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Carbon Reduction in Steel Enterprises Under Carbon–Energy-Material Market Coupling: A System Dynamics Approach

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Abstract

Amid growing concerns over carbon emissions from the steel industry, China, the world's largest steel producer, formally incorporated the steel sector into its national carbon emissions trading system (ETS) in March 2025. This study uses actual and projected data to calculate China's steel industry carbon emissions (2021–2030) and explore its carbon reduction benefits under the carbon market. This study employs a system dynamics approach to innovatively construct a five-party coupled model, thus overcoming the limitations of single-perspective analysis and mitigating the waterbed effect in emissions reduction. Simulation results indicate: (1) The carbon market mechanism exerts a significant leverage effect on carbon prices, serving as the core signal driving industrial low-carbon transformation; (2) discrepancies in carbon emission reduction capabilities among enterprises will intensify structural adjustments, with the increase in the proportion of short-process steelmaking relying on dual drivers of policy guidance and technological innovation; and (3) demand-side emission reduction is the most effective pathway to achieve "dual carbon" goals, as it directly suppresses excess production and aligns with sustainable consumption patterns. This study provides China's steel industry with carbon reduction options under the carbon market, aids the Chinese government's carbon reduction strategy formulation, and offers insights for global carbon management.

Keywords: carbon market; system dynamics; carbon–energy-material market coupling system

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1. Introduction

1.1. Background and Motivation

Amid global economic growth, CO_2 emissions have risen with industrial expansion, demanding effective global warming governance. In response to global climate change, 196 parties to the United Nations Climate Change Conference established the United Nations Framework Convention on Climate Change in Paris. Nonetheless, the global community remains misaligned with the goals outlined in the Paris Agreement, necessitating further mitigation measures to attain net-zero emissions by 2050 [1]. The carbon trading market is a mechanism that can significantly reduce carbon dioxide emissions [2–4]. As the world's largest CO_2 emitter and the world's largest steel-producing country [5], China responded to the international community's initiative to address climate change by establishing a regional pilot carbon trading market to regulate and verify emissions in 2011 [6] and a unified national carbon emissions trading market in 2021, focusing mainly on the market-based operation of carbon emission rights in the power sector. In March 2025, with the

approval of the State Council, China's Ministry of Ecology and Environment issued the Work Plan for Including the Steel, Cement, and Aluminum Smelting Sectors in the National Carbon Emissions Trading Market, formally expanding the national ETS to cover these three industries [7]. Under the phased implementation framework, 2024 was designated as the first regulated emissions year, with the first compliance deadline set for the end of 2025. The allowance allocation mechanism also follows a gradual transition, with allowances for 2024 matching verified emissions and those for 2025 and 2026 allocated based on emissions intensity.

In the newly covered industries, the steel industry, as a typical representative of global energy-intensive industries, accounts for about 25% of total global industrial emissions [8], making it the highest carbon-emitting industry in the global industrial sector [9]. Among all countries, China's iron and steel sector is marked by high energy intensity and heavy pollutant emissions. It dominates global energy usage, contributing 15% of the nation's total energy supply, and its carbon emissions make up over 50% of global steel industry carbon emissions [10]. This structural feature indicates that the low-carbon transformation of the steel industry is essential for achieving China's "dual carbon" goals, which refer to peaking carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060 [5]. Moreover, the decarbonization of China's steel industry has strategic significance for global climate governance [11]. The inclusion of the steel industry in the national carbon market is therefore expected to provide additional market-based incentives for its low-carbon transformation.

To achieve global carbon emissions management, a study of the emission reduction pathways for China's steel industry is required. However, in the context of the expansion of participants in China's carbon market, there has been a paucity of research on the trading mechanisms for the steel industry within the carbon market, with the majority of scholars focusing on studies of the carbon trading market in sectors such as the power sector [12–16]. In light of the aforementioned practical requirements and theoretical gaps, this study posits that there is an urgent need to develop a model that is capable of adequately describing carbon market transactions within the steel industry. This would facilitate exploration of emission reduction pathways under multi-market coupling in the steel industry, identify mechanism compatibility conflicts arising from the expansion of the carbon market, and seek solutions to these issues.

1.2. Literature Review

Existing research has identified two core paths for emissions reduction in the steel industry: optimisation at the production end and intervention through market mechanisms. From the production-end perspective, carbon emissions in China's steel industry are primarily composed of direct carbon emissions from fossil fuel combustion and indirect carbon emissions from electricity consumption [17,18]. For the steel industry's production-side carbon reduction path, China's steel production relies on two processes: the iron ore-based blast furnace-converter process and the scrap-based electric arc furnace process. The long-flow production process is the core process for Chinese steel production, with a structure that accounts for more than 90% of the total. The technology is integrated with the blast furnace process through the oxygen top-blown converter (BOF), where iron ore is pre-treated with pellet or sinter ore for coke reaction, and coke is smelted through coke ovens to complete the raw material. The EAF process accounts for less than 10% of use in China. As a process that uses scrap as the main raw material for production, the EAF is regarded as a secondary process for steel manufacturing, and EAF production relies mainly on electricity to generate heat, using about 70–100% scrap and direct reduced iron (DRI) as the main raw materials [19]. Increasing the production share of short-process steelmaking is

considered an important path for future carbon reduction in the steel industry [20]. Mutual co-operation between industry, government and academia is also needed to achieve the goal of carbon reduction in the steel industry [21].

From the perspective of market-based interventions, the EU Emissions Trading System (EU ETS) and China's national emissions trading system differ in their emissions constraints and allowance allocation mechanisms. The EU ETS operates under a declining absolute emissions cap and primarily allocates allowances through auctions while retaining benchmark-based free allocation for industrial sectors exposed to carbon leakage risks, including steelmaking [22]. By contrast, China's national ETS, which was expanded to cover steel, cement, and aluminium smelting in 2025 [7], follows an emissions-intensity-based allocation approach for these newly covered sectors under its 2026 allowance allocation plan [23]. Thus, whereas the EU ETS directly constrains aggregate emissions through a declining cap, China's current allocation mechanism places greater emphasis on relative emissions performance. These institutional differences also shape how emissions trading interacts with complementary policies. The "waterbed effect" refers to the potential offsetting of emission reductions achieved by complementary policies when reduced allowance demand permits higher emissions elsewhere within an ETS, unless allowance supply is adjusted accordingly [24]. The EU has established a Market Stability Reserve (MSR) to address allowance surpluses and adjust auction supply, although this mechanism does not eliminate all policy interaction risks [25]. Verde et al. [24] noted that China's intensity-based ETS may also experience waterbed effects, but through mechanisms that differ from those of a fixed-cap trading system. These findings highlight the importance of coordinating emissions trading with technological innovation incentives, energy policies, and industrial regulations. Meanwhile, empirical studies of China's carbon trading pilots have documented emission reduction outcomes, regional spillovers, and heterogeneous policy effects [26–28].

Studies beyond China have also investigated technological, material, and regulatory pathways for steel industry decarbonization. At the global level, Lei et al. [8] examined plant-level steel emissions and carbon neutrality pathways. In a UK-related study, Serrenho et al. [9] showed that national emission reduction targets can have implications beyond national borders through changes in steel production and trade, highlighting the importance of a global perspective. In Sweden, Karakaya et al. [29] analysed the transition toward hydrogen-based steelmaking, emphasising the role of innovation systems and collaboration among industrial actors. Vogl et al. [30] assessed the technical and economic feasibility of hydrogen-based direct reduction and demonstrated the importance of electricity prices and scrap utilisation. From a market policy perspective, Graupner et al. [31] investigated how EU ETS allowance allocation benchmarks influence low-carbon investment pathways in Germany's primary steelmaking sector. Collectively, these international studies suggest that steel decarbonization depends on technological innovation, energy and material inputs, and the design of market-based policy incentives.

Beyond evaluations of emissions trading policies, existing studies have also examined energy-saving and emission reduction efficiency from a regional perspective. Guo and Li [32] employed an undesirable output SBM model to evaluate the energy-saving and emission reduction efficiency of 49 cities across China's three major urban agglomerations and spatial econometric models to investigate the influencing factors. Their findings revealed considerable regional disparities, with urbanisation and energy structure exerting significant negative effects across all three urban agglomerations, while industrial structure had a significant negative effect in the Beijing–Tianjin–Hebei region. These findings highlight the importance of structural factors in energy-saving and emission reduction performance. However, the dynamic interactions among carbon market mechanisms, technological innova-

tion, production structures, and market demand within specific energy-intensive industries remain insufficiently explored.

Most of the existing literature focuses on the operation of the carbon market in China's power system [33–35], and there is a lack of research on the inclusion of the carbon market in the rest of China's industries, especially the steel sector. The related benefits and impacts of the steel industry are still at the stage of theoretical research [36]; most of the existing studies take a single perspective on life cycle carbon footprints [37], steel consumption [11], and steel technology innovation [38] to explore the iron and steel industry to achieve carbon reduction, which lacks a synergistic perspective and is prone to fall into the waterbed effect. International research has further provided insights into global emissions displacement, hydrogen-based production, and the policy incentives created by the EU ETS [9,31]. Several studies have demonstrated the effective impact of carbon markets on emissions reduction in China's power sector [39,40], but for the steel industry, the operational effectiveness of the carbon market's emissions reduction framework has yet to be effectively explored. At the same time, research on the two major pathways for emissions reduction in the steel industry is fragmented, and research on the joint carbon reduction effects under "technology–market" synergy is insufficiently developed. The dynamic feedback resulting from multi-stakeholder interactions is difficult to capture.

1.3. Research Contributions

Although carbon emissions trading and its interactions with energy markets have been widely studied, the dynamic relationships among carbon allowance trading, steel production processes, technological innovation, and material and energy consumption in China's steel industry remain insufficiently examined. The production and emission reduction activities of steel enterprises are influenced by government policies, market demand, and technological capabilities, while changes in production and allowance trading may also affect carbon market conditions, creating feedback relationships. System dynamics is therefore suitable for analysing these interactions. Previous research has investigated interactions between energy quota trading and carbon emissions trading [41], modelled the coupling of electricity, carbon, and green certificate markets [42,43], and analysed the relationship between carbon and electricity markets in regional contexts [44].

Building on previous studies of carbon market coupling and steel industry decarbonization, this study develops a system dynamics model that integrates five subsystems: carbon market operation, carbon reduction innovation, policy regulation, energy-material supply, and the natural environment. Unlike existing models that primarily examine transactions and price relationships among energy and carbon markets, this study focuses on how carbon market operations interact with the production structure and emission reduction activities of steel enterprises. The model distinguishes between long- and short-process steelmaking, accounts for the corresponding consumption of energy and raw materials, and incorporates carbon allowance trading, technological innovation, and policy regulation into a common dynamic framework.

The main contribution of this study lies in the integration of these mechanisms and their feedback relationships. First, the model connects steel production structure and material-energy consumption with carbon emissions and allowance trading, allowing changes in production activities to be examined alongside carbon market dynamics. Second, it incorporates enterprise and university R&D activities to describe how technological innovation influences steel production structure and emission reduction capacity. Third, by simulating changes in policy incentives, technological capabilities, enterprise profitability, and steel demand, the model examines how different driving factors affect carbon prices, production structure, and emission reduction outcomes over time. This framework extends existing

market-oriented system dynamics studies to the production and decarbonization processes of the steel industry.

The study finds that the carbon market mechanism has a significant leverage effect on the carbon price, an increase in the proportion of short-process steelmaking relies on the dual driving force of policy and technological innovation, the carbon reduction ability of enterprises is differentiated and intensifies the structural change of the industry, and a reduction in carbon emissions from the demand side can achieve the twin goal of carbon reduction more quickly. These findings enrich the theory of carbon market construction and provide strong support for further improvements by governments and enterprises. This study concludes that in order to further enhance the benefits of carbon reduction, it is necessary to start with both the government and enterprises: the government must synergise technological research and development with industrial transformation, regulatory constraints, and market guidance, while enterprises need to achieve breakthroughs in low-carbon technologies, optimise production processes, and realise supply chain synergies as soon as possible.

The rest of the structure is organised as follows: Section 2 describes the materials and methods, Section 3 describes the simulation and design, Section 4 presents an analysis of the results and Section 5 presents the conclusions and recommendations.

2. Materials and Methods

In order to effectively capture the complex dynamic interactions and feedback mechanisms among the multiple subjects involved in the carbon reduction process in the iron and steel industry, this study adopts a system dynamics approach to construct a coupled model. This approach is particularly suitable for analysing the coupled carbon–energy-material market system with a high-order, multivariate and nonlinear feedback structure. Specifically, a model containing the following five major subsystems is constructed in this section: the carbon market operation subsystem (CMOS), the carbon-reducing innovation subsystem (CRIS), the policy-driven subsystem (PDS), the energy-material supply subsystem (EMSS) and the natural environment subsystem (NES). Through this model, the study simulates and analyses the carbon reduction pathway and its effectiveness in the iron and steel industry under the carbon market mechanism, aiming to provide a theoretical basis for the practice of Chinese iron and steel enterprises, as well as multi-dimensional decision-making support for the design of the global carbon market for the iron and steel industry. It also examines the responses of the coupled system under different scenarios.

2.1. Theoretical Framework Analysis

The material and information flow among the CMOS, CRIS, PDS, EMSS, and NES is dynamic and cyclical (Figure 1). To clarify system relationships, the paper analyses each system's role. From the perspective of carbon reduction technological innovation, some studies have confirmed that innovations from industry–university–research synergy can effectively inhibit carbon emissions [45], and R&D investment also has a diminishing marginal effect on the carbon emission reduction of a company. Thus, it can be assumed that the profit income of enterprises in the carbon market will be invested in their research and development projects, and universities, encouraged by policies and markets, will also upgrade their research and development projects. This will lead to invention patents and technological achievements, together with the research and development of enterprises. The factor flow of such R&D activities approximated by enterprise research institutes and universities will ultimately flow into the carbon market to influence the final carbon reduction results.

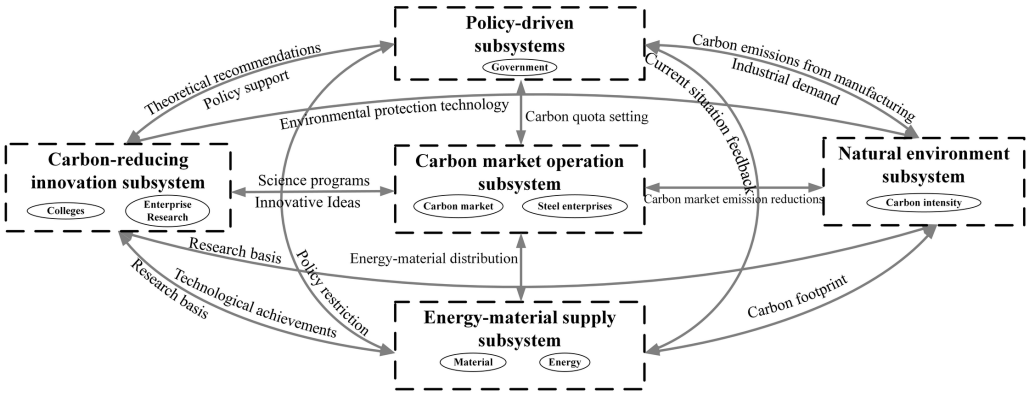

Figure 1. Carbon–energy-material market coupling system.

From the government's perspective, in order to integrate market operations and carbon reduction benefits, the government needs to keep a close eye on the carbon market and promulgate policies that are more in line with reality. Policies directly determine the operation of the carbon market and limit the amount of carbon emitted by long- and short-process iron and steel companies in the energy supply subsystem. Furthermore, government policies have been shown to have a synergistic effect on carbon emission reduction [46].

The activities of steel companies in the carbon market can be divided into production and consumption activities. Focusing on the production activities of iron and steel enterprises, since the production of iron and steel is a complex process, different iron and steel production processes use different energy and raw materials and have different carbon emission factors that affect final carbon emissions. Therefore, it is necessary to break down the production of iron and steel into short-process steelmaking and long-process steelmaking and calculate the energy and raw materials used in the respective processes separately. Ultimately, all carbon emissions will be released into the natural environment and will be accounted for by the relevant organisations.

Focusing on the consumption activities of steel enterprises, this paper divides steel enterprises into advanced steel enterprises with surplus carbon allowances and backward steel enterprises in need of carbon allowances, between which the consumption activities of carbon allowances are subject to the social demand for iron and steel as well as the policy limitations on carbon emissions. The trading activities between steel enterprises are regarded as a whole system that reflects the flow of information and material resources within the carbon market and with the rest of the subsystems, which is named the carbon market operation subsystem in this paper.

Based on the five subsystems of the CMOS, CRIS, PDS, EMSS, and NES, which are summarised and named in this paper, this paper constructs a coupled model for carbon reduction in the iron and steel industry. After constructing the model, it collects relevant data from the China Statistical Yearbook for the past ten years and cleans up and processes the data to carry out simulation and visualisation.

2.2. Modelling

In the model constructed in this study, steel enterprises are divided into two parts: buyer steel enterprises and seller steel enterprises. The production of steel is divided into two parties: long process and short process [47]. The limit of carbon emission is regulated by the government policy, and the carbon reduction technology of steel is influenced by the R&D of enterprises and schools. The carbon market is primarily represented through carbon allowance supply, trading, and price formation. The economic effects of allowance trading are reflected in profit margins and production capacity adjustments of steel enterprises,

while broader financial mechanisms, such as financing activities and carbon-related financial derivatives, are not explicitly modelled. This simplification allows the study to focus on the feedback relationships among carbon trading, enterprise production, technological innovation, and carbon emissions while avoiding additional assumptions associated with financial mechanisms for which reliable parameter data are limited.

To ensure the scientific robustness of the system dynamics model, the following premises are established: (1) The system is assumed to encompass solely China's domestic iron and steel industry [48,49]. (2) Steel production is limited by demand and carbon emissions. (3) It is assumed that seller steel enterprises are steel enterprises with certain carbon reduction technologies and can steadily achieve a certain proportion of carbon reduction to the supply of carbon allowances over the simulation time. (4) The carbon allowances among steel enterprises are fully competitive in terms of trading volume, and the carbon price is dynamically determined by the supply and demand situation in the market [50]. (5) Iron and steel enterprises strictly abide by the limits of carbon allowances, and the sum of carbon emissions of all enterprises will not exceed the carbon allowance limit for the year. (6) The carbon market trading situation is highly transparent, and the information of each participant is timely and effective.

Based on the above assumptions, the model establishes relationships among the five subsystems through technological innovation, production structure adjustment, energy and material consumption, carbon emissions, and carbon allowance trading. These relationships reflect both physical processes and economic mechanisms. Specifically, material consumption and carbon emissions are calculated according to the production characteristics of different steelmaking processes, while carbon allowance trading influences enterprise profitability and production capacity adjustments. The model also incorporates technical and economic considerations through production input coefficients, adjustment delays, trading volume restrictions, and price boundaries. To clarify the interpretation and specification of these relationships, the complete model equations, variable units, parameter values, and corresponding sources are provided in Table S1 of the Supplementary Materials [51–53].

2.2.1. Carbon Reduction Innovation Subsystem

The stock and flow diagram of the CRIS is shown in Figure 2, which represents the relationship between various elements affecting the carbon reduction innovation capacity of enterprises. In the CRIS, colleges, universities, and enterprise research institutes undertake the tasks of cultivating talent and realising scientific and technological achievements. Universities establish the theoretical underpinnings of the carbon reduction innovation system by investigating R&D topics in the iron and steel sector and publishing related academic papers. Enterprise research institutions, leveraging corporate investments and talent attraction, enhance their R&D capacity and the ability to commercialise technological achievements, thereby translating university-developed theories into practical applications and scientific and technological achievements that reduce emissions, which can provide assistance to the operation of iron and steel enterprises.

The number of R&D topics in the iron and steel industry in universities is related to university R&D topics, policy research guidance, and the percentage of R&D topics in the iron and steel industry in universities. Improved policy guidance enhances research on the steel industry in universities. According to the processing of statistical data, it is found that the output of steel industry R&D academic papers in colleges and universities is linearly correlated with the steel industry R&D topics in colleges and universities and the proportion of steel industry R&D topics in colleges and universities. Therefore, the correlation formula can be expressed as:

$$S_{\text{highschoolsteel}} = S_{\text{highschool}} * R_{\text{highschoolsteel}} * L_{gov} \quad (1)$$

$$S_{\text{highschoolpaper}} = 0.623 * S_{\text{highschoolsteel}} + 698391 * R_{\text{highschoolsteel}} \quad (2)$$

where $S_{\text{highschoolpaper}}$ represents the output of academic papers on R&D in the steel industry in universities, $S_{\text{highschoolsteel}}$ represents R&D topics in the steel industry in universities, $S_{\text{highschool}}$ represents R&D topics in universities, $R_{\text{highschoolsteel}}$ represents the percentage of R&D topics in the steel industry in universities, and L_{gov} represents policy guidance.

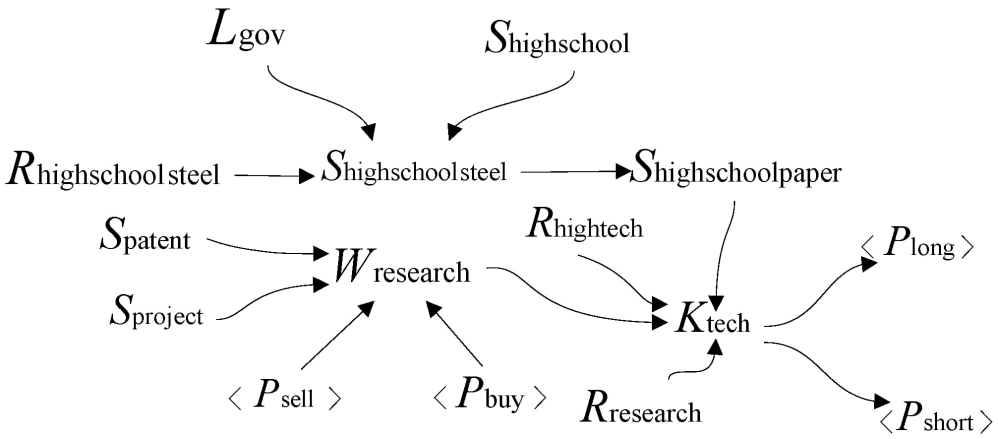

Figure 2. CRIS stock and flow diagram.

The R&D capability of enterprises, on the other hand, is influenced by the profit margins of the steel enterprises on both the buyer and seller sides, the R&D projects of the steel enterprises, and the number of R&D patents in the steel industry. The related functional relationship equation is expressed as follows:

$$W_{\text{research}} = \left(0.6 * S_{\text{patent}} - 1\right) + 0.4 * \left(S_{\text{project}} + 1\right) * \left[\left(1 + \frac{P_{\text{sell}}}{280}\right) * \left(1 + \frac{P_{\text{buy}}}{280}\right)\right] \quad (3)$$

where W_{research} denotes the R&D capability of steel enterprises, S_{patent} denotes the number of R&D patents of steel enterprises, S_{project} denotes the R&D projects of steel companies, P_{sell} denotes the profit of the seller's steel companies and P_{buy} denotes the profit of the buyer's steel companies.

Finally, in accordance with the university steel industry R&D academic paper output and steel industry enterprise R&D capacity, and comprehensive consideration of the conversion rate and the construction of scientific and technological achievements affecting the proportion of long- and short-process production, the specific function is as follows:

$$K_{\text{tech}} = \frac{\ln\left(R_{\text{hightech}} * S_{\text{highschoolpaper}} + R_{\text{research}} * W_{\text{research}}\right)}{2} \quad (4)$$

where K_{tech} represents the technology of scientific and technological achievements, R_{hightech} represents the conversion rate of scientific and technological achievements of universities, and R_{research} represents the conversion rate of R&D capacity of steel enterprises.

2.2.2. Energy-Material Supply Subsystem

The constructed stock and flow diagram of the energy supply subsystem is shown in Figure 3. In the energy supply subsystem, the output of long-process and short-process steel production is influenced by their respective shares. Long-process steel production is mainly based on the blast furnace-converter process, which is highly dependent on the exothermic combustion of fossil fuels (e.g., coke). The raw materials are mainly iron ore and limestone, supplemented by a small amount of scrap, resulting in high carbon emissions. Short-flow steel production, on the other hand, is dominated by electric furnaces, where the heat source

comes from electricity, and the main raw material is steel scrap, supplemented by a small amount of iron and trace amounts of limestone, resulting in relatively low carbon emissions.

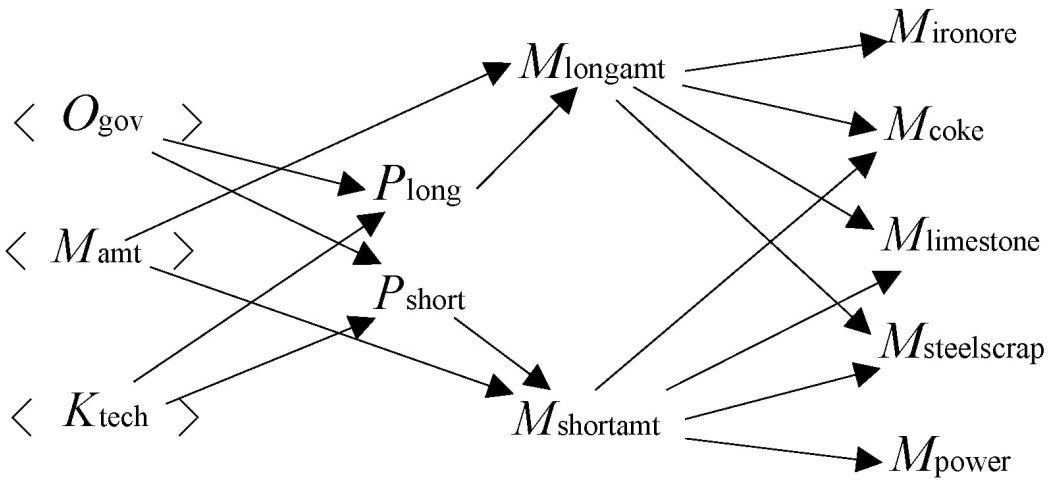

Figure 3. EMSS stock and flow diagram.

Steel production in the long and short processes is derived from a combination of total steel production, scientific and technological successes, and steel production policies, according to their respective shares. The relevant formulae are given as follows:

$$M_{longamt} = P_{long} * M_{amt} \tag{5}$$

$$M_{shortamt} = P_{short} * M_{amt} \tag{6}$$

$$P_{long} = \mathrm{INTEG}(-\frac{K_{tech} * O_{gov}}{\mathrm{INITIAL}(K_{tech})}, \alpha_{long}) \tag{7}$$

$$P_{short} = \mathrm{INTEG}(\frac{K_{tech} * O_{gov}}{\mathrm{INITIAL}(K_{tech})}, \alpha_{short}) \tag{8}$$

where $M_{longamt}$ denotes long-process steel production, $M_{shortamt}$ denotes short-process steel production, M_{amt} denotes steel production, P_{long} denotes the share of long-process steel production, P_{short} denotes the share of short-process steel production, O_{gov} denotes steel production policy making, α_{long} denotes the initial share of long-process steel production, and α_{short} denotes the initial share of short-process steel production.

The raw materials for production at each level are formulated based on the percentage of long and short processes and the formulation within each process. Their specific assignments are as follows:

$$M_{ironore} = \theta_{longiron} * M_{longamt} \tag{9}$$

$$M_{coke} = \theta_{longcoke} * M_{longamt} + \theta_{shortcoke} * M_{shortamt} \tag{10}$$

$$M_{limestone} = \theta_{longlimestone} * M_{longamt} + \theta_{shortlimestone} * M_{shortamt} \tag{11}$$

$$M_{steelscrap} = \theta_{longlsteelscrap} * M_{longamt} + \theta_{shortlsteelscrap} * M_{shortamt} \tag{12}$$

$$M_{power} = \theta_{power} * M_{shortamt} \tag{13}$$

where $M_{ironore}$ denotes iron ore consumption, M_{coke} denotes coke consumption, $M_{limestone}$ denotes limestone consumption, $M_{steelscrap}$ denotes scrap consumption, and M_{power} denotes electricity consumption. The parameter prefixed with θ_{long} is the long-process steelmaking consumption of each raw material, and the parameter prefixed with θ_{short} is the short-process steelmaking consumption of each raw material. The iron ore covered herein is only considered to be used in long-process steelmaking, and the electricity is only considered to be used in short-process steelmaking.

2.2.3. Natural Environment Subsystem

The construction of the stock and flow diagram for the natural environment subsystem model is shown in Figure 4. Within the natural environment subsystem, iron ore, coke, limestone, scrap and electricity each have specific carbon emissions. The carbon footprint of each material is computed by multiplying its carbon emission factor by consumption volume. These individual footprints are then aggregated to determine total CO_2 emissions.

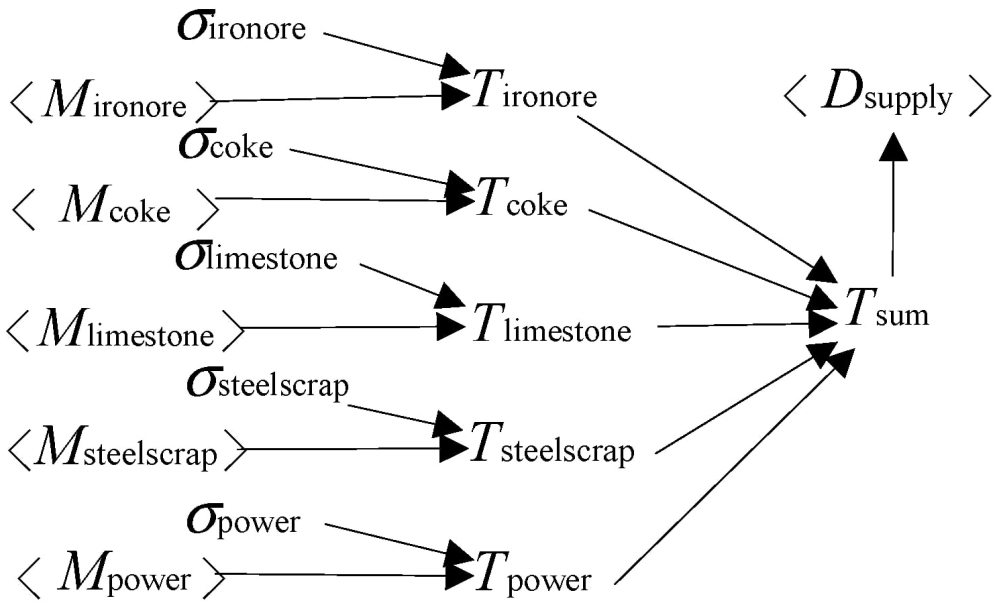

Figure 4. NES stock and flow diagram.

Combining the carbon emission factor with the amount of raw materials used for calculation, the carbon emissions of the relevant raw materials can be derived as follows:

$$T_{\text{ironore}} = \sigma_{\text{ironore}} * M_{\text{ironore}} \quad (14)$$

$$T_{\text{coke}} = \sigma_{\text{coke}} * M_{\text{coke}} \quad (15)$$

$$T_{\text{limestone}} = \sigma_{\text{limestone}} * M_{\text{limestone}} \quad (16)$$

$$T_{\text{steelscrap}} = \sigma_{\text{steelscrap}} * M_{\text{steelscrap}} \quad (17)$$

$$T_{\text{power}} = \sigma_{\text{power}} * M_{\text{power}} \quad (18)$$

where T_{ironore} represents iron ore carbon emissions, T_{coke} represents coke carbon emissions, $T_{\text{limestone}}$ represents limestone carbon emissions, $T_{\text{steelscrap}}$ represents scrap steel carbon emissions, and Tpower represents electricity carbon emissions. σ, which is named after each raw material, represents the corresponding carbon emission factor.

The carbon emissions of each material are summed to obtain the total CO_2 emissions T_{sum}:

$$T_{\text{sum}} = T_{\text{ironore}} + T_{\text{coke}} + T_{\text{limestone}} + T_{\text{steelscrap}} + T_{\text{power}} \quad (19)$$

The emission accounting boundary of the natural environment subsystem covers five specified material and energy inputs: iron ore, coke, limestone, steel scrap, and electricity. The corresponding emissions are calculated by multiplying each input consumption quantity by its emission factor and summing the five components. These components include emissions associated with material inputs, coke-related emissions, process emissions from limestone decomposition, and indirect emissions from electricity consumption. Each component is included once in the model equations, without adding a separate comprehensive upstream emission inventory. Therefore, the calculated emissions represent the scope

of the selected model inputs rather than a complete life cycle carbon footprint. The values, units, calculation equations, and sources of the individual emission factors are provided in Table S1 of the Supplementary Materials.

2.2.4. Policy-Driven Subsystems

Within the PDS, policy regulation is the central component. The system influences the other subsystems mainly through the development of external policy planning, while in its internal operation, the links between the components are relatively loose. For the CMOS, the PDS influences the auction ratio of carbon allowance holdings of seller steel companies; for the NES, policy flexibly adjusts the supply of carbon allowances based on the total carbon dioxide emissions; for the CRIS, the policy incentives lead to an enhancement in the research topics in universities; and for the EMSS, the steel production policy will also have an impact on the amount of long- and short-process steel produced.

For the PDS, most of which is integrated into the operation of the remaining subsystems, and therefore no stock-flow plotting is done, the functional relationships of the variables involved in this subsystem are shown in Table 1 below.

Table 1. PDS parameter list.

Name	Classification	Functional	Unit
Rate of decline of the Social Carbon Emission Reduction Scheme ($Y_{socialrd}$)	auxiliary variable	3.6/12	%
Target carbon emissions (Y_{target})	level variable	$=T_{sum} \times (1 - Y_{socialrd})$	tCO_2
Steel production policy ($Y_{production}$)	auxiliary variable	1/12	%

2.2.5. Carbon Market Operations Subsystem

The stock and flow diagram of the carbon market operation subsystem is shown in Figure 5. In the operation of the carbon market, there are two types of steel enterprises: those with relatively high technological capabilities and low carbon emissions and those with relatively low technological capabilities and high carbon emissions. The former can control their carbon emissions within the carbon emission limits set by the government and make a surplus on their carbon emissions, while the latter, because of their lower technological content, cannot fulfil the government's carbon emission limits in the short term and must seek to purchase carbon allowances in the carbon market. The reallocation of carbon quota holdings in the carbon market generates fluctuations in the price of carbon, which affects the profit margins of both buyers and sellers of iron and steel and, in turn, affects the steel production capacity of both buyers and sellers, which affects the total output of iron and steel, which affects the price of iron and steel, which continues to affect the profit margins of buyers and sellers and realises the internal cycle.

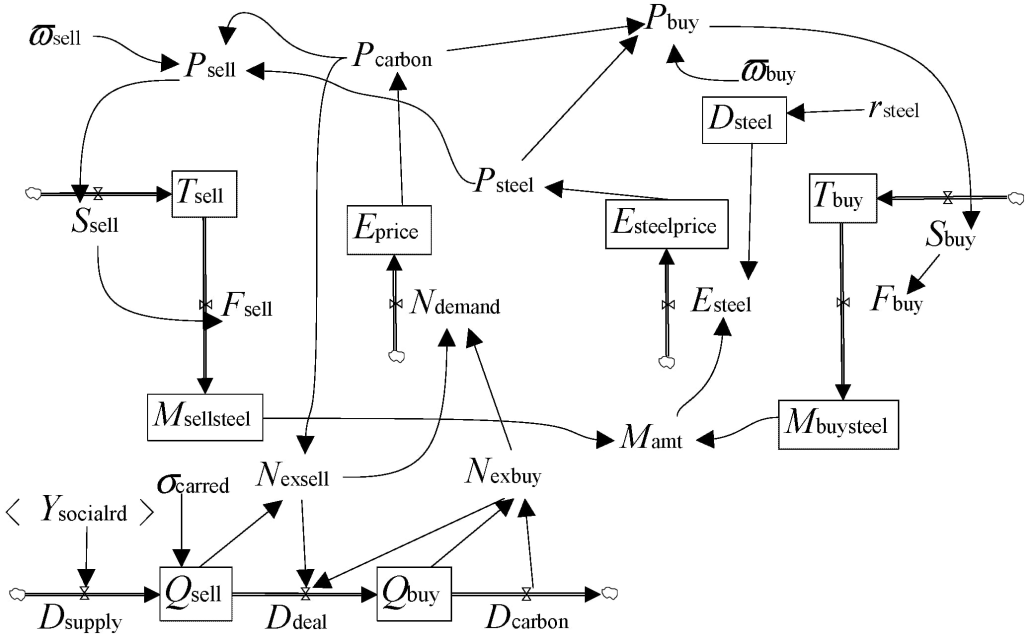

Figure 5. CMOS stock and flow diagram.

The holdings of carbon allowances by buyers and sellers are directly affected by the target carbon emissions set by the policy and are measured against each other based on trading and supply. The relevant formulae are as follows:

$$Q_{\text{sell}} = \text{INTEG}(\sigma_{\text{carred}} * T_{\text{sum}} * (1 - r_{soc}), D_{\text{supply}} - D_{\text{deal}}) \tag{20}$$

$$Q_{\text{buy}} = \text{INTEG}(0, D_{\text{supply}} - D_{\text{deal}}) \tag{21}$$

where Q_{sell} represents the amount of carbon allowances held by the seller's iron and steel enterprises, Q_{buy} represents the amount of carbon allowances held by the buyer's iron and steel enterprises, σ_{carred} represents carbon reduction capacity, r_{soc} represents the rate of decline in the Social Emission Reduction Scheme, D_{supply} represents the supply of carbon allowances, and D_{deal} represents the trading volume of carbon allowances.

When a transaction is completed between a buyer and a seller, a change in the demand for carbon allowances is created in the macro market, which affects the carbon price, which, together with the price of steel and the profits generated by the consumption of traded carbon allowances, affects the profit margins of the buyer and the seller. Due to government control, the carbon price will not normally be too high or too low, so there is a need to limit its range of variation. The relevant formulae are as follows:

$$N_{\text{exsell}} = \frac{P_{\text{carbon}}}{48} * Q_{\text{sell}} \tag{22}$$

$$N_{\text{exbuy}} = IFTHENELSE\left(Q_{\text{buy}} > D_{\text{carbon}}, 0, \frac{48}{P_{\text{carbon}}} * \left(D_{\text{carbon}} - Q_{\text{buy}}\right)\right) \tag{23}$$

$$N_{\text{demand}} = \frac{N_{\text{exbuy}} - N_{\text{exsell}}}{N_{\text{exsell}}} \tag{24}$$

$$E_{\text{price}} = \text{INTEG}(P_{\text{ori}}, N_{\text{demand}}) \tag{25}$$

$$P_{\text{carbon}} = IFTHENELSE\left(\begin{array}{l} SMOOTH3I\left(E_{\text{price}}, 3, P_{\text{ori}}\right) > P_{\text{up}}, P_{\text{up}}, \\ IFTHENELSE\left(\begin{array}{l} SMOOTH3I\left(E_{\text{price}}, 3, P_{\text{ori}}\right) < P_{\text{down}}, P_{\text{down}}, \\ SMOOTH3I\left(E_{\text{price}}, 3, P_{\text{ori}}\right) \end{array}\right) \end{array}\right) \tag{26}$$

$$P_{\text{sell}} = M_{\text{sellsteel}} * \varpi_{\text{sell}} * P_{\text{steel}} + P_{\text{carbon}} * E_{\text{amt}} \tag{27}$$

$$P_{\text{buy}} = M_{\text{buysteel}} * \varpi_{\text{buy}} * P_{\text{steel}} - P_{\text{carbon}} * E_{\text{amt}} \tag{28}$$

where N_{exsell} denotes the expected sales volume of carbon allowances, N_{exbuy} denotes the expected purchase volume of carbon allowances, Pcarbon denotes the carbon price, D_{carbon} denotes the demand for carbon allowances, N_{demand} denotes the excess demand for carbon allowances, E_{price} denotes the change in the price of carbon allowances, P_{ori} denotes the initial price of carbon allowances, P_{up} denotes the upper price of carbon allowances, P_{down} denotes the lower price of carbon allowances, $M_{\text{sellsteel}}$ denotes the steel production of the seller, M_{buysteel} denotes the steel production of the buyer, ϖ_{sell} denotes the profitability coefficient of the seller, ϖ_{buy} denotes the buyer's profitability coefficient, and E_{amt} denotes carbon quota trading volume.

Considering that firms depend on profits to maintain production, following changes in profit margins, firms will make discretionary changes in production capacity to achieve a balance between market demand and their production capacity. The formulae for this change are expressed as follows:

$$S_{\text{sell}} = D_{\text{steel}} * \frac{E_{\text{steel}}}{12} * P_{\text{sell}} \tag{29}$$

$$S_{\text{buy}} = D_{\text{steel}} * \frac{E_{\text{steel}}}{12} * P_{\text{buy}} \tag{30}$$

$$F_{\text{sell}} = DELAYFIXED(S_{\text{sell}}, 12, 0) \tag{31}$$

$$F_{\text{buy}} = DELAYFIXED(S_{\text{buy}}, 12, 0) \tag{32}$$

$$T_{\text{sell}} = \text{INTEG}(0, \text{F}_{\text{sell}} - \text{S}_{\text{sell}}) \tag{33}$$

$$T_{\text{buy}} = \text{INTEG}(0, \text{F}_{\text{buy}} - \text{S}_{\text{buy}}) \tag{34}$$

$$M_{\text{sellsteel}} = \text{INTEG}(O_{\text{sellsteel}}, T_{\text{sell}}) \tag{35}$$

$$M_{\text{buysteel}} = \text{INTEG}(O_{\text{buysteel}}, T_{\text{buy}}) \tag{36}$$

$$M_{\text{amt}} = M_{\text{buysteel}} + M_{\text{sellsteel}} \tag{37}$$

where S_{sell} indicates that the seller's steel production has started to expand, F_{sell} indicates that the seller's steel enterprise has completed its expansion, T_{sell} indicates that the seller's steel enterprise is expanding its production capacity, $O_{\text{sellsteel}}$ indicates that the seller's steel enterprise has an initial production capacity, and $M_{\text{sellsteel}}$ indicates that the seller's steel production, corresponding to which are the buyer's enterprise's relevant parameters. The total steel output M_{amt} is obtained by summing up the two outputs.

The market price of steel is related to market demand as well as market supply, and similar to the price of carbon, the price of steel is controlled by the government and stabilised within a certain range. The correlation function is as follows:

$$D_{\text{steel}} = \text{INTEG}(O_{\text{steel}}, O_{\text{steel}} * r_{\text{steel}}) \tag{38}$$

$$E_{\text{steel}} = P_{\text{steel}} * \left(D_{\text{steel}} * \frac{\left(\frac{(SMOOTH(P_{\text{steel}}, 12))}{P_{\text{steelori}}} \right)^{-0.1} - M_{\text{amt}}}{\left(\frac{(SMOOTH(P_{\text{steel}}, 12))}{P_{\text{steelori}}} \right)^{-0.1}} \right) \tag{39}$$

$$E_{\text{steelprice}} = \text{INTEG}(P_{\text{steelori}}, E_{\text{steel}}) \tag{40}$$

$$P_{\text{steel}} = IFTHENELSE\left(\begin{array}{l} SMOOTH3I\left(E_{\text{steelprice}}, 3, P_{\text{steelori}}\right) > P_{\text{steelup}}, P_{\text{steelup}}, \\ IFTHENELSE\left(SMOOTH3I\left(E_{\text{steelprice}}, 3, P_{\text{steelori}}\right) < P_{\text{steeldown}}, P_{\text{steeldown}}\right), \\ SMOOTH3I\left(E_{\text{steelprice}}, 3, P_{\text{steelori}}\right) \end{array} \right) \tag{41}$$

where D_{steel} denotes the demand for steel, O_{steel} denotes the initial value of steel demand, r_{steel} denotes the growth rate of steel demand, E_{steel} denotes the net demand for steel, P_{steel} denotes the price of steel, $P_{steelori}$ denotes the initial price of steel, $E_{steelprice}$ denotes the change in the price of steel, $P_{steelup}$ denotes the upper limit of the price of steel, and $P_{steeldown}$ denotes the lower limit of the price of steel.

The final flow chart of the coupled carbon–energy-material market model is shown in Figure 6.

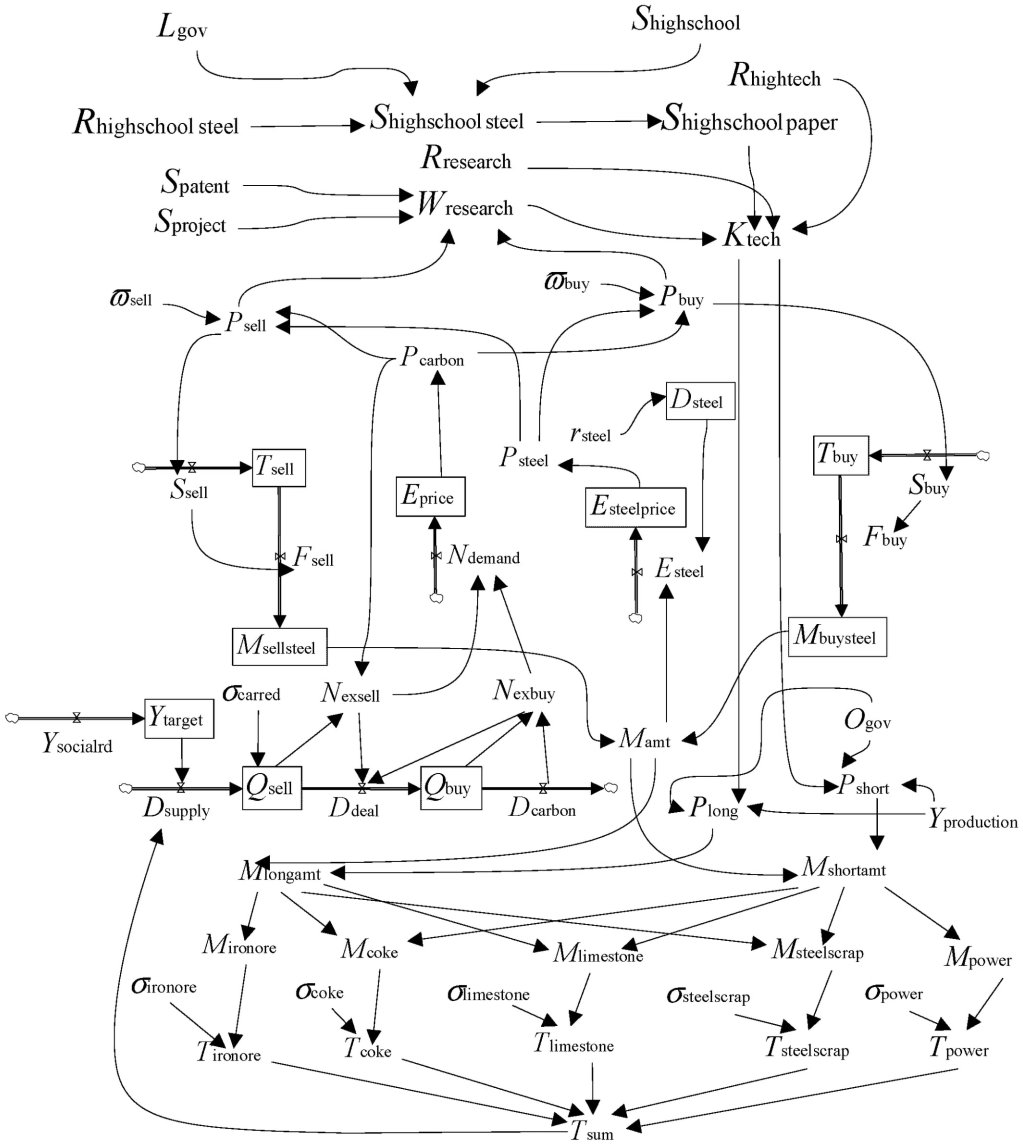

Figure 6. Modelling of coupled carbon–energy-material market systems.

3. Simulation and Design

The national carbon market first included steel enterprises in 2024, but in some pilot regions, the steel industry had been included in local carbon market operations. Considering the authenticity of data collection and the reasonableness of model validation, this paper takes 2021, the year when China's carbon market had just begun its operation, as the base year and constructs a time step of 1 month. Historical data dating back to 2014 are used to construct and validate selected model input series, while the system dynamics simulation itself covers the period from 2021 to 2030, i.e., a model simulation period of 108 months.

The sources of function assignments within each system are described below in order:

(1) CRIS.

Based on the relevant data in the China Science and Technology Statistical Yearbook for each year, table functions are established and assigned to the R&D topics of universities, the number of R&D patents of iron and steel industry enterprises, and the R&D projects of iron and steel industry enterprises. The grey prediction model is adopted to predict the data for future years for which no data are available.

(2) EMSS.

According to the data given by Worldsteel, currently, for the long-process steel production process, an average of 1.37 tonnes of iron ore, 0.78 tonnes of coal, 0.27 tonnes of limestone and 0.125 tonnes of scrap are used to produce one tonne of crude steel. For short-flow steel production processes, an average of 0.586 tonnes of scrap, 0.15 tonnes of coal, 88 kg of limestone, and 2.3 GJ of electricity are used to produce a tonne of crude steel [54]. At the same time, according to the data given by the China Iron and Steel Association, the share of China's "blast furnace-converter" long-process steelmaking in total crude steel production is about 90 per cent, so this paper assigns an initial value of 0.9 to the share of long-process production and 0.1 to the share of short-process production.

(3) The natural environment subsystem.

The National Greenhouse Gas Emission Factor Database and the "Requirements of the greenhouse gas emissions accounting and reporting (GB/T 32151.5-2026)" are used to obtain coke's low-level heat output, carbon content per unit calorific value and fuel carbon oxidation rate. Then, the carbon emission factor of coke is calculated according to the formula "CO_2 emission factor = low-level heat output × carbon content per unit calorific value × fuel carbon oxidation rate × 44/12". Carbon emission factors for iron ore, limestone, electricity and steel scrap are given directly in the material and do not need to be calculated.

(4) PDS.

Based on the Ministry of Commerce's "Circular of the State Council on the Issuance of the Action Plan for Carbon Peak by 2030", which requires that "carbon dioxide emissions per unit of gross domestic product (GDP) will be reduced by 18% by 2025 compared with 2020", an average calculation is made, and the value of the reduction rate of the Carbon Reduction Plan is assigned as 3.6%. According to the "Guidance of the Ministry of Industry and Information Technology and Seven Other Departments on Accelerating the Greening of the Manufacturing Sector", the iron and steel production policy is set at 1%, based on the requirement that "the proportion of short-process steelmaking reaches 20% or more" by 2030.

(5) CMOS.

According to the China Carbon Price Survey Report 2021, the opening carbon price in the national carbon market trading in 2021 is RMB 48. Using this as a benchmark, the initial carbon price is set at RMB 48. Based on the past literature, the upper limit of the carbon price is set at RMB 300 and the lower limit at RMB 10 [55]. Based on industry data, the price of steel is set to have an upper limit of RMB 7000 and a lower limit of RMB 2000, and the current steel price in 2021 is RMB 4137. In terms of the rate of change of the carbon quota price and steel price, three months are considered a cycle, and the SMOOTH function is applied to fit the carbon price. At the same time, the steel supply has suffered from a low degree of growth or even negative growth during the last five years, so the growth rate of steel demand is set at 1%. There are many types of steel; the steel described in this paper is crude steel, but this will not be repeated later.

3.1. Model Checking

Real-world operation is not as simple as a written model. The constructed system dynamics model is influenced by many factors, so it cannot fully reflect the real situation of the industry operation. Therefore, after constructing the model, it is still necessary to test the validity of the model and the reasonableness of the model results.

In the process of constructing the model, the parameters involved are not completely obtained from real data, so it is necessary to estimate the data through the grey prediction method and other prediction methods. At the same time, the data reflected in the model also need to be fitted to reality. Previous forecasting studies have adopted MAPE-based performance criteria, where values below 10% indicate excellent forecasting accuracy, while values of 10–20% and 20–50% indicate good and reasonable forecasting performance [56]. Given that the steel industry has only recently been incorporated into carbon market operations, relevant data are scarce and existing datasets are limited and hard to access. This study thus employs the grey prediction method to fit missing values and conduct numerical validation.

Table 2 is a reference table of the predicted and actual values of the number of research and experimental development projects (topics) in higher education institutions, based on the relevant contents of the China Science and Technology Statistical Yearbook. The construction of the prediction model is based on the grey prediction formula (42) and the calculation of the error, which is within 3% of the true value, far below the upper limit of 10 per cent. Therefore, according to the error results, it can be considered that the predicted number of research and experimental development projects (topics) in higher education institutions is in line with the real situation.

$$\chi^{(1)}(k) = \left(X^{(0)}(1) - \frac{u}{a}\right)e^{-a(k-1)} + \frac{u}{a} \tag{42}$$

Table 2. Projected and actual number of research and experimental development projects (subjects) at higher education institutions.

Vintages	Projected Value (Items)	Actual Value (Item)	Error Value
2014	759,724	766,731	−0.91%
2015	830,621	841,520	−1.30%
2016	908,133	894,279	1.55%
2017	992,878	966,780	2.70%
2018	1,085,531	1,076,903	0.80%
2019	1,186,831	1,188,769	−0.16%
2020	1,297,584	1,288,633	0.69%
2021	1,418,673	1,436,251	−1.22%
2022	1,551,061	1,539,845	0.73%
2023	1,695,803	1,701,829	−0.35%
2024	1,854,052	——	——
2025	2,027,069	——	——
2026	2,216,231	——	——
2027	2,423,046	——	——
2028	2,649,161	——	——
2029	2,896,376	——	——
2030	3,166,660	——	——

Table 3 shows the projected and actual steel production in the base case. China's crude steel production for 2021–2024 is obtained from the crude steel data of China published by Worldsteel [57]. The simulation results are derived from the "steel production" parameter in the model. All deviations from actual figures fall within a 10% margin, confirming the model's validity.

Table 3. Projected and actual steel production in the base case.

Vintages	Simulated Value (×104 t)	Actual Value (×104 t)	Error Value
2021	103,300	103,300	0%
2022	103,800	101,300	2%
2023	106,430	102,900	3%
2024	109,707	100,500	9%

To further evaluate the validity and reliability of the system dynamics model, this study conducted a series of model validation tests based on commonly used system dynamics validation methods, including dimensional consistency, model structure and equation checks, extreme condition tests, and behavioural sensitivity analysis. First, the model was examined using the "Units Check" and "Model Check" functions in Vensim PLE (version 10.3), and the results confirmed that the model passed both the dimensional consistency and equation checks. Second, extreme condition tests were conducted by adjusting the steel production policy adjustment rate. The results showed that the share of short-process steel production remained within a reasonable range under all four specified scenarios. To further assess the model's ability to simulate carbon emissions, the simulated emissions for 2021–2024 were compared with reference values for steel industry carbon emissions constructed using a life cycle emission intensity. Four error metrics, namely, mean absolute error (MAE), mean squared error (MSE), root mean squared error (RMSE), and mean absolute percentage error (MAPE), were employed to quantify the simulation deviations. The results showed a MAPE of 8.26%, indicating a generally satisfactory level of agreement. In addition, a behavioural sensitivity analysis was performed using the annual steel demand growth parameter as the perturbed parameter and steel price as the response variable. The results indicated that although parameter variations caused certain numerical differences, they did not significantly alter the overall evolutionary trend of steel prices. Furthermore, 1000 Monte Carlo simulations were conducted to examine variations in the main output variables under joint perturbations of key parameters. The results showed that most simulation outcomes exhibited a degree of consistency in their overall evolutionary trends. Collectively, these validation tests provide support for the structural rationality and dynamic behaviour of the model. Detailed validation procedures and results are presented in the Supplementary Materials.

3.2. Scenario Design

To explore the carbon reduction pathways of China's steel industry under the coupled carbon–energy-material market, this study designs four categories of scenarios focusing on policy incentives, carbon reduction technologies, enterprise profitability, and steel market demand. These scenarios reflect the main factors influencing the low-carbon transformation of the steel industry and are consistent with the policy directions of technological innovation, production structure optimisation, carbon market regulation, and supply–demand adjustment. In particular, China's policies on high-quality steel industry development and energy conservation emphasise the promotion of electric arc furnace steelmaking,

the utilisation of scrap steel, and the upgrading of low-carbon technologies. Meanwhile, the inclusion of the steel industry in the national emissions trading system provides an institutional basis for examining the influence of carbon reduction capabilities on carbon allowance trading. Accordingly, the following scenarios are established to examine the dynamic responses of steel production, carbon prices, and carbon emissions under different policy and market conditions.

The specific scenarios are designed as follows:

First, the policy incentive scenario is established. *The Guiding Opinions on Promoting the High-Quality Development of the Iron and Steel Industry* [58] emphasise low-carbon technological innovation, capacity replacement, and the development of electric arc furnace steelmaking. These policy directions provide a basis for examining changes in policy support intensity. Accordingly, the government's encouragement coefficient for steel-related research and the steel production policy coefficient are both doubled to simulate stronger policy incentives for technological innovation and production structure adjustment.

The second is the three levels of carbon reduction technological change in seller steel enterprises. In the baseline scenario, seller steel companies are able to generate 20% of surplus carbon allowances and sell them in the carbon market because of their carbon reduction capacity. However, with technological change, a seller steel company may be able to take out a larger share (or cut its share) to trade carbon credits. Meanwhile, China's national emissions trading system introduces carbon-intensity-based allowance allocation for the steel industry, providing incentives for enterprises with better emission reduction performance [59]. The parameter values were selected based on preliminary model testing. The baseline value is 0.2, while 0.1, 0.3571, and 0.5476 represent low, medium, and high carbon reduction capacities, respectively. Preliminary simulation runs showed that these settings produced distinguishable responses in carbon allowance trading and related model variables. Therefore, they were adopted as representative values for comparing different technological conditions.

Thirdly, seller profitability increases. The seller, as an innovative enterprise, has a more advanced technology level compared to the buyer enterprise. The seller produces steel with better performance, which may be sold at a higher price and has stronger profitability, thus influencing changes in the iron and steel industry. Therefore, this paper sets up a scenario in which the seller's profitability coefficient is higher (0.06). This setting is informed by the historical profitability of China's steel industry and represents a relatively favourable operating condition rather than an exact estimate of individual enterprises' profit margins.

Finally, the shrinking steel demand scenario is established. *The Work Plan for Stabilizing Growth in the Steel Industry* [60] identifies insufficient effective demand and supply–demand imbalances as major challenges facing the industry, highlighting the importance of production regulation and market adjustment. To examine the effects of declining market demand on steel production and carbon emissions, the annual steel demand growth rate is set to −1%, representing a hypothetical demand contraction rather than a government-mandated reduction target. This setting is also consistent in magnitude with the World Steel Association's earlier projection of a 1% decline in China's steel demand in 2025 [61].

To visualise the impact, the parameter settings of the different scenarios are shown in Table 4 below.

Table 4. Model parameter values under different circumstances.

Scenario	Categorization	Influencing Variable	Variable Values
Base scenario	-	-	-

Table 4. *Cont.*

Scenario	Categorization	Influencing Variable	Variable Values
Policy incentives scenario	-	L_{gov} $Y_{\text{production}}$	2 2
Carbon reduction technology scenarios	Low Technologies Medium Technologies High Technologies	σ_{carred}	0.1 0.3571 0.5476
Profitability improvement scenario	-	ω_{sell}	0.06
Shrinking steel demand scenario	-	r_{steel}	−0.01

4. Analysis of Results

4.1. Carbon Price Volatility

(1) Simulation analysis under the base scenario.

The carbon price trend for each scenario is shown in Figure 7. In the baseline scenario, the carbon price first rises steadily, then fluctuates, and finally falls sharply. This is mainly because the carbon price in this paper is set based only on the regulation of the closed system within the market, and the systems are closely coupled with each other, with strong rigidity and weak elasticity. In the initial smooth operation of the carbon market, the seller enterprise's surplus carbon quota is greater, and the seller enterprise's demand quota is larger. After about 45 months, the seller market stock gradually tends to be consumed, and it is not enough to meet the demand of the seller market. The coupling system begins to carry out the internal elements of reallocating the regulation, so in the period of 45 months–82 months, there is a certain degree of volatility rise. Based on the baseline scenario, this paper finds that drawbacks are generated only by the regulation of internal factors in the carbon market, i.e., there is a collapse in the allocation of carbon allowances. Combined with the stock of carbon allowances between buyers and sellers in the coupled system in Figure 8, it can be seen that at about 80 months, the seller market in the baseline scenario, because of the fluctuation in various factors, has an abnormal upward appreciation, while at the same time, the buyer market remains relatively stable and shows a decreasing trend.

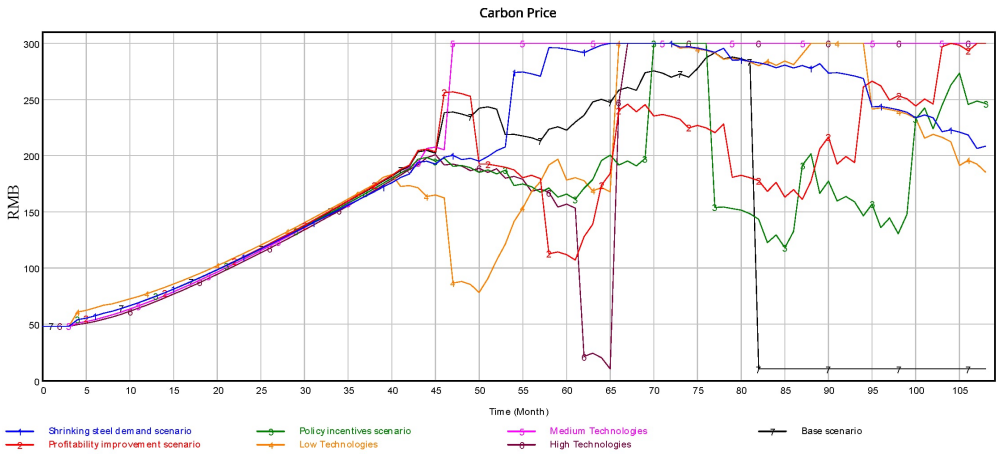

Figure 7. Trends in carbon prices in coupled systems.

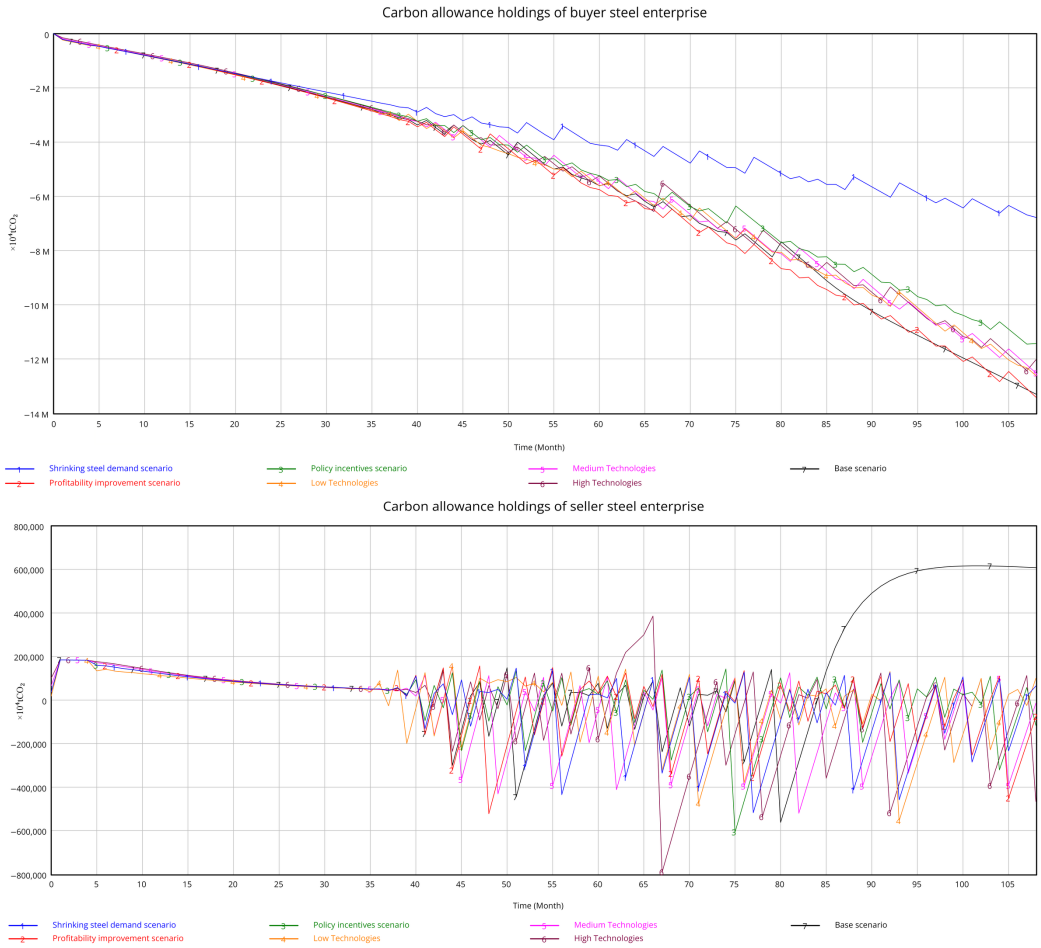

Figure 8. Carbon allowance holdings of steel enterprises on both the buyer and seller sides of a coupled system.

(2) Simulation analysis under hypothetical scenarios.

Based on the simulation graphs of the base case, the trend of carbon price changes under the remaining models can be explored. From the simulation images, it can be seen that in the early period, except for the low technologies scenario, the trend of the other scenarios is similar until 45 months. In the low technologies scenario, the price of carbon declined in the 40th month, and it took one year and almost 60 months for the price to return to its original level. The fluctuation in the carbon price reflects the activity level of the carbon market. The higher the carbon price, the higher the demand for trading carbon credits and the more active the carbon market is; on the other hand, the lower the carbon price, the lower the demand for trading carbon credits and the more depressed the carbon market is. In the low carbon reduction technology scenario, the limited carbon allowances released by sellers are consumed by buyers, with subsequent supply shortages arising from insufficient growth drivers. Under this restriction, buyer firms need to reduce production in order to meet the carbon red line, and at a certain level of reduction, i.e., during the 40–65-month period, buyer firms do not have a high demand for trading carbon allowances, leading to a contraction in the carbon price. Subsequently, as enterprises' production cutbacks fail to align with carbon emission reduction targets, buyer firms generate substantial demand for carbon allowance purchases, triggering a brief surge in carbon prices that persists at elevated levels.

For the other scenarios, the medium carbon reduction technology scenario reaches the carbon price threshold earliest and stays at a high level. The carbon price in the demand

contraction scenario also stays on an upward trend, eventually hits the carbon price threshold, and stays there for a long period of time. In both scenarios, the total amount of carbon allowances available for allocation in the carbon market is larger, and the amount of carbon allowances circulating in the market is larger (Figure 9), so the carbon price level stays stable and high. In contrast, the carbon price in the high carbon reduction technology scenario first experienced a decline, then moved up to the threshold, and then began to experience a decline again at the end of the simulation. This may be due to the fact that a considerable degree of industrial structure replacement occurs in the high reduction technology scenario, where the proportion of firms with high reduction technologies rises to some extent, and the price of carbon declines due to the contraction of buyer firms' demand at a later stage, even though supply increases in the early part of the simulation. The overall direction of the carbon price in the profitability and policy incentive scenarios is similar: both fluctuate within a certain range and are lower than the carbon price in the base case before the steep decline in the base case. Combined with the simulation images of the trading volume, it can be seen that in both scenarios, the trading volume of carbon allowances is generally low and the market is slightly depressed compared to the other scenarios.

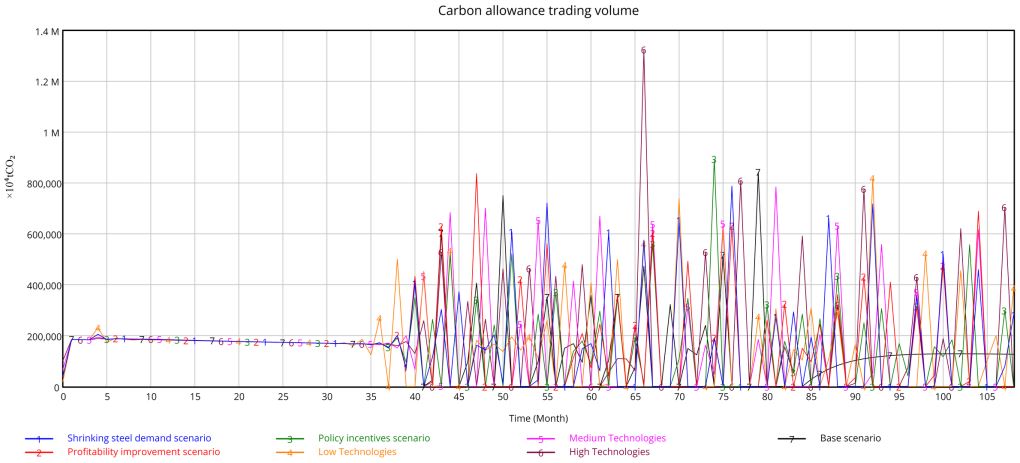

Figure 9. Volume of carbon allowances traded in coupled systems.

4.2. Steel Production

(1) Simulation analysis of long- and short-process production.

The iron and steel industry is required to increase the short-process share to more than 20% by 2025. However, in this system simulation, as shown in Figure 10, it is found that none of the scenarios can achieve steel structural reform within 48 months, i.e., by 2025, if only relying on innovations in science and technology. Two scenarios attained a share exceeding 0.2: the policy incentives scenario, in which short-process production surpassed 0.2 at approximately 58 months, and the high technologies scenario, where rapid structural iteration occurred at around 75 months, reaching 0.3. The former scenario was influenced by policy incentives, which boosted the resources of universities for research in steel and empowered the transformation of scientific and technological achievements to successfully reach the target. In the latter, due to a series of factors such as the operation of the carbon market under high carbon reduction technology, high carbon reduction enterprises realised a strong substitutability for low carbon reduction enterprises, and a qualitative leap occurred after accumulating to a certain extent. Although the timing was delayed, the target was exceeded.

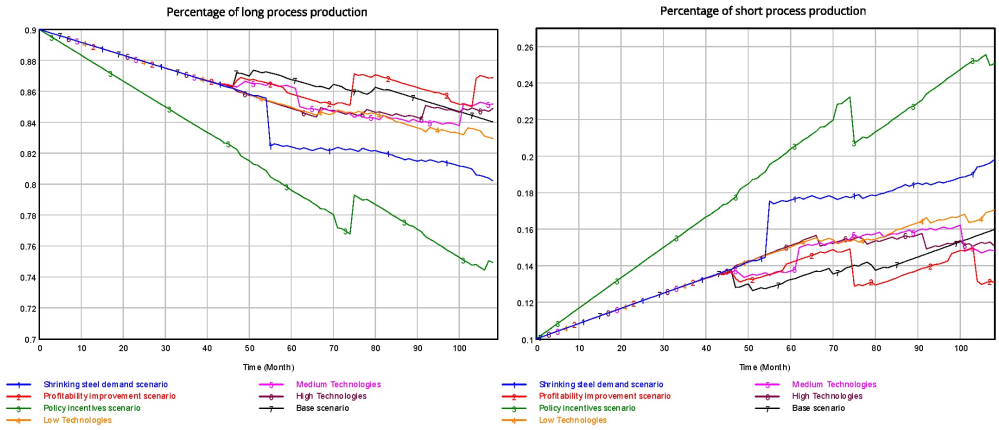

Figure 10. Share of steel production under long and short processes in coupled systems.

Analysing the companies that did not succeed in reaching their targets, it can be seen that, in the base scenario, the increase in the share of short-process production did not reach the target but continued to move upwards, with substitution still taking around a year to complete. In the shrinking steel demand scenario, the steel industry as a whole is depressed, and in order to achieve higher profits, companies have to develop newer technologies and seek to capture a shrinking market share with better quality steel. As a result, the proportion of steel produced in the short-process scenario is relatively high compared to the remaining non-compliant scenarios in the low-demand scenario. In the low technologies scenario, the share of short-process production finally shrinks, presumably because buyers and sellers trade fewer carbon allowances from the carbon market, which is less profitable and less supportive of R&D, causing the share of short-process production to grow negatively.

(2) Simulation analysis of total steel production.

Overall, as shown in Figure 11, except for the shrinking steel demand scenario, the total steel production in all other scenarios does not show a substantial decline, and the rise in the seller's steel production is greater than the decline in the buyer's steel production, with the rise in the total production of steel in the case of profitability enhancement being much higher. In terms of production on both sides of the equation, the seller's high level of technology and ability to realise a sustained surplus of carbon allowances, and therefore a sustained increase in carbon trading revenues in the carbon market, expanded the seller's production capacity, which maintained the same trend of sustained increases in steel production capacity in all scenarios. In contrast, buyer steel production continued to fall, particularly in the case of medium and low technologies.

4.3. Carbon Dioxide Emissions

Total steel production is first converted into long- and short-process steel production; these values are then converted by the raw material's carbon emission factor into the corresponding carbon emission increase, which is finally reflected in cumulative CO_2 emissions. The graphs in Figure 12 show the simulated values of carbon emission increases and cumulative CO_2 emissions. The overall increase in cumulative carbon emissions tends to be linear, except in the shrinking steel demand scenario. Cumulative CO_2 emissions are lower at the end of the simulation than in the base case for all scenarios except the profitability improvement scenario, where the slowing down of cumulative emissions for high-reduction technologies is not evident in the early part of the simulation, but is about to intersect with the policy incentives scenario, which remains low and is expected to have a greater advantage in the longer simulation.

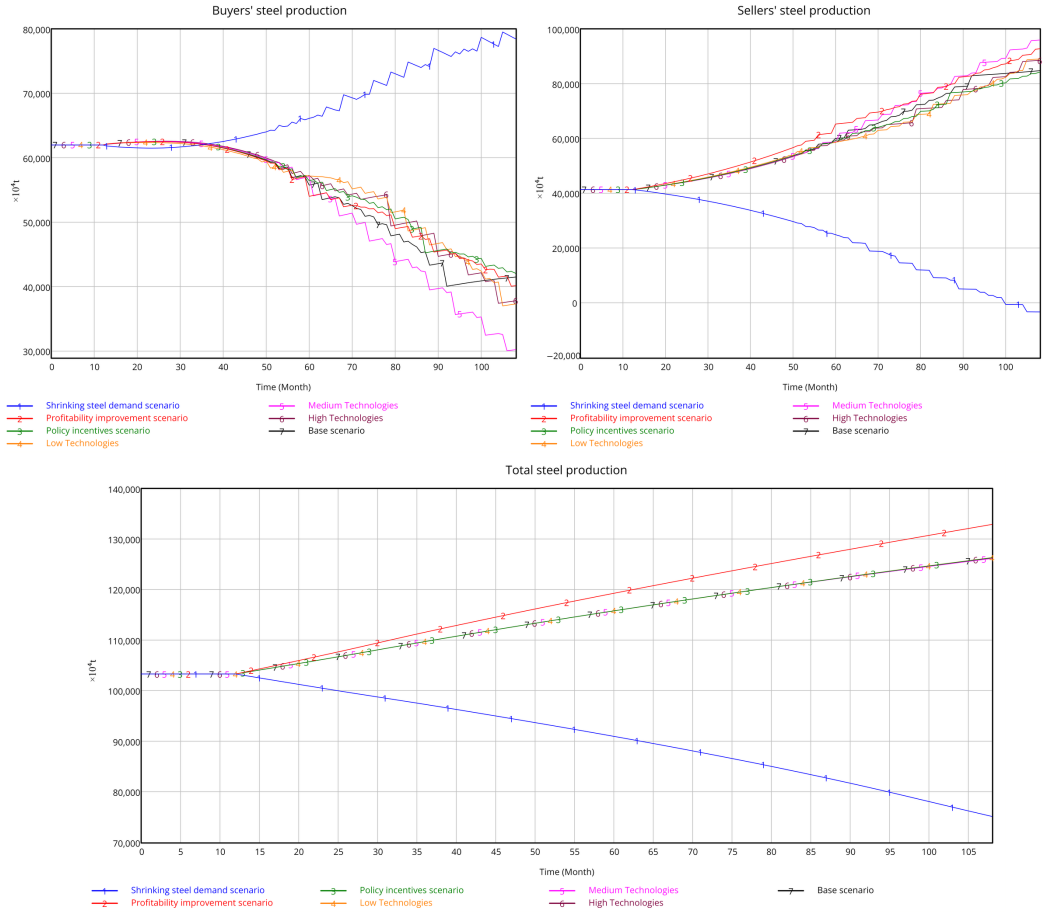

Figure 11. Coupled system of buyers and sellers and total steel production.

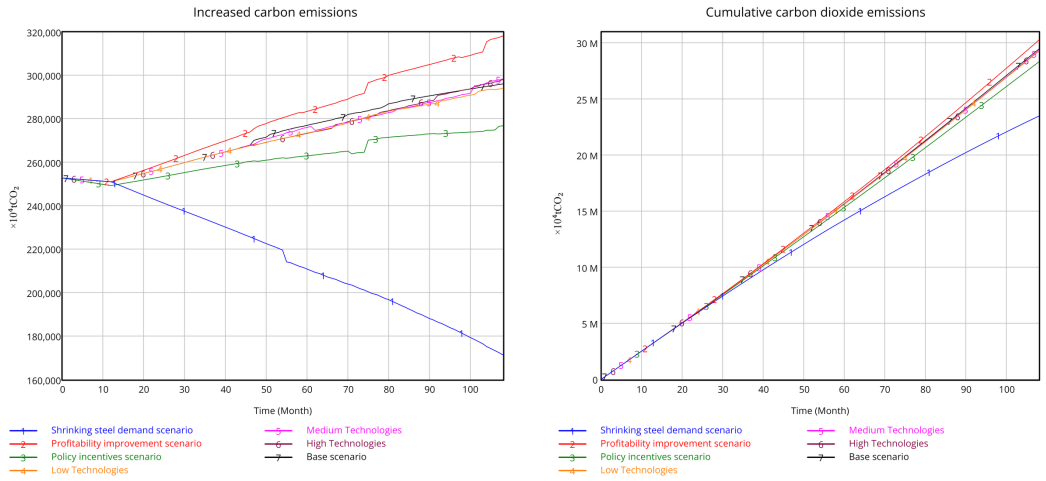

Figure 12. Carbon emission simulation for coupled systems.

Of particular interest are the cumulative CO_2 emissions in the low technologies scenario compared with emissions over the modelling period in a more technologically advanced scenario with an inactive carbon market. A comparative analysis of the previous section shows that this small advantage may be temporary, as the buyer firms, which have a large base, distribute fewer carbon allowances under low-carbon technology and do not purchase carbon allowances when they are first fully reduced due to the inactivity of the market itself, resulting in a fall in the price of carbon. In this case, it is difficult for both buyers and sellers to receive feedback from the carbon market, so the low technologies scenario has the lowest

total steel production of all the steel demand growth scenarios up to 76 months. However, after 76 months, the low technologies scenario starts to exceed the base case in terms of total steel production and becomes the second highest total steel production scenario after the profitability scenario at month 88 of the simulation. Thus, in the long term, the low technologies scenario will overtake the baseline scenario as the scenario with the second highest total CO_2 emissions.

The simulation results in Figure 12 can be further interpreted in conjunction with the changes in total steel production shown in Figure 11. Total carbon emissions depend not only on the scale of steel production but also on the proportions of long- and short-process steelmaking and their corresponding emission intensities. Although changes in production structure can reduce emissions per unit of steel, the growth in total production may offset these reductions. In the simulated scenarios, annual carbon emissions continue to increase in all scenarios except for the shrinking steel demand scenario. Under the assumed contraction in steel demand, the reduction in production scale contributes to an emission peak within the simulation period. This indicates that changes in steel demand and production scale play an important role in determining the overall emission trajectory.

5. Conclusions and Suggestions

5.1. Conclusions

Through the five-party coupled model simulation of carbon reduction in steel enterprises, this paper further expands the research related to the development of Chinese iron and steel enterprises in the carbon market. According to the different system combinations, the main conclusions are as follows:

(1) The carbon market mechanism has a significant leverage effect on carbon price. If not regulated by external factors, the carbon market will be disordered after a period of operation, which is specifically reflected in carbon price fluctuations. Policy interventions such as dynamic adjustment of carbon quotas and price stabilisation mechanisms can effectively mitigate the risk of market collapse. The carbon market is more active under the scenarios of shrinking steel demand and medium-carbon reduction technologies, while the growth in the carbon market under the profitability and policy encouragement scenarios is slightly weaker in the later stage.

(2) Increases in the share of short-process steelmaking are driven by both policy and technological innovation. Total steel production grows in all scenarios except for the shrinking steel demand scenario. Although all scenarios fail to achieve the goal of 20% or more of short-process steel production by 2025, the goal of increasing the share of short-process steel production can be achieved over time in the high carbon-reducing technologies scenario and in the policy incentives scenario.

(3) Divergence in the carbon reduction capacity of enterprises will intensify structural change in the industry. Sell-side iron and steel companies with strong carbon reduction capacity have access to surplus carbon allowances and sell them, expanding their profit margins and promoting the growth of high-quality production capacity, while buy-side companies with low carbon reduction capacity and a shortage of carbon allowances are forced to reduce production and adjust low-quality production capacity. Under the Matthew Effect, the industry undergoes structural change, and R&D investment in low-carbon technologies directly affects the long-term competitiveness of enterprises, driving high-quality capacity to replace low-quality capacity.

(4) Changes in the steel production scale have an important influence on total carbon emissions. Although technological innovation and production structure adjustments can mitigate carbon emissions, continued growth in steel production may offset these reductions. Compared with the baseline scenario, the profitability improvement sce-

nario results in higher cumulative carbon emissions, while the other scenarios reduce cumulative emissions to varying degrees by the end of the simulation period. However, annual carbon emissions continue to rise in all scenarios except the shrinking steel demand scenario, which is the only scenario that achieves an emission peak within the simulation period. This indicates that, under the assumed decline in steel demand, curbing aggregate steel demand and the resulting production scale produces the most pronounced emission reduction effect among the simulated scenarios.

5.2. Suggestions and Discussion

Once the operational logic of the coupled system is mastered, we can develop different strategies for different subjects and variables that have an impact on carbon reduction.

5.2.1. Government Policy Recommendations

(1) There is a need for synergy between the government's technological research and development and industrial transformation. After constructing, simulating, and analysing the aforementioned model, it can be clearly observed that policy incentives and support have a significant positive effect on the generation of carbon reduction benefits. At the same time, in the absence of interference from external factors, the model under the baseline scenario will lead to the phenomenon of carbon price collapse. Therefore, it is necessary for the government to implement a certain level of intervention in the functioning of the carbon market and its related coupled systems, which can be achieved through joint policies of technological development and industrial transformation. In addition, given that in models where profitability increases, carbon emissions instead increase, the government could consider taking some of the proceeds from carbon market transactions and setting up a special fund to subsidise technologically outdated, high-carbon-emitting steel companies, encouraging them to phase out obsolete steelmaking technologies and promoting the adoption of low-carbon processes. This will limit the growth of production in the steel industry and promote the transformation of the industry.

(2) Government regulatory constraints and market guidance need to go hand in hand. The simulation results indicate that although various policy measures can mitigate carbon emissions growth to some extent, only the shrinking steel demand scenario achieves an emissions peak within the simulation period, while emissions continue to increase under the other scenarios. This suggests that controlling excessive steel production and guiding demand-side adjustments are important for achieving emission reduction targets. However, the Monte Carlo simulation reveals variations in emission outcomes under the joint perturbation of key parameters, indicating that the magnitude and trajectory of emission reductions are subject to uncertainty. Therefore, the government should strengthen capacity regulation by strictly controlling new steel production capacity and gradually phasing out obsolete capacity while adjusting policy measures according to changes in market demand and actual emission performance. Meanwhile, priority could be given to low-carbon steel in public infrastructure procurement to encourage enterprises to adopt cleaner production technologies and promote supply-side structural transformation through demand-side incentives. Given the uncertainty associated with model parameters and future market conditions, these policy measures should be implemented progressively and evaluated periodically to ensure their effectiveness and adaptability.

5.2.2. Enterprise Action Pathways

(1) Steel enterprises need to make low-carbon technological breakthroughs and optimise production processes. After the introduction of the carbon market to the steel industry, the constraints of carbon emissions will have a more obvious impact on the production and operation activities of enterprises. To secure a competitive market position in carbon trading and achieve long-term growth, steel enterprises should thus prioritise innovations in electric and hydrogen-based steelmaking processes, gradually replacing the traditional blast furnace-converter production structure. In terms of raw materials and energy, enterprises need to lay out the development of low-carbon steelmaking technologies such as separation of impurities from scrap steel and biomass instead of coke, so as to realise higher waste utilisation rates and reduce iron ore production. Waste utilisation can reduce dependence on iron ore and coke, thereby effectively curbing carbon emissions from the production side.

(2) Steel enterprises need to realise supply chain synergy. In terms of the supply chain, enterprises can set up their own scrap recycling departments and can sign long-term agreements with scrap recycling enterprises and green power suppliers to ensure the supply of low-carbon raw materials and green energy, enabling them to take advantage of carbon quota accounting and realise the reform of the low-carbon industrial chain. Head steel enterprises should give full play to their sense of social responsibility, establish a low-carbon innovation alliance, promote the research and development of emerging common low-carbon technologies, share the research and development costs of related technologies, and realise industry–university–research linkages with universities to promote the industry's overall carbon reduction science and technology forward.

Based on the system dynamics model, this paper reveals the coupling effect of the carbon–energy-material market in the iron and steel industry, but there are still limitations. For example, due to the lack of data published in the statistical yearbook, the latest data in this paper can only be traced back to 2022, and some carbon market-related elements, such as CCER, green certificates, green power, and carbon taxes, are not included in the study, resulting in a simplified model. Specifically, CCER was excluded because it involves a separate voluntary emission reduction and offsetting mechanism beyond the carbon allowance trading process considered in this study. Green certificates and green electricity trading were not included because the model focuses on electricity consumption and its associated carbon emissions, without separately modelling renewable electricity procurement or certificate transactions. Carbon taxation was also excluded because the model represents carbon pricing through allowance trading rather than an additional taxation mechanism. Furthermore, the model was developed using statistical data available through 2022, when several of these policy mechanisms were still undergoing development and adjustment. A future continuation of the study could be based on the actual operation of the iron and steel carbon market. If the relevant parameters are included in the initial construction of the model, a more macroscopic carbon market operation mechanism can be studied.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en19215150/s1, Table S1. Model variables, units, values, and equations; Table S2. Key parameters and sampling ranges for the Monte Carlo simulations; Table S3. Extended-scope comparison of steel industry CO_2 emissions for 2021–2024; Table S4. Error metrics for the extended-scope comparison of steel industry CO_2 emissions; Figure S1. Percentile coverage intervals for carbon price under joint perturbations of key parameters; Figure S2. Percentile coverage intervals for current and cumulative CO_2 emissions under joint perturbations of key parameters; Figure S3. Percentile coverage intervals for the shares of long- and short-process steel production under joint perturbations of key parameters; Figure S4. Results of the dimensional consistency test; Figure S5.

Results of the model structure and equation checks; Figure S6. Dynamic changes in the share of short-process steel production under extreme policy parameter settings; Figure S7. Dynamic changes in current CO_2 emissions under extreme policy parameter settings; Figure S8. Steel price trajectories under perturbations of the annual steel demand growth parameter. Refs [62–70] are cited in Supplementary Materials.

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References

1. Pan, J.; Cross, J.L.; Zou, X.; Zhang, B. To tax or to trade? A global review of carbon emissions reduction strategies. *Energy Strategy Rev.* **2024**, *55*, 101508. [CrossRef]
2. Bayer, P.; Aklin, M. The European Union Emissions Trading System reduced CO_2 emissions despite low prices. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 8804–8812. [CrossRef] [PubMed]
3. Yang, T.; Yi, L.; Li, J.; Liang, Q. Have the pilot carbon markets achieved synergistic control of carbon abatement and pollution reduction? The quasi-experimental evidence from China. *Energy Environ.* **2025**, *36*, 1906–1928. [CrossRef]
4. Zheng, Y.; Tan, R.; Zhang, B. The joint impact of the carbon market on carbon emissions, energy mix, and copollutants. *Environ. Res. Lett.* **2023**, *18*, 045007. [CrossRef]
5. Liu, L.; Wang, X.; Wang, Z. Recent progress and emerging strategies for carbon peak and carbon neutrality in China. *Greenh. Gases Sci. Technol.* **2023**, *13*, 732–759. [CrossRef]
6. Ma, J. Study on innovation path of China's carbon emission trading market construction. *Fresenius Environ. Bull.* **2019**, *28*, 7382–7387.
7. Ministry of Ecology and Environment of the People's Republic of China. Notice on Issuing the Work Plan for Including the Steel, Cement, and Aluminum Smelting Sectors in the National Carbon Emissions Trading Market. Available online: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202503/t20250326_1104736.html (accessed on 19 October 2026).
8. Lei, T.; Wang, D.; Yu, X.; Ma, S.; Zhao, W.; Cui, C.; Meng, J.; Tao, S.; Guan, D. Global iron and steel plant CO_2 emissions and carbon-neutrality pathways. *Nature* **2023**, *622*, 514–520. [CrossRef] [PubMed]
9. Serrenho, A.C.; Mourão, Z.S.; Norman, J.; Cullen, J.M.; Allwood, J.M. The influence of UK emissions reduction targets on the emissions of the global steel industry. *Resour. Conserv. Recycl.* **2016**, *107*, 174–184. [CrossRef]
10. Tang, C.; Guo, Z.; Pan, J.; Zhu, D.; Li, S.; Yang, C.; Tian, H. Current situation of carbon emissions and countermeasures in China's ironmaking industry. *Int. J. Miner. Metall. Mater.* **2023**, *30*, 1633–1650. [CrossRef]
11. Xu, D.; Liu, E.; Duan, W.; Yang, K. Consumption-Driven Carbon Emission Reduction Path and Simulation Research in Steel Industry: A Case Study of China. *Sustainability* **2022**, *14*, 13693. [CrossRef]
12. Liu, S.; Jiang, Y.; Yu, S.; Tan, W.; Zhang, T.; Lin, Z. Electric power supply structure transformation model of China for peaking carbon dioxide emissions and achieving carbon neutrality. *Energy Rep.* **2022**, *8*, 541–548. [CrossRef]
13. Xu, S.; Xu, Q. Impacts of carbon emissions allowance limitations on carbon price with power generation rights trading in China. *J. Clean. Prod.* **2024**, *470*, 143312. [CrossRef]
14. Sun, Y.; Zheng, J.; Yang, L.; Li, X. Allocation and trading schemes of the maritime emissions trading system: Liner shipping route choice and carbon emissions. *Transp. Policy* **2024**, *148*, 60–78. [CrossRef]
15. Pechstein, J.; Bullerdiek, N.; Kaltschmitt, M. A "book and Claim"-Approach to account for sustainable aviation fuels in the EU-ETS—Development of a basic concept. *Energy Policy* **2020**, *136*, 111014. [CrossRef]
16. Di Foggia, G.; Beccarello, M.; Jammeh, B. EU ETS Price Signals in the Power Sector: Evidence on Decarbonisation and Policy Overlap. *Energies* **2026**, *19*, 4333. [CrossRef]

17. Jiang, W.; Jung, T.Y.; Dai, H.; Xiang, P. Technology portfolio assessment for near-zero emission iron and steel industry in China. *Adv. Clim. Change Res.* **2023**, *14*, 469–478. [CrossRef]
18. Lin, B.; Wu, R. Designing energy policy based on dynamic change in energy and carbon dioxide emission performance of China's iron and steel industry. *J. Clean. Prod.* **2020**, *256*, 120412. [CrossRef]
19. Hao, H.; Wu, H.; Wei, F.; Xu, Z.; Xu, Y. Scrap Steel Recycling: A Carbon Emission Reduction Index for China. *Sustainability* **2024**, *16*, 4250. [CrossRef]
20. Qiao, Y.; Wang, G. Recent Status of Production, Administration Policies, and Low-Carbon Technology Development of China's Steel Industry. *Metals* **2024**, *14*, 480. [CrossRef]
21. Papadis, E.; Tsatsaronis, G. Challenges in the decarbonization of the energy sector. *Energy* **2020**, *205*, 118025. [CrossRef]
22. European Commission. EU ETS Emissions Cap. Available online: https://climate.ec.europa.eu/areas-action/carbon-markets/eu-emissions-trading-system-eu-ets/eu-ets-emissions-cap_en (accessed on 19 October 2026).
23. Ministry of Ecology and Environment of the People's Republic of China. Notice on Issuing the Total Allowance and Allocation Plan for the Power Sector for 2025 and 2026 and the Steel, Cement and Aluminium Smelting Sectors for 2026. Available online: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202609/t20260903_1165029.html (accessed on 19 October 2026).
24. Verde, S.F.; Galdi, G.; Alloisio, I.; Borghesi, S. The EU ETS and its companion policies: Any insight for China's ETS? *Environ. Dev. Econ.* **2021**, *26*, 302–320. [CrossRef]
25. European Commission. Market Stability Reserve. Available online: https://climate.ec.europa.eu/areas-action/carbon-markets/eu-emissions-trading-system-eu-ets/market-stability-reserve_en (accessed on 19 October 2026).
26. Wang, X.; Su, X.; Feng, Y. Trading our way to a greener future: How environmental rights trading reduces urban carbon emissions in China—Empirical analysis based on China's emission rights trading. *Environ. Sci. Pollut. Res.* **2024**, *31*, 15671–15688. [CrossRef] [PubMed]
27. Wang, B.; Duan, M. Have China's emissions trading systems reduced carbon emissions? Firm-level evidence from the power sector. *Appl. Energy* **2025**, *378*, 124802. [CrossRef]
28. Zhang, H.; Zhang, R.; Li, G.; Li, W.; Choi, Y. Has China's Emission Trading System Achieved the Development of a Low-Carbon Economy in High-Emission Industrial Subsectors? *Sustainability* **2020**, *12*, 5370. [CrossRef]
29. Karakaya, E.; Nuur, C.; Assbring, L. Potential transitions in the iron and steel industry in Sweden: Towards a hydrogen-based future? *J. Clean. Prod.* **2018**, *195*, 651–663. [CrossRef]
30. Vogl, V.; Åhman, M.; Nilsson, L.J. Assessment of hydrogen direct reduction for fossil-free steelmaking. *J. Clean. Prod.* **2018**, *203*, 736–745. [CrossRef]
31. Graupner, Y.; Weckenborg, C.; Spengler, T.S. Effects of European emissions trading on the transformation of primary steelmaking: Assessment of economic and climate impacts in a case study from Germany. *J. Ind. Ecol.* **2024**, *28*, 1524–1540. [CrossRef]
32. Guo, J.; Li, J. Efficiency evaluation and influencing factors of energy saving and emission reduction: An empirical study of China's three major urban agglomerations from the perspective of environmental benefits. *Ecol. Indic.* **2021**, *133*, 108410. [CrossRef]
33. Chang, X.; Wu, Z.; Wang, J.; Zhang, X.; Zhou, M.; Yu, T.; Wang, Y. The coupling effect of carbon emission trading and tradable green certificates under electricity marketization in China. *Renew. Sustain. Energy Rev.* **2023**, *187*, 113750. [CrossRef]
34. Chen, Y.; Lin, J.; Roland-Holst, D.; Liu, X.; Wang, C. Declining Renewable Costs, Emissions Trading, and Economic Growth: China's Power System at the Crossroads. *Energies* **2023**, *16*, 656. [CrossRef]
35. Ying, Z.; Xin-gang, Z. The impact of Renewable Portfolio Standards on carbon emission trading under the background of China's electricity marketization reform. *Energy* **2021**, *226*, 120322. [CrossRef]
36. Li, D.; Di, Q.; Zhang, H.; Zhang, D.; Han, Z.; Duan, Y. Research on the Impact of Output Adjustment Strategy and Carbon Tax Policy on the Stability of the Steel Market. *Energies* **2022**, *15*, 6678. [CrossRef]
37. Song, X.; Du, S.; Deng, C.; Shen, P.; Xie, M.; Zhao, C.; Chen, C.; Liu, X. Carbon emissions in China's steel industry from a life cycle perspective: Carbon footprint insights. *J. Environ. Sci.* **2025**, *148*, 650–664. [CrossRef] [PubMed]
38. Yu, X.; Tan, C. China's pathway to carbon neutrality for the iron and steel industry. *Glob. Environ. Change* **2022**, *76*, 102574. [CrossRef]
39. Meng, X.; Yu, Y. Can renewable energy portfolio standards and carbon tax policies promote carbon emission reduction in China's power industry? *Energy Policy* **2023**, *174*, 113461. [CrossRef]
40. Xu, Y.; Zhao, S.; Chu, B.; Zhu, Y. Emission Reduction Effects of China's National Carbon Market: Evidence Based on the Power Sector. *Energies* **2024**, *17*, 2859. [CrossRef]
41. Haowei, C. Synergy effects of the energy quota trading system and carbon emissions trading system: A case study of China. *Energy Sustain. Dev.* **2025**, *87*, 101733. [CrossRef]
42. Pan, Z.; Wang, Y.; Guo, J.; Zhang, X.; Xue, S.; Li, W.; Chen, Z.; Liu, Z. Modeling the Tripartite Coupling Dynamics of Electricity–Carbon–Renewable Certificate Markets: A System Dynamics Approach. *Processes* **2025**, *13*, 868. [CrossRef]
43. Ma, T.; Peng, L.; Wu, G.; Wei, Y.; Zou, X. Research on Multi-Scale Electricity–Carbon–Green Certificate Market Coupling Trading Based on System Dynamics. *Processes* **2025**, *13*, 109. [CrossRef]

44. Lu, Y.; Xiang, J.; Geng, P.; Zhang, H.; Liu, L.; Wang, H.; Kong, J.; Cui, M.; Li, Y.; Zhong, C.; et al. Coupling Mechanism and Synergic Development of Carbon Market and Electricity Market in the Region of Beijing–Tianjin–Hebei. *Energies* **2023**, *16*, 1726. [CrossRef]
45. Song, Y.; Zhang, J.; Song, Y.; Fan, X.; Zhu, Y.; Zhang, C. Can industry-university-research collaborative innovation efficiency reduce carbon emissions? *Technol. Forecast. Soc.* **2020**, *157*, 120094. [CrossRef]
46. Yu, X.; Wan, K.; Du, Q. Can carbon market policies achieve a "point-to-surface" effect?—Quasi-experimental evidence from China. *Energy Policy* **2023**, *183*, 113803. [CrossRef]
47. Feng, M.; Liu, G.; Yue, Q.; Wang, H. Energy Saving and Carbon Reduction in Steel Production: Synergy and Optimization Based on Long and Short Processes. *Steel Res. Int.* **2025**, *96*, 185–199. [CrossRef]
48. Metcalf, G.E. Five myths about carbon pricing. *Oxf. Rev. Econ. Pol.* **2023**, *39*, 680–693. [CrossRef]
49. Lin, B.; Jia, Z. What will China's carbon emission trading market affect with only electricity sector involvement? A CGE based study. *Energy Econ.* **2019**, *78*, 301–311. [CrossRef]
50. Lin, B.; Zhao, H. Green electricity system dynamics under the carbon border adjustment mechanism. *Renew. Energy* **2026**, *256*, 124069. [CrossRef]
51. Wang, H.; Feng, T.; Li, Y.; Kong, J. Synergistic optimization of trading decisions and market mechanisms in the 'electricity-carbon-certificate' markets. *China Popul. Resour. Environ.* **2024**, *34*, 18–29.
52. Li, Q.; Gao, H. ColLaborative modelling between carbon market and electricity market based on carbon tax mechanism. *Mod. Electron. Tech.* **2024**, *47*, 76–84.
53. Cheng, Y.; Mu, D.; Tong, W. Dynamic Model for the Carbon Trading Market and Its Application: Case Study on Guangdong Province. *J. Syst. Sci. Math. Sci.* **2017**, *37*, 383–392.
54. Worldsteel. Raw Materials. Available online: https://worldsteel.org/zh-hans/about-steel/raw-materials/ (accessed on 1 June 2025).
55. Chang, C.; Mai, T.; McAleer, M. Establishing national carbon emission prices for China. *Renew. Sustain. Energy Rev.* **2019**, *106*, 1–16. [CrossRef]
56. Wu, W.; Jiang, J.; Li, Q. A Novel Discrete Grey Model and Its Application. *Math. Probl. Eng.* **2019**, *2019*, 9623878. [CrossRef]
57. Worldsteel. Total Production of Crude Steel. Available online: https://worldsteel.org/data/annual-production-steel-data/?ind=P1_crude_steel_total_pub/CHN/IND (accessed on 19 October 2026).
58. Ministry of Industry and Information Technology of China; National Development and Reform Commission; Ministry of Ecology and Environment. Guiding Opinions on Promoting the High-Quality Development of the Iron and Steel Industry. Available online: https://www.miit.gov.cn/jgsj/ycls/gt/art/2022/art_368e1aae99704e9281a618dc73c046f7.html (accessed on 19 October 2026).
59. National Development and Reform Commission; Ministry of Industry and Information Technology; Ministry of Ecology and Environment; State Administration for Market Regulation; National Energy Administration. Action Plan for Energy Conservation and Carbon Reduction in the Steel Industry. Available online: https://www.gov.cn/zhengce/zhengceku/202406/P020240608361880883927.pdf (accessed on 19 October 2026).
60. Ministry of Industry and Information Technology; Ministry of Natural Resources; Ministry of Ecology and Environment; Ministry of Commerce; State Administration for Market Regulation. Work Plan for Stabilizing Growth in the Steel Industry (2025–2026). Available online: https://www.miit.gov.cn/zwgk/zcwj/wjfb/tz/art/2025/art_e0b143ab438a4de4973ba9031c75b673.html (accessed on 19 October 2026).
61. Worldsteel. Worldsteel Short Range Outlook—October 2025. Available online: https://worldsteel.org/media/press-releases/2025/worldsteel-short-range-outlook-october-2025/ (accessed on 19 October 2026).
62. *Standard's GB/T 32151.5-2026*; State Administration for Market Regulation. Standardization Administration of China: Beijing, China, 2026.
63. National Bureau of Statistics of China. China Statistical Yearbook on Science and Technology (Various Years). Available online: https://www.stats.gov.cn/sj/ndsj/ (accessed on 18 October 2026).
64. National Center for Climate Change Strategy and International Cooperation. National Greenhouse Gas Emission Factor Database. Available online: https://data.ncsc.org.cn/factories/index (accessed on 18 October 2026).
65. Ministry of Ecology and Environment of the People's Republic of China; National Bureau of Statistics of China. Announcement on the Release of the 2021 Electricity Carbon Dioxide Emission Factors. 2024. Available online: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202404/t20240412_1070565.html (accessed on 18 October 2026).
66. General Office of the Ministry of Ecology and Environment of the People's Republic of China. Guidelines for Accounting and Reporting of Enterprise Greenhouse Gas Emissions: Iron and Steel Industry (CETS-AG-03.01-V01-2024). 2025. Available online: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202501/t20250124_1101316.html (accessed on 18 October 2026).
67. State Council of the People's Republic of China. Notice of the State Council on Issuing the Action Plan for Carbon Dioxide Peaking before 2030. 2021. Available online: https://www.mofcom.gov.cn/zcfb/zgdwjjmywg/art/2021/art_12733a8cdc5a4b9d865f5f9496020dce.html (accessed on 18 October 2026).

68. Ministry of Industry and Information Technology of the People's Republic of China; National Development and Reform Commission; Ministry of Finance; Ministry of Ecology and Environment; People's Bank of China; State-owned Assets Supervision and Administration Commission of the State Council; State Administration for Market Regulation. Guiding Opinions on Accelerating the Green Development of Manufacturing. 2024. Available online: https://www.gov.cn/zhengce/zhengceku/202403/content_6935684.htm (accessed on 18 October 2026).
69. National Bureau of Statistics of China. China Statistical Yearbook (Various Years). Available online: https://data.stats.gov.cn/ (accessed on 18 October 2026).
70. Slater, H.; de Boer, D.; Qian, G.; Wang, S. *2021 China Carbon Pricing Survey*; ICF: Beijing, China, 2021. Available online: https://www.cet.net.cn/uploads/soft/220223/1_1405539881.pdf (accessed on 18 October 2026).

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