to incorporate developments in power supply systems involving wind and scenery complementary power generation systems and energy storage systems for regulation, which can result in lower-cost green electricity while ensuring the smooth production of electric arc furnaces.

Impact of the purchased coke and byproduct gas utilisation

In addition to purchasing electricity, iron and steel, enterprises usually purchase intermediate smelting products, such as pellet ore and coke, to supplement their production capacity. As coke is an essential energy source for the iron-making process, and the coking process is the second most carbon-intensive process after blast furnace iron-making, enterprises prefer to purchase coke through independent coking enterprises. Independent coking enterprises have an advantage in waste energy recovery, and their coking process is less carbon-intensive than the steel co-production process. However, from the community perspective, the increased proportion of purchased coke in the steel industry cannot effectively mitigate carbon emissions. Therefore, considering the indirect emissions caused by purchased coke, the influence factors which purchased coke shares with different types of carbon emissions of enterprises are determined by taking the case enterprise as an example.

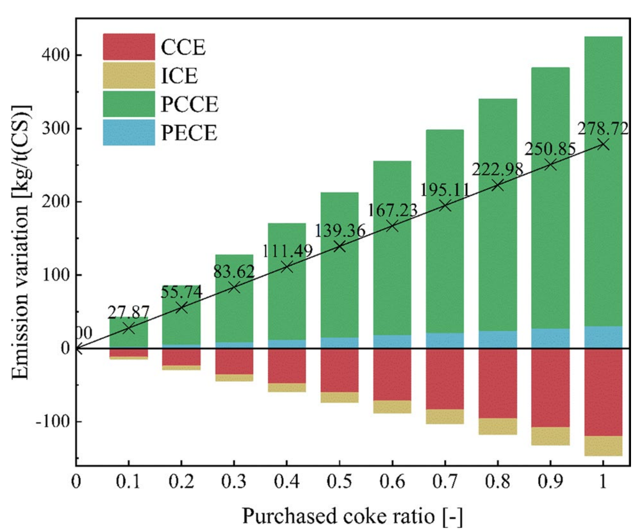


Fig. 9 Impact of the proportion of purchased coke on CO_2 emissions in the steel enterprise

As shown in Fig. 9, when the purchased coke increases from 0 to 435.1 kg/t (CS), the direct carbon emission intensity of the enterprise is further reduced by 120.09 and 26.25 kg/t (CS) of combustion emission and process emission, respectively. This reduction is due to the reduced coke production in the coking process, and the corresponding reduction of recovered coke oven gas supplied to combustion for power generation. The decreased recovered steam and self-generated electricity in the coking process increased purchased electricity emissions by 30.86 kg/t (CS). In addition, purchased coke emissions increased by 394.2 kg/t (CS), and carbon emissions per ton of steel increased from 1752.73 to 2031.45 kg/t (CS), for a total increase of 278.72 kg/t (CS).

Therefore, with specific crude steel productions, the direct carbon emissions can be reduced by increasing purchased coke. Still, the increase in indirect emissions of purchased electricity and coke leads to the existing situation that enterprises cannot reduce the emissions per ton of steel by purchasing coke alone. Suppose the independent coking enterprises further optimise their energy structure, production methods and waste energy recovery and utilisation so that the indirect emission factor of the coke can be lower than 0.265 kgCO_2/kg (Coke). In that case, the purchased coke can alleviate the carbon emission problem of enterprises. However, the cost of purchased coke is usually higher than self-produced coke. To achieve green and low-cost iron making, enterprises should reasonably determine the amount of purchased coke, optimise the supporting coking process, including dry coke quenching and coal wetting technologies, and focus on reducing the blast furnace coke ratio.

It is worth noting that byproduct gas is less efficient than natural gas or power coal when used for power and heat generation. While developing low-carbon steel and iron, full use of hydrogen-rich and CO-rich high-value gas resources should be made while actively promoting the preparation of liquefied natural gas from coke oven gas, synthetic methanol and blast furnace blowing byproduct gas and methane reforming to produce hydrogen. As the responsibility for carbon emission of the remaining byproduct gas should be attributed to the steel enterprises, the development of a symbiotic system in the steel industry is the main focus of the low-carbon development of enterprises. Purification technologies with high adsorption selectivity and good adsorption–desorption reversibility, such as pressure swing adsorption (PSA) technology, make it technically possible to recover coke oven gas that can be extracted as a high-purity hydrogen resource and desorption gas that can be used as an alternative fuel gas (Van Acht et al. 2020). Meanwhile, the process route of coke oven gas injection is well established and reliable, and 39% carbon reduction can be achieved by blast furnace injection of COG and recovery of top gas (Li et al. 2022; Rahmatmand et al. 2023). Additionally, hydrogen can be mixed with CO_2 and CO from blast furnace gas treated by a denitrification unit to synthesise methanol and increase corporate carbon emission offsets (Xu et al. 2022). A scenario involving coke oven gas and blast furnace gas synthesis process for methanol is designed for the case company to achieve high-value utilisation of byproduct gas. It is assumed that the alternative fuel gases in the process include PSA desorption gas, methanol plant purge gas and purchased natural gas, all of which can be used as auxiliary production fuels and feedstock for self-propelled plants. The relevant process parameters and the main gas components are shown in Tables 6 and 7.

As shown in Fig. 10, the synthetic methanol scenario reduces the direct combustion gas emissions, realises the chemical fixation of carbon and high-value utilisation of gas resources and reduces the combustion emissions and process emissions by 9.87 and 19.84 kg/t (CS), respectively. However, due to increased hydrogen production units, BFG purification units and methanol synthesis, and the decrease of power generation in power plants, the increase in purchased power consumption of enterprises leads to a rise in purchased power emissions by 23.79 kg/t (CS). Overall, the total emission reduction is 5.92

Table 6 Synthetic methanol process parameter (Chen et al. 2018)

	COG [m^3]	BFG [m^3]	Electricity [kWh]	Methanol [kg]	Desorption gas [m^3]	Purge gas [m^3]
Input	66.1	30.96	17.88	–	–	–
Output	–	–	–	14.43	35.37	12.11

Table 7 Data related to case enterprise gas

Gas type	COG	BFG	LDG	Desorption gas	Purge gas
CO content [%]	6.6	27	58.9	12.32	7.12
CO_2 content [%]	2.9	11	20	5.41	16.11
Lower heating value [kJ/m^3]	17,240	3775	7560	22,820	9504
Carbon emission factor [kgCO_2/m^3]	0.656	0.538	1.157	1.225	0.210

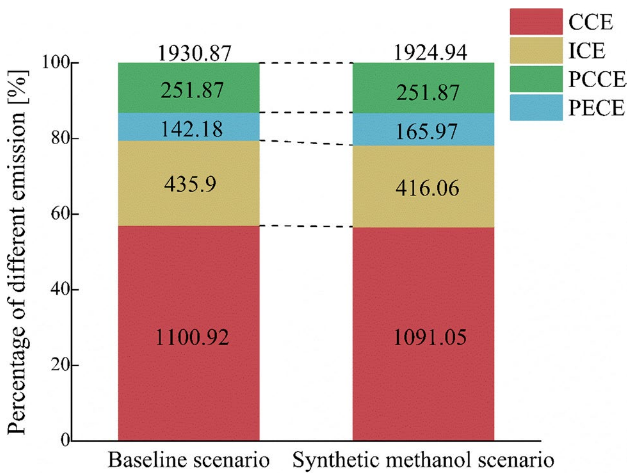


Fig. 10 Impact of the methane synthesis from byproduct gas on CO_2 emissions in the steel enterprise

kg/t (CS). Therefore, considering the current dilemma of high carbon emissions, high energy consumption and low profitability in China's steel industry, the utilisation of process hydrogen resources should be strengthened. The symbiotic relationship between the steel and chemical industries should be vigorously developed to realise the high-value utilisation of resources and increased carbon emission credits.

Conclusions and policy implications

Conclusions

This paper aims to construct a complete carbon emission calculation model through an in-depth analysis of the carbon emission mechanism in typical steel production processes and by combining the carbon accounting methods of different countries and organisations. The model is based on the effects of material and energy flows and divides carbon emissions into two categories: industrial emissions caused by carbonaceous material flows and combustion emissions caused by carbonaceous energy flows. This paper also considers the indirect emissions caused by the intermediate products purchased by enterprises during the production process, including the purchased electricity and coke emissions. Different carbon emission influencing factors are explored based on the carbon matter flow analysis method, providing favourable support for enterprises to develop targeted low-carbon development routes.

A typical steel enterprise is selected as a case study for analysis, with a total carbon emission of 1930.87 kg/t (CS). CCE is the largest, accounting for 57% of the total emissions, at 1100.86 kg/t (CS), and primarily caused by blast furnace gas, accounting for 71.3% of the CCE. Next is ICE, accounting for 22.6% of the total emissions, at 435.96 kg/t (CS), mainly caused by coke, accounting for 66.3% of the ICE emission. PECE and PCCE account for 7.4% and 13% of the total emissions, or 142.18 kg/t (CS) and 251.87 kg/t (CS), respectively. Therefore, optimisation of the iron-making system is critical for reducing carbon emissions, which account for 69.06% of the total emissions. Notably, blast furnace gas, coke and purchased coke are the key factors affecting CO_2 emissions. Among these factors, coke is a reductant and blast furnace skeleton, providing heat as carbonaceous energy and participating in the iron production process as a carbonaceous material.

The effects of scrap steel use, the share of electric furnace steel production, green electricity, purchased coke and byproduct gas utilisation on CO_2 emissions are considered for various emission types. Increasing the scrap utilisation rate of integrated steel-making can effectively reduce carbon emissions, and when the scrap ratio increases from 0 to 1, the reduction rate of ICE reaches 30.43%, and the combined emissions of enterprises are reduced by 527.68 kgCO_2/t (CS). Compared with the blind use of low scrap ratio electric furnace steel-making, increasing the current converter scrap ratio has more potential to reduce emissions. Increasing the electric furnace steel production ratio can break the carbon emission reduction limit of the enterprises' original production process. Emissions can reduce 667.97 kgCO_2/t (CS) if all-electric furnace steel-making becomes possible. Using an all-scrap electric furnace can reduce carbon emissions by 89.17% of the whole process. At the same time, during an all-scrap electric arc furnace short smelting process, the enterprises' tons of steel power indirect emissions will account for 69.04% of the total emissions. Green electricity has become the key to reducing emissions, but it also highlights the high requirements for the power supply system of steel enterprises. Although enterprises can develop means of outsourcing coke to avoid the direct carbon emission of 146.34 kg/t (CS) in the plant, the indirect emission of outsourced coke and the production cost of enterprises should be considered. Enterprises should reasonably choose the amount of outsourcing and fully use the process' high-value resources to develop a symbiotic steel and chemical industry alliance to maximise the green economic development of steel enterprises.

The system boundary delineated in this study does not fully encompass the entire life cycle of iron and steel. Factors such as the raw material extraction process and the demand for iron and steel products also influence the path towards achieving carbon neutrality in the iron and steel industry. Thus, extending the boundary to thoroughly examine the impacts across the full industrial chain of the iron and steel industry could be a promising direction for future research. Simultaneously, it should be noted that this study employs default values for some carbon emission factors, which could potentially affect the precision of the calculation results and introduces certain limitations. Consequently, establishing a localised baseline database for the industry is currently a research priority.

Policy implications

Drawing from the analysis and discussion of the results, the study proposes the following recommendations:

(1) Enhancing energy efficiency and accelerating the development of an integrated energy system optimisation and management system for comprehensive steel production. The findings of this research indicate the primary source of carbon emissions in iron and steel production stems from the combustion of fossil fuels. To decrease reliance on external fossil fuels, it is essential to further augment the energy efficiency of the process, explore the potential of waste heat and residual energy and strive for regional energy self-sufficiency. This can reduce external procurement while simultaneously improving the optimal scheduling of energy mediums. It also necessitates the forecasting and analysis of energy mediums, predominantly composed of gas, steam and electrical power, as well as the complementary use of new energy resources like wind and solar power. Consequently, the company has established an integrated energy system for the entire iron and steel production process. Regarding policy support, it is urgent to establish an energy efficiency monitoring and reporting system. Enterprises that are utilising advanced technologies should be appropriately rewarded to incentivise iron and steel companies to invest in energy efficiency enhancement technologies and equipment. This will facilitate an energy efficiency upgrade in the iron and steel industry, leading to a reduction in energy consumption and carbon emissions.

(2) Swiftly advancing process optimisation along with the application and development of groundbreaking low-carbon technologies is crucial. For the steel industry, while the proportion of industrial production process emissions is less than that of combustion emissions, reducing this type of emissions is the determining factor for the steel industry to genuinely achieve carbon neutrality. In the short term, increasing the proportion of short processes that rely on electric arc furnaces for steel scrap proves to be effective. In the long term, the development of hydrometallurgical processes and carbon capture, utilisation and storage, such as hydrogen-based blast furnaces and shaft furnaces, is key to attaining carbon neutrality. Concurrently, external constraints should be intensified to encourage the growth of green and low-carbon enterprises. The steel industry should also be integrated into the carbon trading market system as soon as feasible, in order to drive the reduction of the industry's carbon emission intensity through market forces.

(3) Research on carbon emissions in the iron and steel industry necessitates the backing of fundamental databases, and the acceleration of the construction of localised databases in China. Currently, domestic basic data is insufficient, predominantly relying on mature foreign databases. We should proactively engage in the development of localised databases, and encourage enterprises to perform monitoring and assessment of carbon footprint related indicators. This will facilitate the accumulation of foundational data and help build a set of carbon emission coefficients for Chinese iron and steel products with regional characteristics. Furthermore, in the context of carbon tariffs, it is imperative to thoroughly investigate life cycle carbon emission data. This will allow us to utilise its evaluative and guiding role, actively establish a product carbon labeling system, enhance enterprises' awareness of low-carbon competition and prevent the weakening of the price advantage of exported goods. This, in turn, will counteract the decrease in China's international competitiveness in commodities.

Author contribution Yueqing Gu: conceptualisation; writing—original draft; writing—review and editing; formal analysis. Chongchao Pan: supervision; conceptualisation; formal analysis; writing—original draft; writing—review and editing; visualisation. Yunren Sui: writing—original draft; visualisation. Bowen Wang: writing—original draft; visualisation. Cunhai Wang: writing—original draft; visualisation. Zeyi Jiang: investigation, writing—original draft. Yusong Liu: investigation; writing—original draft; visualisation.

Funding This paper is supported by the Ministry of Industry and Information Technology Public Service Platform Project for Industrial Technology Foundation in 2021, No. 2021-H029-1-1, and the Science and Technology Project of State Grid Corporation of China, No. SGTYHT/21-JS-223.

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

Declarations

Ethical approval Not applicable.

Consent to publish Not applicable.

Consent to participate Not applicable.

Competing interests The authors declare no competing interests.

References

Chen QQ, Gu Y, Tang ZY, Wei W, Sun YH (2018) Assessment of low-carbon iron and steel production with CO_2 recycling and utilization technologies: a case study in China. Appl Energy 220:192–207. https://doi.org/10.1016/j.apenergy.2018.03.043

Chen DM, Li JQ, Wang Z, Lu B, Chen G (2022) Hierarchical model to find the path reducing CO_2 emissions of integrated iron and steel production. Energy (Oxf). 258. https://doi.org/10.1016/j.energy.2022.124887

Duan HY, Hou CH, Yang W, Song JN (2022) Towards lower CO_2 emissions in iron and steel production: life cycle energy demand-LEAP based multi-stage and multi-technique simulation. Sustain Prod Consum 32:270–281. https://doi.org/10.1016/j.spc.2022.04.028

Elsheikh H, Eveloy V (2022) Assessment of variable solar- and grid electricity-driven power-to-hydrogen integration with direct iron ore reduction for low-carbon steel making. Fuel (Lond) 324. https://doi.org/10.1016/j.fuel.2022.124758

Feng C, Zhu R, Wei GS, Dong K, Dong JF (2022) Typical case of carbon capture and utilization in Chinese iron and steel enterprises: CO_2 emission analysis. J Clean Prod 363. https://doi.org/10.1016/j.jclepro.2022.132528

IPCC (2006) Guidelines for national greenhouse gas inventories. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/. Accessed 22 March 2023

ISO (2006) Life cycle assessment principles and framework. https://www.iso.org/standard/37456.html/. Accessed 19 March 2023

Jia X, Zhang Y, Tan RR, Li Z, Wang S, Wang F, Fang K (2022) Multi-objective energy planning for China's dual carbon goals. Sustain Prod Consum 34:552–564. https://doi.org/10.1016/j.spc.2022.10.009

Kuramochi T (2016) Assessment of midterm CO_2 emissions reduction potential in the iron and steel industry: a case of Japan. J Clean Prod 132:81–97. https://doi.org/10.1016/j.jclepro.2015.02.055

Li ZY, Qi Z, Wang ZX, Zhang LC, Liang D, Dong Q (2022) Numerical investigation of coke oven gas (COG) injection into an ironmaking blast furnace (BF). Int J Hydrogen Energy 47:31109–31128. https://doi.org/10.1016/j.ijhydene.2022.07.036

Li ZX, Andersson F, Nilsson LJ, Ahman M (2023) Steel decarbonization in China - a top-down optimization model for exploring the first steps. J Clean Prod 384. https://doi.org/10.1016/j.jclepro.2022.135550

Liu Z, Sun TC, Yu Y, Ke PY, Deng Z, Lu CX, Huo D, Ding X (2022) Near-real-time carbon emission accounting technology toward carbon neutrality. Engineering 14:44–51. https://doi.org/10.1016/j.eng.2021.12.0192095-8099

National Development and Reform Commission (2013) Greenhouse gas emission accounting methods and reporting guidelines for Chinese steel production enterprises (Trial). https://www.cets.org.cn/bzgf/5956.jhtml. Accessed 22 Sept 2023

Pan CC, Wang BW, Hou XW, Gu YQ, Xing Y, Liu YS, Wen W, Fang J (2022) Carbon peak path of the Chinese iron and steel industry based on the LMDI−STIRPAT model. Chinese J Eng Des 45:1–14. https://doi.org/10.13374/j.issn2095-9389.2022.04.25.002

Rahmatmand B, Tahmasebi A, Lomas H, Honeyands T, Koshy P, Hockings K, Jayasekara A (2023) A technical review on coke rate and quality in low-carbon blast furnace ironmaking. Fuel (Lond) 336. https://doi.org/10.1016/j.fuel.2022.127077

Ren L, Zhou S, Peng TD, Ou XM (2021) A review of CO_2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China. Renew Sustain Energy Rev 143. https://doi.org/10.1016/j.rser.2021.110846

Ren L, Zhou S, Ou XM (2023) The carbon reduction potential of hydrogen in the low carbon transition of the iron and steel industry: The case of China. Renew Sustain Energy Rev 171. https://doi.org/10.1016/j.rser.2022.113026

Shao T, Pan X, Li X, Zhou S, Zhang S, Chen W (2022) China's industrial decarbonization in the context of carbon neutrality: a sub-sectoral analysis based on integrated modelling. Renew Sustain Energy Rev 170:112992. https://doi.org/10.1016/j.rser.2022.112992

Standardization Administration (2015) Requirements of the greenhouse gas emission accounting and reporting-part 5: Iron and steel production enterprise: GB/T 32151.5-2015. https://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=C3237A45CDE613A6F008F81498A4C328/. Accessed 22 March 2023

Standardization Administration (2017) Guides for energy efficiency assessment of blast furnace pr-ocess: GB/T 34193–2017. https://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=99B2EC0FB6DC9099D2B5155A945CC45A. Accessed 19 March 2023

Sun WQ, Wang Q, Zhou Y, Wu JZ (2020) Material and energy flows of the iron and steel indust-ry: status quo, challenges and perspectives. Appl Energy 268. https://doi.org/10.1016/j.apenergy.2020.114946

Tan XC, Li H, Guo JX, Gu BH, Zeng Y (2019) Energy-saving and emission-reduction technology selection and CO_2 emission reduction potential of China's iron and steel industry under energy substitution policy. J Clean Prod 222:823–834. https://doi.org/10.1016/j.jclepro.2019.03.133

Tian WJ, An HF, Li XJ, Li H, Quan K, Lu X, Bai H (2022) CO_2 accounting model and carbon reduction analysis of iron and steel plants based on intra- and inter-process carbon metabolism. J Clean Prod 360. https://doi.org/10.1016/j.jclepro.2022.132190

Tong Y, Wang K, Liu J, Zhang Y, Gao J, Dan M, Yue T, Zuo P, Zhao Z (2023) Refined assessment and decomposition analysis of carbon emissions in high-energy intensive industrial sectors in China. Sci Total Environ 872. https://doi.org/10.1016/j.scitotenv.2023.162161

Van Acht S, Laycock C, Carr S, Maddy J, Guwy AJ, Lloyd G, Raymakers L (2020) Simulation of integrated novel PSA/EHP/C process for high-pressure hydrogen recovery from Coke Oven Gas. Int J Hydrogen Energy 45:15196–15212. https://doi.org/10.1016/j.ijhydene.2020.03.211

Wang DZ, Bao YP, Gao F, Xing LD (2022a) Effect of converter scrap ratio on carbon emission in BF-LD process. J Sustain Metall 8:1975–1987. https://doi.org/10.1007/s40831-022-00620-x

Wang XL, Zhang TY, Nathwani J, Yang FM, Shao QL (2022b) Environmental regulation, technology innovation, and low carbon development: revisiting the EKC Hypothesis, Porter Hypothesis, and Jevons' Paradox in China's iron & steel industry. Technol Forecast Soc Change 176. https://doi.org/10.1016/j.techfore.2022.121471

Wang XY, Yu BY, An RY, Sun FH, Xu S (2022c) An integrated analysis of China's iron and steel industry towards carbon neutrality. Appl Energy 322. https://doi.org/10.1016/j.apenergy.2022.119453

WRI, WBCSD (2008) Sector toolsets: iron and steel. http://www.ghgprotocol.org/calculation-tools/iron-and-steel-sector/. Accessed 19 March 2023

WSA (2021) Climate change and the production of iron and steel 2021. https://worldsteel.org/publications/policy-papers/climate-change-and-the-production-of-iron-and-steel/. Accessed 19 March 2023

WSA (2022) World steel in figures 2022. https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/. Accessed 19 March 2023

WSA (2023) CO_2 Emissions data collection user guide, version 11. https://worldsteel.org/steel-topics/environment-and-climate-change/climate-action/climate-action-data-collection/. Accessed 19 March 2023

Xu WQ, Wan B, Zhu TY, Shao MP (2016) CO_2 emissions from China's iron and steel industry. J Clean Prod 139:1504–1511. https://doi.org/10.1016/j.jclepro.2016.08.107

Xu YP, Liu RH, Shen MZ, Lv ZA, Chupradit S, Metwally A, Sillanpaa M, Qian Q (2022) Assessment of methanol and electricity co-production plants based on coke oven gas and blast furnace gas utilization. Sustain Prod Consum 32:318–329. https://doi.org/10.1016/j.spc.2022.05.005

Yang LZ, Jiang T, Li GH, Guo YF (2017) Discussion of carbon emissions for charging hot metal in EAF steelmaking process. High Temp Mater Process 36:615–621. https://doi.org/10.1515/htmp-2015-0292

Yang Y, Xu WQ, Wang Y, Shen JR, Wang YX, Geng ZB, Wang Q, Zhu TY (2022) Progress of CCUS technology in the iron and steel industry and the suggestion of the integrated application schemes for China. Chem Eng J 450. https://doi.org/10.1016/j.cej.2022.138438

Yu X, Tan C (2022) China's pathway to carbon neutrality for the iron and steel industry. Glob Environ Change 76. https://doi.org/10.1016/j.gloenvcha.2022.102574

Yuan Y, Na H, Du T, Qiu Z, Sun J, Yan T, Che Z (2023) Multi-objective optimization and analysis of material and energy flows in a typical steel plant. Energy (Oxf) 263:125874. https://doi.org/10.1016/j.energy.2022.125874

Yue Q, Chai XC, Zhang YJ, Wang Q, Wang HM, Zhao F, Ji W, Lu YQ (2022) Analysis of iron and steel production paths on the energy demand and carbon emission in China's iron and steel industry. Environ Dev Sustain. https://doi.org/10.1007/s10668-022-02234-5

Zhang Q, Li Y, Xu J, Jia GY (2018) Carbon element flow analysis and CO_2 emission reduction in iron and steel works. J Clean Prod 172:709–723. https://doi.org/10.1016/j.jclepro.2017.10.211

Zhang Q, Wei ZQ, Ma JL, Qiu ZY, Du T (2019) Optimization of energy use with CO_2 emission reducing in an integrated iron and steel plant. Appl Therm Eng 157. https://doi.org/10.1016/j.applthermaleng.2019.04.045

Zhang HX, Sun WQ, Li WD, Ma GY (2022) A carbon flow tracing and carbon accounting method for exploring CO_2 emissions of the iron and steel industry: an integrated material-energy-carbon hub. Appl Energy 309. https://doi.org/10.1016/j.apenergy.2021.118485

Zhang S, Yi B, Guo F, Zhu P (2022) Exploring selected pathways to low and zero CO2 emissions in China ' s iron and steel industry and their impacts on resources and energy. J Clean Prod 340. https://doi.org/10.1016/j.jclepro.2022.130813

Zhang JS, Shen JL, Xu LS, Zhang Q (2023) The CO_2 emission reduction path towards carbon ne-utrality in the Chinese steel industry: a review. Environ Impact Assess Rev 99. https://doi.org/10.1016/j.eiar.2022.107017

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.