*Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-19*
DOI: *10.15244/pjoes/236147* ONLINE PUBLICATION DATE: 2026-11-06

*Original Research*

# Investigating a Two-Dimensional Carbon Cost Control Method Based on "Carbon Flow–Value Flow"

**Dawei Wu[1, 2], Caiping Zhang[2, 4]*, Qingliang Tang[3], Lei Zhang[3], Fengshihao Wang[1, 2]**

[1]School of Resources, Environment and Safety Engineering, University of South China, Hengyang 421200, P. R. China
[2]Institute for Carbon Neutrality and Nuclear Energy Development Innovation, University of South China, Hengyang 421200, P. R. China
[3]School of Business, Western Sydney University, Sydney 2199, Australia
[4]School of Economics, Management and Law, University of South China, Hengyang 421200, P. R. China

*Received: 08 May 2026*
*Accepted: 07 September 2026*

## Abstract

Achieving carbon peaking and carbon neutrality requires coordinated action across macro, meso, and micro levels. For Chinese firms, reducing carbon emissions and controlling carbon costs are important challenges. Using Nanjing Iron and Steel Co., Ltd. (NJ Steel) as a case, this study proposes a two-dimensional "carbon flow–value flow" cost control method that traces carbon-containing material and energy inputs, transformation, and emissions through steel production, maps these flows to internal resource transfer costs and external environmental damage costs, and identifies process-level control points and optimization measures. Carbon flow analysis indicated that coking, ironmaking, and steelmaking are high-emission processes. Value flow analysis showed that these processes also incur high carbon costs and are therefore key control points. Within the process-level quantitative boundary and simulated optimization scenarios, internal resource transfer costs and external environmental damage costs were RMB 1,176 million and RMB 1,442 million lower than baseline, respectively. After accounting for technical retrofit investment and key parameter uncertainty, carbon cost reductions ranged from approximately RMB 1,879 million to RMB 3,941 million across the sensitivity scenarios. The findings provide practical guidance for enterprises seeking to strengthen carbon emissions management, optimize carbon cost control, and advance their low-carbon transition.

**Keywords:** carbon cost, carbon flow, value flow, control effect

*e-mail: 871758842@qq.com
0000-0002-1075-037X

© 2026 This article is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0)

## Introduction

With the accelerated formation of the global carbon regulatory system, enterprises' carbon emission behavior is undergoing a historical transformation from "external public damage" to "internalized cost constraint" [1, 2]. Based on the rapid development of China's carbon emission trading market, the quota control mechanism covering high-emission industries such as power generation, steel, and cement has transformed greenhouse gas emissions from an unconstrained activity into explicit cost elements [3]. As of 2025, carbon dioxide emissions covered by China's carbon market have exceeded 220 million tons. If enterprises fail to pay off the quotas in full within the specified time limit, they will face severe economic penalties and even production restrictions. Internationally, the full implementation of the EU's Carbon Border Adjustment Mechanism has extended carbon cost pressures to international trade, with export enterprises facing tariff costs of more than 80 euros per ton of carbon dioxide equivalent [4, 5]. As profit-oriented organizations, enterprises pursue the goal of maximizing profits or minimizing costs. Under increasingly strict carbon emission constraints and the long-term transition toward a low-carbon economy, minimizing carbon costs has become a rational choice for enterprises. Achieving this goal requires scientific carbon cost control. In the short term, enterprises are constrained by the carbon emission trading system and must fulfill their emission-reduction obligations each year. In the long run, enterprises' decisions – including those related to investment, financing, and operations – are constrained by factors such as low-carbon laws, regulations, policies, and systems [6, 7]. Carbon emission rights have evolved from environmental rights and interests to a new factor of production, and the efficiency of their cost management and control is directly related to enterprises' market competitiveness and survival [8, 9].

Compared with general operating costs, carbon costs exhibit distinct characteristics, which directly lead to differences in their control objectives and management methods [10]. However, the academic community has not yet reached a consensus on the specific definition and scope of carbon costs, resulting in diverse definitional perspectives. Early studies focused on the direct economic consequences under the carbon market mechanism, narrowly defining carbon costs as the cost of purchasing quotas for excessive emissions. These studies directly equate carbon costs with carbon emission costs, reporting that the two have conceptual consistency, or regard them as the monetized value of ecological damage caused by carbon emissions from an environmental perspective [7, 11]. An alternative view emphasizes the investments made by enterprises to fulfill their emission-reduction responsibilities or comply with regulations, defining carbon costs as voluntary or mandatory emission-reduction control costs [12]. Some studies further broaden this definition to include all-cycle low-carbon business expenditures such as the procurement of low-carbon raw materials, technology development, and fixed costs [13, 14]. Therefore, differences between the carbon costs and environmental damage costs of carbon emissions become pronounced under different carbon trading and carbon tax systems [13, 15]. Some scholars advocate a broader understanding, reporting that carbon costs should cover all costs related to greenhouse gas emissions and can be calculated based on energy consumption and waste emissions [16, 17]. As a branch of environmental costs, carbon costs differ from environmental costs in that the latter require consideration of long-term impacts and the evaluation of environmental damage, whereas carbon costs can be measured and analyzed based on enterprise production activities [18]. In particular, carbon costs can be divided into four categories, namely, prevention costs, detection costs, carbon emission costs, and contingent costs [19]. The concept of carbon costs has evolved from narrow transaction costs to broad all-cycle costs, from end-of-pipe treatment costs to source prevention and process control costs, and from single accounting to multi-dimensional classification and model-based accounting. The varied definitions reflect the differences in research perspectives – including market mechanisms, environmental responsibilities, management accounting, policy analysis, and life-cycle assessment – indicating the complexity and context dependence of carbon costs [20]. Therefore, in the context of enterprise cost control, the scope of carbon costs must be defined with reference to the specific research object. On this basis, this study focuses on process-level carbon costs incurred during the steel-manufacturing stage. Because carbon emissions from steel production arise mainly from the input and consumption of carbon-containing materials and energy, carbon cost is defined here as the outflow of economic benefits arising from carbon inputs and emissions during product manufacturing and is divided into internal resource transfer costs and external environmental damage costs. The former capture the internal economic consequences of the input, transfer, use, and loss of carbon-containing resources, whereas the latter capture the external environmental consequences of carbon emissions.

However, existing cost control methods have yet to incorporate the flows and losses of carbon-containing resources and their internal economic consequences, together with the external environmental damage caused by emissions, into a unified process-level analytical framework. Cost control methods have successively gone through standard costing, target costing, life-cycle assessment, activity-based costing, and value-chain costing [21]. Recent life-cycle studies integrate energy use, emissions, and costs within cross-process or infrastructure boundaries, while research on the digital economy emphasizes the role of digitalized management in carbon reduction [22]. Analysis of the evolution of traditional cost control methods reveals that the scope of enterprise cost control has extended from the production

stage to the entire internal and external value chain of the enterprise [23-25]. The focus of cost control has also shifted from strict pre-planning and post-hoc variance analysis to cost-driver management. It is necessary to determine the underlying drivers of costs from the perspective of the enterprise's internal and external value chain, eliminate non-value-added activities, and improve the efficiency and effectiveness of value-added operations [26, 27]. However, traditional cost control methods have three structural defects. First, there is a lack of external cost measurements. For example, standard costing and activity-based costing focus on the internal resource consumption of the enterprise, ignoring external environmental damage costs such as the climate damage and ecological degradation caused by carbon emissions. This results in the exclusion of the costs of quotas for excess emissions in the carbon-trading market from the enterprise-pricing model [28, 29]. Second, there is a disconnect between the driving factors of material flow. Although value-chain costing extends to upstream and downstream activities, it cannot quantify the carbon element conversion rate at the "unit-chain" level and struggles to determine the root causes of physical losses, such as the failure to utilize residual blast furnace gas for power generation [30]. Third, long-cycle coordination is lacking. Life-cycle costing covers the physical cycle of the product, yet it does not meet the coordination requirements of annual carbon quotas and the 3-5-year revenue cycle of China Certified Emission Reduction projects. It lacks a mapping mechanism for "material flow–emission reduction–carbon assets". This limitation reflects the one-dimensional focus on monetary flows in traditional methods, whereas carbon cost control requires a dual-dimensional approach that minimizes economic costs while optimizing carbon footprints [31, 32]. Table 1 compares the applicability of traditional cost control methods in carbon management scenarios.

To overcome the aforementioned limitations, this study constructs a two-dimensional control framework of "carbon flow–value flow". In particular, carbon flow and value flow analyses are conducted according to the circulation law of carbon-containing resources. Internal resource circulation costs and external environmental damage costs are then calculated, and the formation and structure of carbon costs are investigated. Based on material flow analysis, the circulation of carbon elements along the "input–conversion–output" pathway is tracked, and the carbon conversion rate is quantified at the process level [23]. Economically, resource value flow accounting is integrated with the Life-cycle Impact Assessment Method Based on Endpoint Modeling (LIME2) [33] to quantify internal resource transfer costs and external environmental damage costs. Across temporal and spatial dimensions, a carbon-asset discount model is constructed to address the mismatch between annual compliance requirements and the investment cycle of emission-reduction technologies.

The rest of this paper is organized as follows. The Materials and Methods section details the theoretical framework, methods, and data sources of the two-dimensional "carbon flow–value flow" carbon cost control approach. The Results and Discussion section applies the proposed method to NJ Steel, clarifies key links in carbon cost control, and proposes corresponding control measures. The Conclusions section summarizes the main findings and implications.

## Materials and Methods

At present, total carbon emissions and carbon emission intensity in China are relatively high, with the majority concentrated in infrastructure construction. In July 2021, China's carbon-trading market was launched, marking China's entry into the era of the low-carbon economy [34]. Such a move requires enterprises to strengthen their strategies for energy conservation, emission reduction, and green production to achieve sustainable development. In the future, higher carbon prices and active carbon compensation measures will substantially promote carbon emission reduction [35, 36]. The concept that carbon emissions are no longer free urges high-emission enterprises to integrate carbon emission reduction into decisions related to strategy, investment, and technology. Carbon costs represent an important factor influencing these decisions [37]. The notion that carbon emissions directly affect enterprises' benefits has emerged, prompting enterprises to actively incorporate emission reduction into their strategic plans for future development.

Table 1. Applicability of traditional cost control methods in carbon management.

| Method | Control focus | Limitations in carbon management |
|---|---|---|
| Standard costing | Product cost | Absence of external cost measurement |
| Target costing | Internal value-chain cost of the enterprise | Difficulty in coping with the dynamic fluctuation of carbon prices |
| Life-cycle method | Full life-cycle cost of the product | Disconnection between short-cycle fulfillment and long-cycle benefits |
| Activity-based costing | Product life-cycle cost | Absence of external cost measurement |
| Value-chain costing | Internal and external value-chain costs of enterprises | Immeasurability of material flow conversion efficiency |

The process of carbon cost control analysis is based on the examination of carbon value flow. Based on the principle of element flow conservation, value analysis is conducted on the flow of carbon-containing resources at each stage of the carbon flow pathway; this constitutes the process of carbon value flow analysis [38]. The analysis of carbon and energy flows can be used to establish an "input–output" model to examine carbon emissions from production processes [39]. Value flow assigns a monetary value to the carbon elements based on carbon flow, forming a "value flow" [40, 41]. Both the "Guide for Enterprise Greenhouse Gas Emissions Accounting and Reporting–Iron and Steel Industry" (Ministry of Ecology and Environment of China, 2025) and the "Guidelines for Compiling Provincial Greenhouse Gas Inventories (2025 Edition)" (Ministry of Ecology and Environment of China, 2026) are based on the enterprise level. These guidelines use the energy and material consumption of steel enterprises in the input–output calculation method to determine greenhouse gas emissions.

Within a product life-cycle framework, analyzing and controlling the key stages of corporate carbon cost consumption can extend the carbon cost accounting boundary and help achieve energy-conservation and emission-reduction goals [42, 43]. Accordingly, this study confines its research boundary to the steel-product manufacturing stage and examines the coking, sintering, ironmaking, steelmaking, and steel-rolling processes, with particular attention to carbon and value flows within each production workshop. Within this boundary, process-level quantification comprises two monetized components: first, internal resource transfer costs arising from the input, transfer, use, and loss of carbon-containing materials and energy in each process; and second, external environmental damage costs caused by $CO_2$ emissions from each process. Carbon flow provides the physical basis for value-flow accounting and enables the identification of high-emission and resource-loss processes, whereas carbon value flow monetizes the use of carbon-containing resources and the consequences of emissions to identify cost-control priorities at the input, transfer, and output stages. Carbon risk management, carbon disclosure, and policy compliance adjustment costs are organization-level indirect carbon-management expenditures that do not arise directly from the carbon flow of any single production process and are therefore outside the process-level quantitative boundary of this study.

## Data Sources

This paper selects NJ Steel as a case study. Founded in 1958, it is a key steel enterprise established under the country's "Second Five-Year Plan", serving as the cradle of Jiangsu's steel industry, the leading enterprise in the province's special-steel new-materials industrial chain, and a cornerstone of Nanjing's pillar industries. NJ Steel actively practices "green, low-carbon, and sustainable" development. With the vision of "fully building a low-carbon ecosystem covering all processes and business areas and becoming a pioneer in global green steel" for low-carbon development, the company promotes green and low-carbon development in accordance with the principle of "industrializing green development and greening industrial development" and has established a relatively complete framework for its "dual-carbon" initiatives. Currently, the company is actively advancing research on and the application of key direct and rapid emission-reduction technologies, represented by carbon capture, utilization, and storage, to achieve the resource utilization of carbon dioxide. On August 22, 2024, NJ Steel was included in the first batch of carbon peaking and carbon neutrality pilot lists in Jiangsu Province. Its development process, core business, digital transformation, environmental protection concept, and development vision are all representative of the industry. NJ Steel has a complete production process comprising coking, sintering, ironmaking, steelmaking, and steel rolling. Data for each process are derived from the company's 2023 annual report, social responsibility report, and production report.

## A Two-Dimensional Carbon Cost Analysis Method Based on "Carbon Flow–Value Flow"

### *Calculation of Carbon Value Flow*

"Value flow" refers to the transfer of value, expressed in monetary terms, as raw materials, energy, and human resources are transformed into products and services for consumers. "Carbon value flow" can be defined as a management activity that conducts value accounting for the flow of carbon-containing materials and energy in different spaces according to the carbon flow route in the production process.

The carbon value stream can be calculated using a step-by-step carry-forward method, in which value transfer is established based on the quantity of carbon elements transferred at each physical-quantity center. By multiplying the quantity of carbon elements in each physical-quantity center by the unit price of the corresponding raw materials, the transfer cost of carbon elements can be determined. In the overall production process, each physical-quantity center will continuously invest in new raw materials, energy, and other costs. This results in an accumulation of carbon element costs, changing the value of carbon elements. Therefore, it is necessary to account for each production-based physical-quantity center along the flow of carbon elements to form a carbon value stream for value measurement and analysis. At the output link of the "unit chain", outputs are divided into two categories: effectively utilized carbon elements (positive products) and carbon elements in waste gas (negative products). After assigning monetary values to outputs and aligning them with the direction of carbon flows, the value transfer diagram of the entire production process can be constructed,

explaining the economic losses across different physical-quantity centers. Problems within the enterprise can be analyzed with the two-dimensional carbon value stream model, supporting the optimization of carbon emission management processes, improvements in production technologies, and upgrades to machinery and equipment. Based on the above, the formula for the cost of carbon elements can be described as:

$$TC_i = EC_i + WC_i \tag{1}$$

where $TC_i$ is the cost of carbon elements in the i-th process; $EC_i$ is the cost of effectively utilized carbon elements in the i-th process; and $WC_i$ is the cost of carbon elements lost in waste in the i-th process.

The latter two items can be decomposed as:

$$EC_i = V_{i,j}.\pi_{i,j}.O_i \tag{2}$$

$$WC_i = V_{i,j}.\pi_{i,j} \tag{3}$$

where $V_{i,j}$ is the cost of the j-th material in the i-th process; $\pi_{i,j}$ is the carbon element content of the j-th material in the i-th process; and $O_i$ is the utilization rate of carbon elements in the i-th process.

Formula (1) reflects the cost composition of carbon elements in each production process, including the input cost at the input end, the cost of effectively utilized carbon elements, and the cost of carbon elements lost in waste. Formulas (2) and (3) are the allocation formulas for the cost of effectively utilized carbon elements and the cost of carbon elements lost in waste, respectively. The proportion of the cost of effectively utilized carbon elements to the total carbon asset cost represents the utilization rate of carbon elements.

*Internal Resource Flow Cost*

The cost accounting for carbon flow value is determined using a material flow analysis model that incorporates carbon elements. Material flow analysis explores the mass of carbon element inputs and outputs during production based on the principle of element flow conservation. The value flow then assigns monetary values to these flows, facilitating value analysis.

Carbon elements entering the production process include those provided by the initial or previous process, as well as additional carbon element inputs. The outflow of carbon elements consists of three components. The first component includes the carbon elements entering the subsequent production process or those in the finished products, denoted as the effectively utilized elements. Next are the carbon elements available for recycling, including defective products and raw materials required in the production process – which can be reused. The last component contains elements such as the exhaust gases emitted externally. The principle of element conservation is satisfied during the production process; that is, the input carbon elements are equal to the output carbon elements.

*External Environmental Damage Cost*

External environmental damage refers to the external damage caused by negative products to the environment. The negative products referred to in this study are primarily carbon dioxide. The external environmental damage costs of carbon dioxide emissions refer to the costs incurred by an enterprise due to the adverse impacts on the external environment beyond its production system. Internalizing the environmental damage costs caused by an enterprise's external carbon emissions can promote enterprises to actively reduce carbon emissions by forcing them to assume environmental responsibilities and gradually adopt a low-carbon business model. Due to the lack of environmental laws and regulations and measurement difficulties, enterprises generally do not consider the environmental damage costs caused by their operations. However, in the context of China's commitment to achieving a carbon peak before 2030 and carbon neutrality by 2060, the environmental impact caused by carbon emissions cannot be ignored. Therefore, the external environmental damage costs caused by carbon emissions should be analyzed. The external damage value is estimated using LIME2 [33]. This method comprehensively considers 11 environmental areas, such as global warming, ozone layer depletion, and urban air pollution, evaluating them separately. Such a wide-ranging assessment is suitable for calculating the external damage value of steel enterprises.

To distinguish physical and monetary boundaries, elemental carbon flows are expressed as masses of elemental carbon (tC), whereas carbon dioxide emissions used to value external damages are expressed in $tCO_2$ and converted as follows:

$$E_{CO_2,i} = M_{C,i} \times \frac{44}{12} \tag{4}$$

where $M_{C,i}$ is the mass of elemental carbon in process i (tC) and $E_{CO_2,i}$ is the corresponding mass of carbon dioxide ($tCO_2$). Recovered coke oven gas, blast furnace gas, and converter gas are treated as carbon reallocated within the production-system boundary rather than as direct reductions in $tCO_2$. For readability, carbon-flow quantities exceeding one million tC are reported to four decimal places in million tC in the text (1 million tC = $10^6$ tC), whereas the corresponding carbon-flow diagram presents the exact values in tC. Based on this conversion, the external environmental damage cost for each process is calculated by monetizing the corresponding carbon dioxide emissions as follows:

$$C_{EXT,i} = \frac{E_{CO_2,i} \times 1{,}000 \times w_{CO_2} \times r}{10{,}000} \tag{5}$$

where $C_{EXT,i}$ is the external environmental damage cost, measured in RMB 10,000; 1,000 converts metric tons to kilograms; $w_{CO_2}$ is the LIME2 monetization coefficient; $r$ is the RMB/JPY exchange rate; and 10,000 converts RMB to units of RMB 10,000. The baseline scenario uses the representative (median) $CO_2$ value in the LIME2 integration coefficient list published by the Life Cycle Assessment Society of Japan, 2.327273977 JPY/kg $CO_2$, with $r$ = 0.063347094 RMB/JPY.

*Analysis of Carbon Cost Composition*

During an enterprise's production process, the internal resource flow cost of each physical-quantity center must be calculated accordingly. First, the quantities of positive and negative products containing carbon elements should be determined and multiplied by their respective market prices. Fig. 1 presents the specific calculation method.

Fig. 1 shows that carbon elements in positive products flow from one physical-quantity center to the next for continued production. However, the carbon elements in each link cannot be fully utilized; the unused portion constitutes negative products, which represent losses in the enterprise's production process. For the convenience of analysis, the input of carbon elements in Fig. 1 is represented as a one-time full input in the production process, and all subsequent flows are the carbon elements input in the first process. In actual production, in addition to the internal flow, the external re-input of carbon elements must also be considered according to specific production conditions.

The external environmental damage costs are calculated by multiplying the carbon emissions of each physical-quantity center by the LIME2 coefficient. Fig. 2 presents the calculation process.

The total carbon cost is composed of the internal resource flow costs of carbon-containing resource

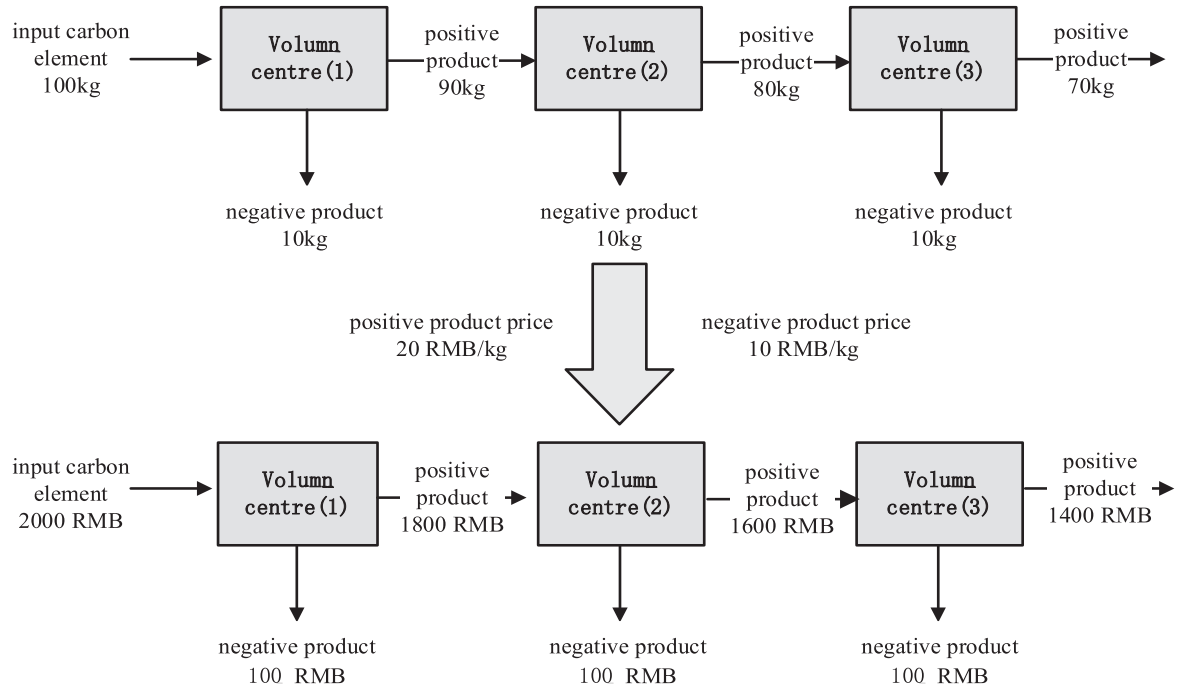



Fig. 1. Internal resource flow cost.

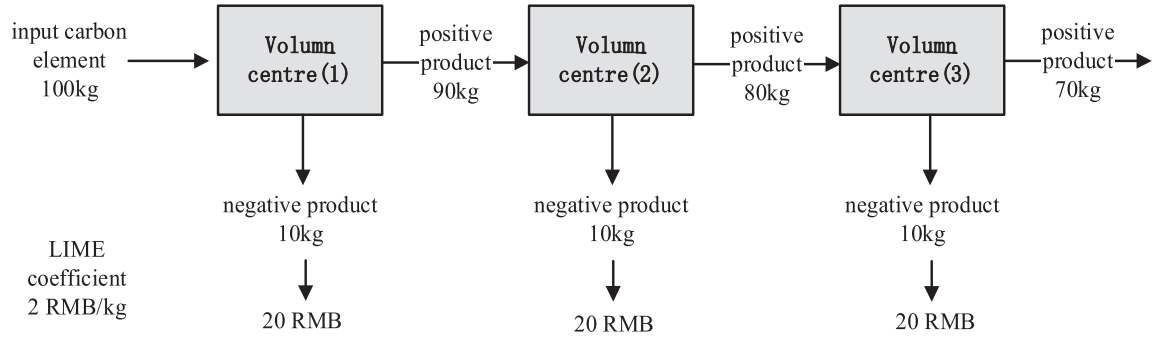



Fig. 2. External environmental damage cost.

consumption and the external environmental damage costs caused by carbon emissions. On the one hand, resource flow cost accounting depicts the enterprise's production process from the perspective of the internal value flow of carbon elements, thereby helping to identify key points for carbon cost control. On the other hand, external environmental damage costs are considered from the perspective of the enterprise's social responsibility, valuing the environmental impact caused by waste (mainly carbon dioxide emissions) discharged during production. The combination of "internal" and "external" can comprehensively reflect the impact of the enterprise's carbon element flow. This allows the enterprise to take effective countermeasures to reduce resource consumption at the input stage, improve the resource utilization rate at the flow stage, and enhance the waste recycling rate at the output stage.

## Application of the "Carbon Flow–Value Flow" Method in NJ Steel

### *Carbon Cost Control Approach*

Large amounts of carbon emissions are generated in each production process, and the utilization rate of carbon elements is relatively low. Profit statement analysis from NJ Steel reveals that the proportion of carbon costs to the total profit is low, indicating relatively modest carbon costs. Therefore, NJ Steel is in the improvement area (Area A in Fig. 3), and its production processes need to be enhanced to increase the carbon element utilization rate. Fig. 3 depicts the corresponding decision process.

### *Carbon Cost Control Measures*

According to the carbon cost accounting of NJ Steel – based on the carbon value flow – the processes

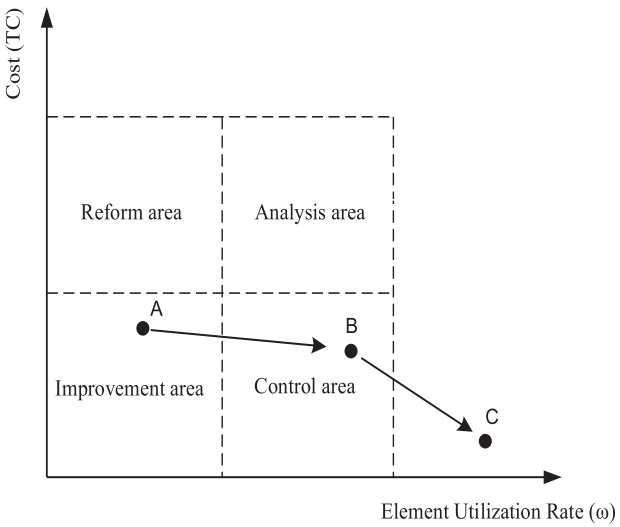



Fig. 3. Optimization decision diagram of NJ Steel's carbon cost control.

with high carbon emissions are coking (9.4146 million tC), ironmaking (11.0077 million tC), and steelmaking (3.5499 million tC). These three processes also have the highest carbon costs, which are coking (RMB 12,448.36 million), ironmaking (RMB 5,579.66 million), and steelmaking (RMB 2,468.17 million), respectively. Assuming that merchant steel output remains constant and considering the input cost, the recycling technology of NJ Steel must be improved to effectively control the carbon emissions of high-emission processes. Therefore, the circular economy concept and low-carbon technology should be introduced into the production process to improve the utilization rate of carbon elements through recycling. According to the law of conservation of matter, the improvement of the utilization rate of carbon elements will inevitably lead to a reduction in carbon emissions. The adoption of low-carbon technology can also achieve the goal of energy conservation and emission reduction.

China's "Circular Economy Promotion Law" defines the circular economy (recycling economy) as "the general term for the reduction, reuse, and resource utilization activities carried out by integrating resource conservation and environmental protection into production, consumption, and waste management". From a macro perspective, the circular economy is an objective choice for China to transform from an extensive economic development model to a resource-intensive economic development model. The "reduction, reuse, and resource utilization" activities pursued by the circular economy are consistent with China's construction of a resource-saving, environmentally friendly, and low-carbon society. From a meso perspective, the circular economy can be applied to ecological industrial parks to achieve a "win-win" situation among enterprises through the recycling of resources. At the micro level, enterprises can reduce resource inputs at the source by developing a circular economy and recycling waste. For NJ Steel, advancing circular economy practices and waste recycling practices represents an effective approach for reducing carbon emissions and controlling carbon costs.

The concept of low-carbon technology as a key solution to climate change is still evolving. This type of environmentally friendly technology is characterized by three key features: a primary focus on carbon emission reduction; coverage of the whole chain from energy production to consumption; and accounting for economic and ecological benefits. Although the academic community has not yet formed a unified definition, the concept essentially refers to decoupling economic development from carbon emissions through technological innovation. Most scholars associate low-carbon technology with various technologies adopted to achieve a low-carbon economy, generally referring to all technologies, products, or processes that can reduce carbon emissions in all human activities. The low-carbon technology system can be divided into three main categories: (1) carbon-reduction technology,

which is mainly applied to energy-intensive industries for energy efficiency improvement and emission control, covering clean coal technology, unconventional natural gas development, etc.; (2) carbon-free technology, with the utilization of renewable energy as the core, including photovoltaic power generation, wind power generation, and nuclear energy utilization; and (3) carbon removal technology, with representative technologies such as carbon capture and storage and other negative emission solutions. This classification systematically covers all technical paths, from source control to end-of-pipe treatment. In this paper, carbon-reduction technology is employed in the ironmaking process of NJ Steel.

The following control measures can be implemented when applying circular economy principles and low-carbon technology to the three high-emission processes of coking, ironmaking, and steelmaking in NJ Steel:

(1) The addition of "coke oven gas purification equipment" during the coking process. As the main carbon emission source in NJ Steel, the annual emissions of the coking process are 9.4146 million tC, accounting for a substantial proportion of the total production system emissions. Analysis shows that the lack of a coke oven gas purification system is the key driver of high emissions. Purification technologies commonly used in the industry, such as hydroquinone – ammonium binuclear cobalt phthalocyanine sulfonate – ferrous sulfate wet oxidation desulfurization, multi-stage purification desulfurization, and the combined process of deacidification, ammonia distillation, and crude benzene recovery, can effectively recover volatile organic compounds such as methane and ethylene. By enabling the closed-loop utilization of carbon elements, this approach delivers environmental and economic benefits. The integrated technology scheme thus provides a feasible path for carbon emission reduction in the coking process.

(2) The adoption of "swirling-cut high-temperature top-fired hot blast stove energy-saving technology" and "blast furnace gas residual pressure turbine power generation systems" during the ironmaking process. In NJ Steel's production process, the carbon emissions attributed to the ironmaking process are 11.0077 million tC, representing the largest emission source and a key focus area. In recent years, NJ Steel has adopted numerous technologies to improve the production process. For this process, the "swirling-cut high-temperature top-fired hot blast stove energy-saving technology" has been implemented. This technology is a new-generation hot blast stove system characterized by high temperature, high efficiency, and long service life, and can reduce fuel consumption by 8%-12% during the production process. The blast furnace gas discharged during this process can be collected and reused through the "blast furnace gas residual pressure turbine power generation system".

(3) The integration of "converter gas dry recovery technology" during the steelmaking process. The carbon emissions in the steelmaking process of NJ Steel are determined as 3.5499 million tC. During the steel-production process, a large amount of converter gas is discharged. The converter gas dry recovery technology can be adopted to address this issue. This technology facilitates the recycling of the converter gas, which can simultaneously reduce carbon costs and improve the carbon element utilization rate.

## Results and Discussion

### "Carbon Flow–Value Flow" Analysis before Control

The Intergovernmental Panel on Climate Change Guidelines propose three principal approaches for calculating carbon emissions: direct measurement, material balance, and empirical calculation. The direct measurement method involves on-site monitoring of fuel equipment, with emissions and activity data obtained through factory inspection. Although the estimates obtained by this method are relatively accurate, the workload and costs are high, and it is difficult to directly obtain activity and emissions data. These factors pose considerable challenges to the implementation of this method. The material balance method is based on the law of conservation of mass and analyzes the material inputs and outputs, adhering to the principle that total input equals total output. This paper analyzes carbon resources in the production process of steel enterprises based on the material balance method. The empirical calculation method uses a weighted calculation based on carbon emission coefficients derived under the same production conditions. These coefficients are then used as general parameters to calculate the current carbon emissions of the product.

NJ Steel has a complete production process comprising "coking–sintering–ironmaking–steelmaking –steel rolling". In particular, coke and sinter are produced through the coking and sintering processes, respectively. These two components, together with materials such as iron ore, are used in the blast furnace to produce molten iron, which is then cast into steel billets. Subsequently, in accordance with production requirements, various steel products are manufactured using hot-rolling or cold-rolling technology.

Table 2 reports the division of material centers and the input–output elements of NJ Steel's production system. In the sintering process, limestone, coal, coke oven gas, blast furnace gas, and converter gas are input to produce sinter and carbon dioxide. In the coking process, high-temperature dry distillation is carried out using inputs such as purchased electricity, coal, coke oven gas, and blast furnace gas to produce coke and coke oven gas, whereas carbon dioxide is emitted from direct and indirect emission sources. In the ironmaking process, coke and iron ore undergo oxidation-reduction reactions in the blast furnace to reduce the carbon content of the iron ore. According to

Table 2. Division of material centers and input–output factors.

| Production Process | Production Process | Input Energy and Resources | Output Products | |
|---|---|---|---|---|
| | | | Positive Products | Negative Products |
| Sintering | Sintering, pelletizing | Limestone, coal, coke oven gas, blast furnace gas, converter gas | Sinter | Waste such as carbon dioxide |
| Coking | High-temperature dry distillation | Coal, coke oven gas, blast furnace gas | Coke | Waste such as carbon dioxide |
| Ironmaking | Ironmaking | Iron ore, sinter, natural gas, coal, coke, coke oven gas, blast furnace gas | Pig iron | Waste such as carbon dioxide |
| Steelmaking | Steelmaking | Limestone, scrap iron, pig iron, natural gas Coke oven gas, blast furnace gas | Crude steel | Waste such as carbon dioxide |
| Steel rolling | Steel rolling | Natural gas, coke oven gas, blast furnace gas | Merchant steel | Waste such as carbon dioxide |

Source: Compiled from relevant materials of NJ Steel.

the principle of mass conservation, carbon dioxide is generated in this process. In the steelmaking process, molten iron is used to make steel, which is then cast into steel ingots and billets through a continuous casting machine, reducing the carbon content in the molten iron. The steel-rolling process can be divided into hot-rolling and cold-rolling stages, depending on the specific processes and equipment used. In the hot-rolling stage, steel billets are placed between rotating rolls at high temperatures to alter their shape. The cold-rolling process employs hot-rolled steel coils as raw materials; after pickling to remove oxide scale, they are rolled. Following processing at different stages, the carbon content in the steel varies depending on the product. Each production process consumes resources and energy, resulting in direct or indirect carbon emissions. This boundary design, which uses material centers as analytical units and traces the transfer and emissions of carbon-containing resources along each production link, is also supported by recent research. Manufacturing-oriented carbon accounting emphasizes the need to trace emissions through equipment, materials, and production links [44], whereas carbon balance-sheet and flow-statement logic further links embodied carbon emissions, periodic carbon footprints, and cost responsibility [45]. On this basis, China's carbon trading policy provides an institutional incentive to reduce corporate environmental costs by encouraging green innovation and internalizing environmental costs within firm-level decisions. Therefore, the carbon flow analysis constructed in this study according to the transfer patterns of carbon-containing resources forms the material basis for enterprises to identify emission sources and control carbon costs.

Table 3 presents data on the material, carbon, and value flows for each process across the coking, sintering, ironmaking, steelmaking, and steel-rolling stages. All data are sourced from NJ Steel's 2023 annual report, social responsibility report, and production report.

## Carbon Flow Analysis after Control

For the three high-carbon-emission processes of coking, ironmaking, and steelmaking, this paper optimizes the production process by incorporating coke oven gas purification, energy-saving rotary-cut, high-temperature, top-fired hot-blast stove technology, blast furnace top gas recovery turbine units, and converter gas dry recovery technology. This transforms the initial linear carbon flow into an interconnected circular recycling system. The significance of this transformation from a linear carbon flow to an interconnected circular recycling system is not limited to physical emission reduction. Under emissions trading systems, carbon management systems are closely related to corporate carbon performance [46], digital greenhouse gas tracking and trading mechanisms can improve traceability and verification in industrial decarbonization [47], and emissions trading itself can further affect corporate financial decisions and operating performance [48]. Therefore, while reducing actual carbon emissions, the optimization measures proposed in this study also help NJ Steel establish a more traceable carbon management process that can respond to carbon-market constraints.

As shown in Fig. 4, the optimized carbon flow achieves process improvement through these four key control points, and each control node is marked with a circle. For the coke oven gas purification treatment, the input stage consists of 4.5507 million tC embodied in coke oven gas and 9.4146 million tC embodied in carbon dioxide. The output stage includes 1.7342 million tC embodied in recyclable coke oven gas, 2.8165 million tC embodied in coke oven gas discharged into the environment, and 9.4146 million tC embodied in carbon dioxide. The total carbon element mass at the input end is equal to that at the output end. The recycled coke oven gas is divided into four pathways and enters the input stages of subsequent production steps, as indicated by the dotted lines in Fig. 4. Specifically, it contributes

Table 3. Carbon flow and value flow of NJ Steel's production process in 2023.

| Production Process | Classification | Substance Name | Carbon Flow (tC) | Value Flow (RMB 10,000) |
|---|---|---|---|---|
| Coking | Inflow | Electricity | 255743 | 18.58 |
| | | Coal | 19858263 | 1251071 |
| | | Coke oven gas | 37881 | 3.03 |
| | | Blast furnace gas | 4544339 | 90.89 |
| | Outflow | Coke | 13315358 | 838868 |
| | | Coke oven gas | 3248125 | 259.85 |
| Sintering | Inflow | Iron ore | 0 | —— |
| | | Limestone | 1697508 | 59413 |
| | | Coal | 354561 | 22337 |
| | | Blast furnace gas | 75063 | 1.50 |
| | | Electricity | 679208 | 49.34 |
| | Outflow | Converter gas | 6647 | 0.27 |
| | | Sinter | 0 | —— |
| Ironmaking | Inflow | Iron ore | 0 | —— |
| | | Sinter | 0 | —— |
| | | Natural gas | 10295 | 2.10 |
| | | Coal | 358576 | 22590 |
| | | Electricity | 218804 | 15.90 |
| | | Coke | 16347763 | 1029909 |
| | | Coke oven gas | 787501 | 63.00 |
| | | Blast furnace gas | 6171281 | 123.43 |
| | Outflow | Blast furnace gas | 14198663 | 283.97 |
| | | Pig iron | 1836800 | 687575 |
| Steelmaking | Inflow | Limestone | 489708 | 17140 |
| | | Scrap iron (scrap steel) | 311200 | 62240 |
| | | Pig iron | 2280384 | 770770 |
| | | Natural gas | 10823 | 2.21 |
| | | Electricity | 238438 | 17.32 |
| | | Coke oven gas | 41670 | 3.33 |
| | | Blast furnace gas | 87487 | 1.75 |
| | Outflow | Crude steel | 505638 | 184769 |
| | | Converter gas | 22434 | 0.90 |
| Steel rolling | Inflow | Natural gas | 74178 | 15.13 |
| | | Coke oven gas | 419510 | 33.56 |
| | | Crude steel | 505638 | 184769 |
| | | Electricity | 438274 | 31.84 |
| | | Blast furnace gas | 296626 | 5.9325 |
| | Outflow | Merchant steel | 644900 | 304623.89 |

Data source: NJ Steel annual reports, sustainability reports, etc.

0.0730 million tC to the sintering process, 1.0150 million tC to the ironmaking process, 0.0584 million tC to the steelmaking process, and 0.5878 million tC to the steel rolling process, totaling 1.7342 million tC.

Comparative analysis of pre- and post-carbon flow optimization reveals a marked reduction in the carbon-emission intensity of the coking process. Under the baseline scenario, total carbon input to and output from the coke oven gas purification stage was 13.9653 million tC in each case, confirming closure of the stage-level carbon balance. Specifically, 4.5507 million tC embodied in the input coke oven gas was divided into 1.7342 million

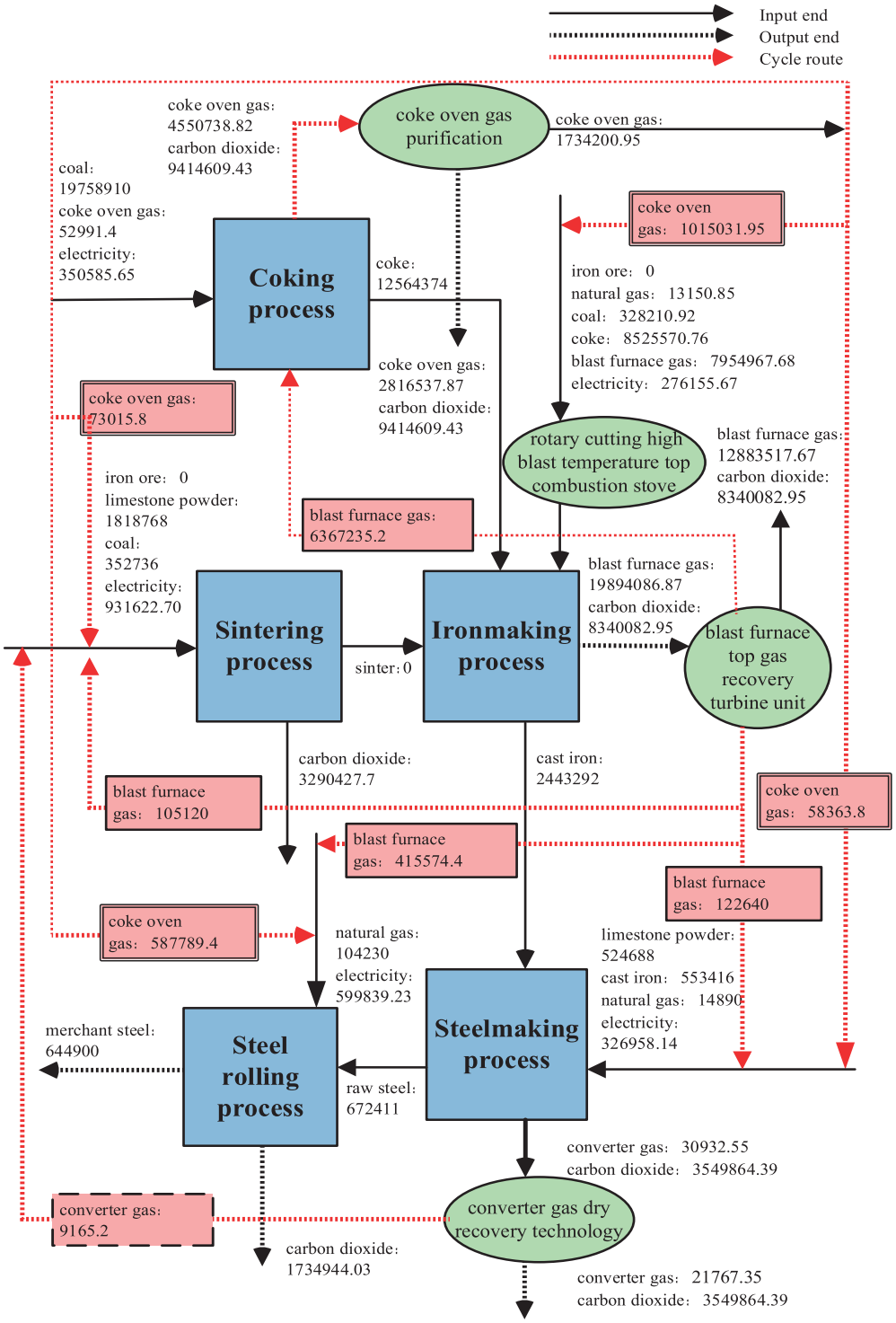



Fig. 4. Carbon flowchart of NJ Steel after control (all flows are expressed in tC).
Note: All quantities and the related discussion of carbon flows are expressed as masses of elemental carbon (tC). Recovered gas represents carbon reallocated within the production-system boundary rather than a direct reduction in $tCO_2$. The monetized $CO_2$ emissions in Table 5 were obtained by multiplying tC by 44/12.

tC recovered and 2.8165 million tC discharged, while 9.4146 million tC embodied in $CO_2$ remained unchanged across the stage. In the modeled post-control scenario, the recovered fraction was directed to reuse rather than environmental discharge. This improvement is principally due to the resource utilization of recyclable gas. By reallocating 1.7342 million tC embodied in recovered coke oven gas to the sintering, ironmaking, steelmaking, and steel rolling processes, direct emissions are reduced, and an equivalent amount of fossil fuel is replaced. This result indicates that green technological upgrading can translate external pressures such as carbon trading into internal reductions in energy consumption and managerial improvement only when it is embedded in specific production processes. This is consistent with enterprise-level evidence showing that emissions trading systems can reduce the energy intensity of high-carbon enterprises through green technological innovation and digital transformation [49].

The second control measure is the swirling-cut, high-temperature, top-fired hot-blast stove energy-saving technology in the ironmaking process. This technology employs a rotary-cut burner to increase the hot air temperature by nearly 100°C, reduce the coke ratio in blast furnace smelting, increase the coal injection ratio, and achieve fuel savings of 8%-12%. To ensure a conservative and robust analysis, the lowest fuel-saving ratio of 8% is used in the calculation. Before optimization, the input stage requires 14,294 tC in natural gas, 356,751 tC in coal, 22.9239 million tC in coke, 1.1033 million tC in coke oven gas, 8.6467 million tC in blast furnace gas, and 300,169 tC in electricity. The carbon element mass at the input stage is equal to that at the output stage. After the process is optimized, the input stage – indicated by the dotted line – consists of 13,151 tC in natural gas, 328,211 tC in coal, 21.0899 million tC in coke, 1.0150 million tC in coke oven gas, 7.9550 million tC in blast furnace gas, and 276,156 tC in electricity. After optimization, total carbon input to and output from the ironmaking process was 30.6775 million tC in each case, confirming closure of the process-level carbon balance. The outputs comprised 2.4433 million tC in cast iron, 19.8941 million tC in blast furnace gas entering the recovery unit, and 8.3401 million tC embodied in $CO_2$. This corresponds to a reduction of 2.6676 million tC relative to the baseline.

The third measure, also in ironmaking, is the addition of a blast furnace top gas recovery turbine unit. The input stage consists of 13,151 tC in natural gas, 328,211 tC in coal, 21.0899 million tC in coke, 1.0150 million tC in coke oven gas, 7.9550 million tC in blast furnace gas, and 276,156 tC in electricity. The output stage includes 7.0106 million tC embodied in recyclable blast furnace gas, 12.8835 million tC embodied in blast furnace gas discharged into the environment, and 8.3401 million tC embodied in carbon dioxide. The carbon element mass at the input stage is equal to that at the output stage. The recovered blast furnace gas then enters the input stages of subsequent production steps, with the recycling paths indicated by dotted lines in Fig. 4. Specifically, the 7.0106 million tC of recovered blast furnace gas was reallocated among the coking, sintering, steelmaking, and steel rolling processes through the dotted pathways shown in Fig. 4; the exact route-specific quantities are reported in the figure. Under the unoptimized carbon-flow roadmap, 19.8941 million tC embodied in blast furnace gas and 8.3401 million tC embodied in $CO_2$, totaling 28.2342 million tC, would have been discharged from the ironmaking process. After control, the carbon discharged to the environment from the ironmaking process comprised 12.8835 million tC embodied in blast furnace gas and 8.3401 million tC embodied in $CO_2$, totaling 21.2236 million tC, a reduction of 7 .0106 million tC.

The fourth measure is the application of converter gas dry recovery technology in steelmaking. The input stage consists of 30,933 tC in converter gas and 3.5499 million tC embodied in carbon dioxide. The output stage includes 9,165 tC in recyclable converter gas, 21,767 tC in converter gas discharged into the environment, and 3.5499 million tC embodied in carbon dioxide. The carbon element mass at the input stage is equal to that at the output stage. The recovered converter gas enters the input stages of subsequent production steps, with the recycling paths indicated by dotted lines in Fig. 4. Specifically, 9,165 tC of recovered converter gas enters the sintering process. Total carbon input to and output from the converter gas recovery stage was 3.5808 million tC in each case, confirming closure of the stage-level carbon balance. Specifically, 30,932.55 tC of carbon in input converter gas was divided into 9,165.20 tC recovered and 21,767.35 tC discharged, while 3.5499 million tC embodied in $CO_2$ remained unchanged across the stage. In the modeled post-control scenario, the recovered fraction was directed to reuse rather than environmental discharge.

## Analysis of the Value Flow after Control

As shown in Fig. 5, the optimized coking process recovered 1.7342 million tC embodied in coke oven gas. Based on this, the value of the saved resources was calculated. At the output stage of the coking process, carbon element costs include the costs of carbon-containing resources such as coke oven gas, coal, and electricity. Monetary values in Fig. 5 are reported in units of RMB 10,000. The cost of coke oven gas is 4.24, the cost of coal is 1,244,811.33, and the cost of electricity is 20.15. These three components total 1,244,835.72 units of RMB 10,000 for the coking process, that is, RMB 12,448.36 million. By optimizing the coke oven gas purification process, the system generated a recyclable gas resource value of 138.74 units of RMB 10,000 (RMB 1.3874 million). This portion of recycled resources achieved value transformation through four pathways: sintering 5.84, ironmaking 81.20, steelmaking 4.68, and steel rolling 47.02 units of RMB 10,000, which sum to 138.74. These recycled carbon sources re-entered

the steel manufacturing process as raw materials, forming a circular economy model of "purification–reuse–value-added" (Fig. 5). Within the simulated scenario, the recovery and reuse of this gas enable the closed-loop utilization of 1.7342 million tC and generate carbon-asset value, illustrating the combined environmental and economic benefits of carbon-flow optimization. For the subsequent sensitivity analysis, the RMB 146 million investment is drawn from a representative project in the National Development and Reform Commission catalogue and is treated as a fixed implementation-cost proxy.

Following the application of the four control measures, the internal resource costs of carbon emissions in the sintering, ironmaking, steelmaking, and steel-rolling processes are RMB 859.33 million, RMB

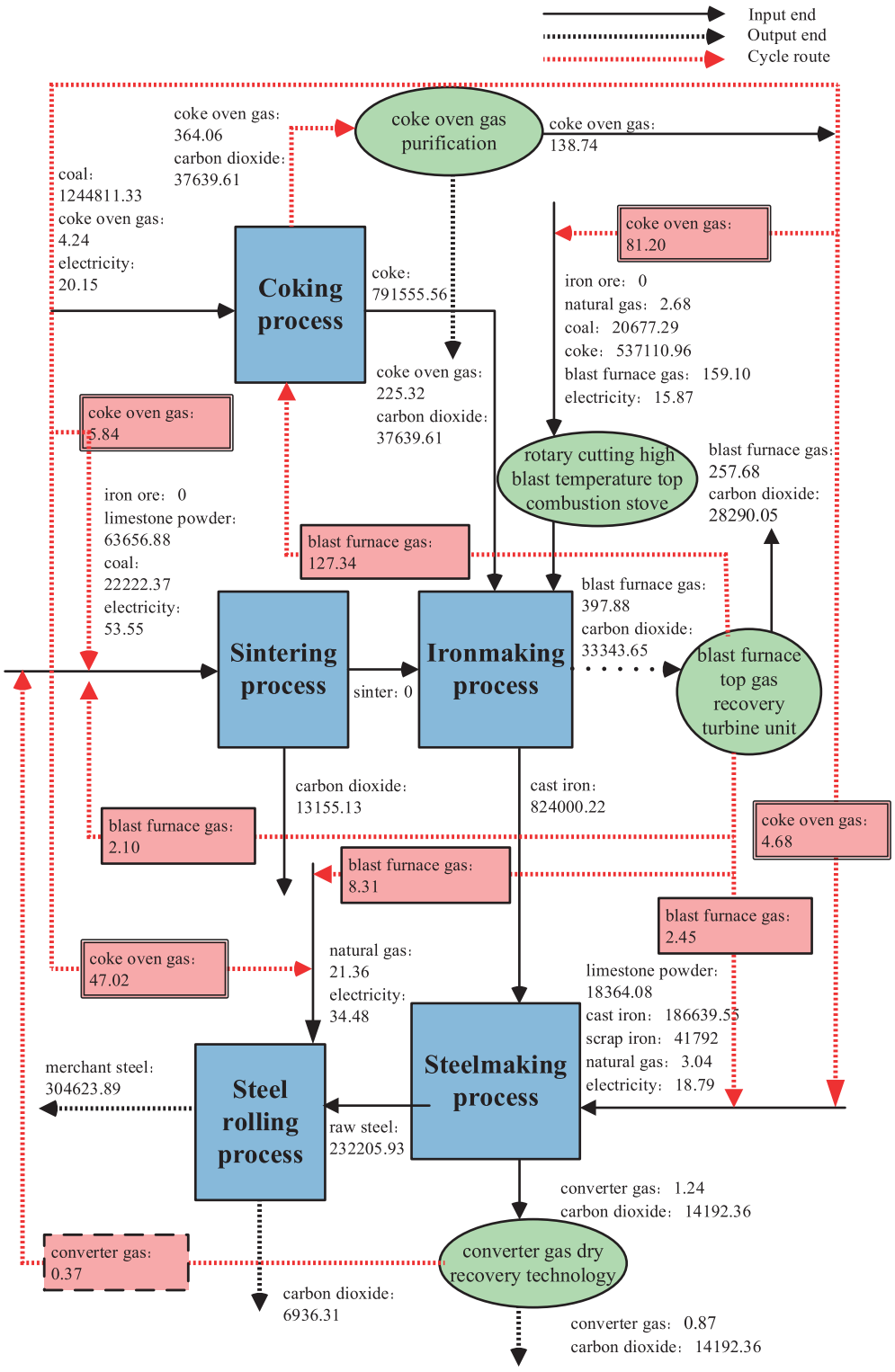



Fig. 5. Value flowchart of NJ Steel after control (numbers are expressed in RMB 10,000).

Table 4. Value transfer of carbon resources in each process after control.

| Production process | Internal resource transfer cost (RMB 10,000) |
|---|---|
| Sintering | 85932.80 |
| Ironmaking | 557965.90 |
| Steelmaking | 246817.46 |
| Steel rolling | 55.84 |
| Total | 890772.00 |

5,579.66 million, RMB 2,468.17 million, and RMB 0.56 million, respectively, as summarized in Fig. 5. By reinvesting the recyclable carbon elements into the production system, a substantial reduction in raw material consumption is achieved, thereby reducing carbon cost expenditures. The optimized carbon value flow analysis shows that, while maintaining the total carbon value of the final product – merchant steel – at RMB 3,046.24 million, emissions are reduced and efficiency is improved (Fig. 5).

The advantage of low-carbon technology lies in reducing material inputs and improving utilization efficiency. The above optimization measures fully demonstrate the role of the circular economy model: through resource recycling, they not only reduce resource inputs but also reduce the environmental damage caused by waste. Therefore, the low-carbon technologies in this case should not be understood merely as engineering measures for emission reduction; they also change the operational flexibility of the enterprise when it faces carbon quotas, cost constraints, and performance targets. Firm-level evidence from the power sector shows that emissions trading systems can reduce carbon emissions [50], with environmental protection and firm performance improvement proceeding in parallel. This logic explains why NJ Steel's technological transformation is reflected simultaneously in reduced resource inputs, lower waste-related damage, and improved value flow.

Table 4 reveals that after optimization, the internal transfer costs of each process have decreased to varying degrees. Through the recycling of resources, the carbon cost inflow at the input stage of each production process is reduced. Fig. 5 presents the value transfer flow after control.

Based on the carbon emissions of each production process at NJ Steel after control in 2023, the external environmental damage costs can be estimated using the LIME2 method, as shown in Table 5. As can be seen from Table 5, the external environmental damage costs are directly linked to carbon emissions. By implementing optimization measures to reduce carbon emissions, environmental damage is mitigated, leading to a corresponding decrease in damage costs. After control, the total environmental damage cost is RMB 14,233 million. This treatment means that external damage costs are no longer merely an ex post accounting item, but are transformed into comparable management information. Recent carbon accounting research similarly indicates that carbon accounting and integrated reporting can make decarbonization practices more visible during firms' transition toward net-zero business models [51]. In this case, avoided emissions are further converted into reductions in damage costs, making the relationships among technological choices, emission outcomes, and economic consequences clearer.

## Comparative Analysis of Carbon Costs before and after Control

Table 6 reports the carbon costs of each production process after control, whereas Table 7 presents the comparison with pre-control levels. Carbon cost control increases the use of coke oven gas, blast furnace gas, and converter gas and reduces carbon emissions from each process, thereby lowering carbon costs. As shown in Table 7, internal resource transfer costs and external environmental damage costs decrease by RMB 1,176 million and RMB 1,442 million, respectively, after control, yielding a total carbon cost reduction of RMB 2,618 million. Technical-retrofit investment is incorporated into the subsequent sensitivity analysis.

Table 5. External environmental damage costs of NJ Steel after control in 2023.

| Production process | $CO_2$ emissions ($tCO_2$) | $CO_2$ emissions (kg) | External damage cost (RMB 10,000) |
|---|---|---|---|
| Coking | 34520235 | 34520234580 | 508918 |
| Sintering | 12064902 | 12064901570 | 177868 |
| Ironmaking | 30580304 | 30580304160 | 450833 |
| Steelmaking | 13016169 | 13016169430 | 191892 |
| Steel rolling | 6361461 | 6361461440 | 93785 |
| Total | 96543071 | 96543071180 | 1423296 |

Note: Calculations used the median LIME2 $CO_2$ monetization coefficient of 2.327274 JPY/kg $CO_2$ and an exchange rate of 0.063347094 RMB/JPY.

Table 6. Total carbon costs of NJ Steel after control.

| Production process | Internal resource transfer cost (RMB 10,000) | External environmental damage cost (RMB 10,000) | Carbon cost (RMB 10,000) |
|---|---|---|---|
| Coking | 1244836 | 508918 | 1753754 |
| Sintering | 85933 | 177868 | 263801 |
| Ironmaking | 557966 | 450833 | 1008799 |
| Steelmaking | 246817 | 191892 | 438710 |
| Steel rolling | 56 | 93785 | 93840 |
| Total | 2135608 | 1423296 | 3558904 |

Note: Values are rounded to the nearest RMB 10,000; row totals were calculated from unrounded values.

Table 7. Changes in NJ Steel's carbon costs before and after control (RMB 10,000).

| Cost category | Before control | After control | Modeled reduction |
|---|---|---|---|
| Internal resource transfer cost | 2,253,244 | 2,135,608 | 117,636 |
| External environmental damage cost | 1,567,497 | 1,423,296 | 144,201 |
| Total carbon cost | 3,820,741 | 3,558,904 | 261,837 |

To test the sensitivity of the results to the process-efficiency assumption, the fuel-saving rate of the swirling-cut high-temperature top-fired hot blast stove was set at 8%, 10%, and 12%. The 8% rate is the conservative baseline used in the main control scenario and the lower bound of the technical range published by the National Development and Reform Commission, whereas 10% and 12% represent the intermediate scenario and the technical upper-bound scenario, respectively. All other process parameters, the LIME2 coefficient, the exchange rate, and the external environmental damage cost were held constant. To assess the carbon cost reduction after implementation costs have been considered, this study employed the one-time technical-retrofit investment of RMB 146 million reported for a representative 3,200 m³ blast-furnace project in the National Development and Reform Commission catalogue as a proxy [52]. The three fuel-saving-rate scenarios represent different performance levels achieved after the installation of the same technology rather than different project scales. Therefore, the investment is held constant across the three scenarios and is deducted in full from the pre-investment reduction in internal resource transfer costs reported in Table 7. To maintain consistency with the terminology in Table 8, "internal resource transfer cost" denotes the reduction in internal costs after deducting the technical-retrofit investment, and "carbon cost reduction" is the sum of the internal resource transfer cost and the external environmental damage cost. The results are reported in Table 8.

To address uncertainty in the LIME2 monetization parameter, this study employed the integrated $CO_2$ coefficient list published by the Life Cycle Assessment

Table 8. One-factor sensitivity analysis of the simulated carbon cost reduction (RMB 10,000).

| Fuel-saving-rate scenario | Fuel-saving rate (%) | Internal resource transfer cost | External environmental damage cost | Carbon cost reduction | Parameter scenario | LIME2 coefficient (JPY/kg $CO_2$) | Internal resource transfer cost | External environmental damage cost | Carbon cost reduction |
|---|---|---|---|---|---|---|---|---|---|
| Conservative baseline | 8 | 103036 | 144201 | 247237 | Low (P10) | 1.369074 | 103036 | 84829 | 187865 |
| Intermediate scenario | 10 | 132375 | 144201 | 276576 | Baseline (P50) | 2.327274 | 103036 | 144201 | 247237 |
| Technical upper bound | 12 | 161715 | 144201 | 305916 | High (P90) | 4.697615 | 103036 | 291070 | 394106 |

Note: The 8%-12% fuel-saving rates and the RMB 146 million investment for a representative project are taken from the National Key Energy-Saving Technology Promotion Catalogue (Fifth Batch) issued by the National Development and Reform Commission [52]. P10, P50, and P90 denote the 10$^{th}$, 50$^{th}$, and 90$^{th}$ percentiles, respectively, of the LIME2 $CO_2$ monetization coefficient [33].

Society of Japan, which is based on 50,000 Monte Carlo simulations, and specified a low scenario (P10, 10th percentile), baseline scenario (P50, median), and high scenario (P90, 90th percentile). Across these three scenarios, post-control emissions, the exchange rate, the internal resource transfer cost under the conservative 8% baseline, and the RMB 146 million technical-retrofit investment were held constant; only the LIME2 coefficient changed. Consequently, the external environmental damage cost and the carbon cost reduction varied [33].

### Internal Resource Transfer Costs and External Environmental Damage Costs

After deducting the one-time technical-retrofit investment of RMB 146 million, the internal resource transfer costs under the 8%, 10%, and 12% fuel-saving scenarios were RMB 1,030.36 million, RMB 1,323.75 million, and RMB 1,617.15 million, respectively, while the corresponding carbon cost reductions were RMB 2,472.37 million, RMB 2,765.76 million, and RMB 3,059.16 million. Across the three LIME2 scenarios, the internal resource transfer cost was fixed at RMB 1,030.36 million under the conservative 8% baseline, and the low, baseline, and high scenarios yielded carbon cost reductions of RMB 1,878.65 million, RMB 2,472.37 million, and RMB 3,941.06 million, respectively. Overall, the carbon cost reduction across the two sets of sensitivity scenarios ranged from RMB 1,878.65 million to RMB 3,941.06 million. In all specified scenarios, the carbon cost reduction remained positive, and changes in the parameters affected only the magnitude of the reduction rather than the directional conclusion that process optimization lowers carbon costs. This indicates that the direction of the accounting result remains stable within the tested parameter ranges. The range also reflects the potential variation associated with assumptions about technical efficiency and the monetization of external damages. The fuel-saving rate primarily affects the internal resource transfer cost, whereas the LIME2 coefficient primarily affects the external environmental damage cost. Thus, Table 8 shows how changes in key parameters affect the carbon cost reduction within the tested parameter ranges. From a broader environmental-efficiency perspective, process-level improvements in resource efficiency also provide an important micro-level foundation for coordinating industrial development and environmental protection.

## Conclusions

This study conducted a case analysis of NJ Steel and, building on the strengths of existing cost control approaches, proposed a two-dimensional "carbon flow–value flow" framework for carbon cost control. By applying this method, key carbon cost control points were identified, and corresponding optimization measures were proposed. The main findings are summarized as follows:

This paper defines carbon cost as the total potential economic outflows resulting from carbon inputs and carbon emissions during the product manufacturing process in enterprise operations. This encompasses internal resource transfer costs and external environmental damage costs. The definition highlights that carbon-containing resources are consumed throughout the entire product life cycle, and their emissions carry environmental cost implications.

Moreover, by analyzing carbon flows in accordance with the transfer patterns of carbon-containing resources, the coking, ironmaking, and steelmaking processes were identified as high-emission segments. Carbon value flow analysis further indicates that these stages also incur high carbon costs, identifying them as critical control points. Drawing on circular economy principles, the study suggests enhancing carbon resource recycling and adopting low-carbon technologies to reduce carbon costs at the source.

Finally, under the simulated post-control scenario, internal resource transfer costs and external environmental damage costs were RMB 1,176 million and RMB 1,442 million lower than the pre-control baseline, respectively, yielding a total carbon cost reduction of RMB 2,618 million. After incorporating technical-retrofit investment into the sensitivity analysis, the carbon cost reduction ranged from RMB 1,879 million to RMB 3,941 million across the fuel-saving-rate and LIME2 parameter scenarios. In all specified scenarios, the carbon cost reduction remained positive, and changes in key parameters affected only the magnitude of the reduction rather than the directional conclusion that process optimization lowers carbon costs. This indicates that the central conclusion derived from the proposed method is robust within the tested parameter ranges; at the same time, the range reflects the effect of key-parameter changes on the magnitude of the simulated results. Because the technical-retrofit investment is based on data for a representative project reported in an official catalogue, enterprises should still evaluate projects based on the actual condition of their equipment, engineering quotations, construction schedules, and the stringency of carbon constraints.

The cost changes reported in this study cover only process-level carbon costs in the steel-product manufacturing stage that can be traced directly through carbon flow–value flow. Organization-level indirect carbon-management expenditures, including carbon risk management, carbon disclosure, and policy compliance adjustment costs, are important to overall corporate carbon management but are outside the process-level quantitative boundary. Consequently, the current carbon cost estimates do not include these organization-level indirect expenditures, which constitutes a limitation of the study arising from the research boundary.

Beyond this boundary limitation, the study has three additional limitations. First, the method relies

on high-resolution carbon flow–value flow ledgers and integrated data systems that accurately link process-level data on materials, energy, intermediate products, waste, emissions, and prices. It also requires cross-departmental coordination and specialist support. Measurement, matching, or allocation errors may propagate simultaneously into physical and monetary estimates, and small- and medium-sized enterprises face more pronounced constraints in terms of data infrastructure and implementation costs. Second, LIME2 was developed in the Japanese environmental and valuation context. Currency conversion and sensitivity analysis across low to high parameter values capture variation in the monetization coefficient, but applying LIME2 in China may still introduce localization errors arising from differences in ecological exposure, policy and institutional settings, and social preferences. Third, the fuel-saving-rate sensitivity analysis varies only the 8%-12% process-efficiency parameter, and the RMB 146 million technical-retrofit investment is drawn from an official representative project rather than NJ Steel's actual engineering settlement. The analysis therefore does not capture equipment aging, operating fluctuations, construction and financing conditions, operation and maintenance costs, or simultaneous variation in multiple parameters. More generally, the values reported in this study reflect accounting differences between scenarios under fixed output and specified parameters; their interpretation is limited to the model settings and is not used to identify causal effects.

Future research should first collect and separately account for the actual expenditures associated with carbon risk management, carbon disclosure, and policy compliance adjustment. Where a clear and defensible allocation basis is available, these expenditures may then be incorporated into an enterprise-wide carbon cost accounting framework. Building on this extension, future research may proceed in three further directions. First, standardized carbon flow–value flow ledgers and integrated data tools should be improved, with simplified accounting modules and phased implementation pathways designed for small and medium-sized enterprises. Second, China-specific environmental damage coefficients should be developed and cross-validated against carbon prices, social cost estimates, and environmental tax benchmarks. Third, future studies should collect firm-specific data on engineering investments, construction periods, financing, depreciation, and operation and maintenance; conduct dynamic, multi-parameter, or probabilistic sensitivity analyses of technical efficiency, gas recovery rates, energy and carbon prices, output, and exchange rates; and test the framework's scalability in corporate groups, industrial parks, and supply-chain settings.

Achieving carbon peaking and carbon neutrality is a broad and profound systematic economic and social transformation. It requires top-down design and policy support, as well as bottom-up implementation, practical innovation, and pragmatic actions. As China progresses toward carbon peaking and carbon neutrality, more industrial enterprises will inevitably be included in the carbon emissions trading market. Facing increasingly strict carbon emission regulations, reducing carbon emissions and carbon costs, and improving carbon performance have become rational priorities for enterprises, particularly those with high emissions. Although this paper takes NJ Steel as the case study, the findings provide useful implications for enterprises seeking to strengthen carbon emission management, improve carbon cost control, and advance their low-carbon transition.

Actively exploring scientific carbon emission reduction management systems can provide effective solutions for enterprises to reduce carbon emissions and control carbon costs. Developing and issuing "Guidelines for Carbon Cost Control" is a key countermeasure. The "carbon flow" and "value flow" proposed in this study overcome the limitations of traditional cost methods that focus on the total cost and ignore the cost-generating process. They can provide scientific management tools for enterprises to identify high-carbon-emission processes and optimize the carbon emission cost structure. Promoting these methods across all enterprises and institutions can provide micro-institutional support for China to achieve carbon peaking and carbon neutrality.

Carbon flow analysis can clearly show the transfer direction and quantity of carbon-containing resources, providing an effective management tool for enterprises to formulate carbon emission inventories and identify key carbon emission areas.

The value flow reflects, in monetary terms, the economic cost that an enterprise must bear due to the use of carbon-containing resources. This encourages enterprises to raise awareness of using clean materials and energy. The external environmental damage cost caused by carbon emissions also encourages enterprises to reduce environmental damage and improve environmental benefits by improving production processes and adopting low-carbon technologies.

The carbon cost control process clearly reflects the internal logical relationship among the use of carbon-containing resources, carbon emissions, and carbon costs. This finding highlights that enterprises must adopt cleaner resources and energy to control carbon risks at the source. The demand for clean materials and energy, in turn, promotes the development of China's clean resource market and the transformation of energy and industrial structures.

## Acknowledgments

This study was financially supported by the National Social Science Foundation Late Grant Program [Grant No. 23FGLB011]; the Hunan Natural Science Foundation [Grant No. 2024JJ5328]; and the Postgraduate Scientific

Research Innovation Project of Hunan Province [Grant No. LXBZZ2024245].

## AI Usage Disclosure Statement

During manuscript revision, the authors used Codex (OpenAI) to assist with language polishing, text formatting adjustments, and consistency checks. The authors reviewed and verified the content and take full responsibility for the content of this study.

## Conflict of Interest

The authors declare no conflict of interest.

## References


1. METCALF G.E. On the Economics of a Carbon Tax for the United States. Brookings Papers on Economic Activity. **2019**, 405, **2019**.
2. WANG X., SUN X., AHMAD M., CHEN J. Energy transition, ecological governance, globalization, and environmental sustainability: Insights from the top ten emitting countries. Energy. **292**, 130551, **2024**.
3. WANG K., WANG Z., XIAN Y., SHI X., YU J., FENG K., HUBACEK K., WEI Y.-M. Optimizing the rolling out plan of China's carbon market. iScience. **26** (1), 105823, **2023**.
4. ZHU J., ZHAO Y., ZHENG L. The Impact of the EU Carbon Border Adjustment Mechanism on China's Exports to the EU. Energies. **17** (2), 509, **2024**.
5. STEDE J., PAULIUK S., HARDADI G., NEUHOFF K. Carbon pricing of basic materials: Incentives and risks for the value chain and consumers. Ecological Economics. **189**, 107168, **2021**.
6. YU M., CRUZ J.M., LI D., MASOUMI A.H. A multiperiod competitive supply chain framework with environmental policies and investments in sustainable operations. European Journal of Operational Research. **300** (1), 112, **2022**.
7. YING H., YANG H., CIFUENTES-FAURA J., RAUF A. The role of carbon trading in enhancing enterprise green productivity and ESG performance: A quasi-natural evidence from China. Business Strategy and the Environment. **34** (2), 1691, **2025**.
8. MA G., LIANG M., SUN W. Effect Analysis of Carbon Information on Enterprise Value Based on Big Data. Mathematical Problems in Engineering. **2022** (1), 4406064, **2022**.
9. SONG Y., LI Y., LIU T. Carbon asset remolding and potential benefit measurement of machinery products in the light of lean production and low-carbon investment. Technological Forecasting and Social Change. **186** (Part B), 122166, **2023**.
10. JIA Z., LIN B. Rethinking the choice of carbon tax and carbon trading in China. Technological Forecasting and Social Change. **159**, 120187, **2020**.
11. VAN DEN BREMER T.S., VAN DER PLOEG F. The Risk-Adjusted Carbon Price. American Economic Review. **111** (9), 2782, **2021**.
12. ZHANG H.R., LI X.L. Carbon cost management from the perspective of low-carbon economy. Friends of Accounting. (25), 36, **2012** [in Chinese].
13. DOLPHIN G., MERKLE M. Emissions-weighted carbon price: Sources and methods. Scientific Data. **11** (1), 1017, **2024**.
14. ZHANG C.P., SONG K.Y., LIU M.J. Research on the two-dimensional carbon cost control framework of "internal low-carbon operation - external government regulation". Communication of Finance and Accounting. (32), 67, **2018** [In Chinese].
15. LUO W., ZHANG Y., GAO Y., LIU Y., SHI C., WANG Y. Life cycle carbon cost of buildings under carbon trading and carbon tax system in China. Sustainable Cities and Society. **66**, 102509, **2021**.
16. ZHANG F., HONG L., XU Y. Prospects for green steelmaking technology with low carbon emissions in China. Carbon Energy. **6** (2), e456, **2024**.
17. TOL R.S.J. Social cost of carbon estimates have increased over time. Nature Climate Change. **13** (6), 532, **2023**.
18. DING R.J., YIN L. Analysis of enterprise carbon cost control based on process. China Mining Magazine. **24** (3), 60, **2015** [In Chinese].
19. ZHOU Z.F., HUANG Y., LI S.H. Carbon costs of process manufacturing enterprises: classification, accounting, and control. World Sci-Tech R & D. **38** (2), 403, **2016** [In Chinese].
20. BUI B., WANG Z., TEKATHEN M. Carbon toolmaking: Responding to multiple interacting logics in carbon management. Accounting, Auditing & Accountability Journal. **37** (1), 227, **2024**.
21. KAMBANOU M.L., SAKAO T. Using life cycle costing (LCC) to select circular measures: A discussion and practical approach. Resources, Conservation and Recycling. **155**, 104650, **2020**.
22. HE B., DING W., ZHANG D. Does the Digital Economy Matter for Carbon Emissions in China? Mechanism and Path. Polish Journal of Environmental Studies. **34** (6), 7123, **2025**.
23. KOKUBU K., KITADA H., NISHITANI K., SHINOHARA A. How material flow cost accounting contributes to the SDGs through improving management decision-making. Journal of Material Cycles and Waste Management. **25** (5), 2783, **2023**.
24. HAMRAOUI L., BERGANI A., ETTOUMI M., ABOULAICH A., TAHA Y., KHALIL A., NECULITA C. M., BENZAAZOUA M. Towards a circular economy in the mining industry: Possible solutions for water recovery through advanced mineral tailings dewatering. Minerals. **14** (3), 319, **2024**.
25. CHEN H., ZHENG Y., ZHOU K., CHENG R., ZHENG X., MA Z., SHI L. Carbon emission efficiency evaluation of wastewater treatment plants: evidence from China. Environmental Science and Pollution Research. **30** (31), 76606, **2023**.
26. TOL R.S.J. Trends and biases in the social cost of carbon. Annals of the New York Academy of Sciences. **1548** (1), 248, **2025**.
27. PAULIUK S., FISHMAN T., HEEREN N., BERRILL P., TU Q., WOLFRAM P., HERTWICH E.G. Linking service provision to material cycles: A new framework for studying the resource efficiency–climate change (RECC) nexus. Journal of Industrial Ecology. **25** (2), 260, **2021**.
28. STADTHERR F., WOUTERS M. Extending target costing to include targets for R&D costs and production investments for a modular product portfolio – A case

study. International Journal of Production Economics. **231**, 107871, **2021**.
29. VANHOUCKE M. Tolerance limits for project control: An overview of different approaches. Computers & Industrial Engineering. **127**, 467, **2019**.
30. WALLS C., PUTRI A.R.K., BECK G. Material flow cost accounting as a resource-saving tool for emerging recycling technologies. Clean Technologies. **5** (2), 652, **2023**.
31. BELANY P., HRABOVSKY P., KOLKOVA Z. Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings. Energy Reports. **7**, 2470, **2021**.
32. HOLMAN C., MCCORD K.H., HU A., DILLON H.E., ANTONOPOULOS C.A. Future grid mix impacts on whole-building life cycle assessment. Environmental Research: Infrastructure and Sustainability. **5** (1), 015025, **2025**.
33. ITSUBO N., INABA A. LIME2: life-cycle impact assessment method based on endpoint modeling. Japan Environmental Management Association for Industry, Tokyo, pp. 108-553, **2010**.
34. LIN B.Q. Generalized energy conservation under the background of carbon neutrality - new connotation of energy conservation based on industrial structure adjustment, low-carbon consumption, and circular economy. Journal of Xiamen University (Arts & Social Sciences). **72** (2), 10, **2022** [In Chinese].
35. CUI J., WANG C., ZHANG J., ZHENG Y. The effectiveness of China's regional carbon market pilots in reducing firm emissions. Proceedings of the National Academy of Sciences. **118** (52), e2109912118, **2021**.
36. ZHANG X., LIU Z., YANG L. Does the carbon emission trading scheme truly enhance green innovation efficiency? From the perspective of market mechanism and government intervention. Polish Journal of Environmental Studies. **34** (6), 8435, **2025**.
37. LIU X.J. Research on carbon cost accounting of coal-fired power enterprises from the perspective of MFCA. China Management Informationization. **21** (3), 40, **2018** [In Chinese].
38. XIAO X., LI Z. Resource value flow accounting: theoretical framework and application model. Finance and Accounting Monthly. (1), 16, **2018** [In Chinese].
39. DU X.Q., ZHOU J.C., SHANGGUAN F.Q., LI X.P., CUI Z.F. Analysis of $CO_2$ emissions and emission reduction measures in the pre-ironmaking system based on carbon flow. Sintering and Pelletizing. **47** (1), 24, **2022** [In Chinese].
40. ZHANG C.P., GUO S.Y. On carbon cost accounting based on "carbon flow - value flow". Finance and Accounting Monthly. (23), 8, **2019** [In Chinese].
41. ZHANG C.P., HE T., LIU M.J. Research on carbon performance evaluation of papermaking enterprises from the perspective of carbon value flow. Journal of Dalian University of Technology (Social Sciences). **42** (2), 50, **2021** [In Chinese].
42. XU X.A. Analysis of enterprise carbon cost accounting based on resource value flow - taking the steel industry as an example. Communication of Finance and Accounting. (22), 132, **2020** [In Chinese].
43. PAN X.B., HUANG Y.F. On the proposal and implementation process of China's carbon neutrality vision. Resources Conservation & Environmental Protection. (9), 126, **2021** [in Chinese].
44. GE W., CAO H., LI H., ZHANG Q., WEN X., ZHANG C., MATIVENGA P. Data-driven carbon emission accounting for manufacturing systems based on meta-carbon-emission block. Journal of Manufacturing Systems. **74**, 141, **2024**.
45. REICHELSTEIN S. Corporate carbon accounting: Balance sheets and flow statements. Review of Accounting Studies. **29** (3), 2125, **2024**.
46. JIANG Y., LUO L., TSANG A., ZHANG Y. Carbon emission trading scheme and carbon performance: The role of carbon management system. The British Accounting Review. **57** (3), 101492, **2025**.
47. BABEL M., KOERNER M.F., STROEHER T., STRUEKER J. Accelerating decarbonization digitally: Status quo and potentials of greenhouse gas emission tracking and trading. Journal of Cleaner Production. **469**, 143125, **2024**.
48. WANG Y., LYU C. Carbon emissions trading system and corporate financial decisions: Evidence from China. Carbon Management. **17** (1), 2618351, **2026**.
49. SHI W., ZHANG Y.J., LIU J.Y. Investigating the role of emissions trading system in reducing enterprise energy intensity: Evidence from China. Energy Economics. **140**, 108005, **2024**.
50. WANG B., DUAN M. Have China's emissions trading systems reduced carbon emissions? Firm-level evidence from the power sector. Applied Energy. **378**, 124802, **2025**.
51. DI VAIO A., ZAFFAR A., CHHABRA M., BALSALOBRE-LORENTE D. Carbon accounting and integrated reporting for net-zero business models towards sustainable development: A systematic literature review. Business Strategy and the Environment. **33** (7), 7216, **2024**.
52. NATIONAL DEVELOPMENT AND REFORM COMMISSION OF THE PEOPLE'S REPUBLIC OF CHINA. National Key Energy-Saving Technology Promotion Catalogue (Fifth Batch). National Development and Reform Commission of the People's Republic of China, Beijing, **2012** [In Chinese].