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Analysis and Prediction of Energy, Environmental and Economic Potentials in the Iron and Steel Industry of China

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Abstract: The green and low-carbon transformation of the iron and steel industry stands as a pivotal cornerstone in the development of China. It is an inevitable trajectory guiding the future of industry. This study examined the energy consumption and carbon emission trends in the iron and steel industry. Variations under different scenarios were analyzed while emphasizing production control, changes in production structure and energy efficiency improvement. The analysis integrated the extreme energy efficiency model. This study proposed methods to enhance energy efficiency in the iron and steel industry. The costs of energy efficiency improvement and production structure changes were assessed using marginal energy saving and abatement cost curves. The findings showed that the carbon emission reduction contribution of crude steel production decline is the highest, while energy efficiency improvement technology offers the smallest, whose contribution, however, is substantial and cannot be overlooked by 2030. Energy efficiency improvement in the Chinese iron and steel industry results in an average unit energy saving and abatement cost of 27.0 yuan. It results in a total abatement cost of 21.02 billion yuan and a potential abatement of 780 Mt. Considering abatement potential, altering production structure offers significantly higher cumulative abatement compared to energy efficiency improvement technology. This is because the per unit abatement cost of production structure change is 702.7 yuan. However, this high cost poses a challenge to widespread adoption. The integration of the iron and steel industry into the carbon trading system necessitates reinforcing market constraints and expediting process adjustments. These steps are crucial to achieving the green and low-carbon transformation of the industry.

Keywords: extreme energy efficiency; energy-saving potential; carbon emission reduction; marginal carbon abatement cost; iron and steel industry

Citation: Gu, Y.; Liu, W.; Wang, B.; Tian, B.; Yang, X.; Pan, C. Analysis and Prediction of Energy, Environmental and Economic Potentials in the Iron and Steel Industry of China. *Processes* **2023**, *11*, 3258. https://doi.org/10.3390/pr11123258

Academic Editor: Dominic C. Y. Foo

Received: 23 October 2023
Revised: 7 November 2023
Accepted: 13 November 2023
Published: 21 November 2023

1. Introduction

The iron and steel industry is a key driver of the national economy of China, simultaneously serving as one of the primary contributors to the energy consumption and carbon emissions of the country. In 2020, the crude steel production of China reached 1.065 billion tons, representing 57% of global production. CO_2 emissions from the iron and steel industry comprise 15–18% of the overall carbon emissions of China [1]. As the aerospace, automobile manufacturing, and biomedical industries further enhance their demands for steel strength and quality, steel products must not only fulfill the new performance criteria but also adhere to regulations governing energy consumption limits for products. This underscores the pressing demand within downstream sectors for environmentally friendly, low-carbon iron and steel products, compelling the iron and steel industry to initiate a transition towards sustainability [2–4]. The production energy structure, changes in processes, raw material imports, and technological adjustments are some of the issues that must be addressed for the iron and steel industry of China to achieve low carbon emissions. On the other hand, low-carbon smelting requires energy conservation, process optimization, and the implementation of breakthrough low-carbon technologies [5]. During the carbon peak stage, energy conservation and consumption reduction in the smelting process remain pivotal for carbon emissions reduction. The *Capacity Replacement* and *Ultra-low Emissions* initiatives as well as the *Extreme Energy Efficiency* transformation project could intensify energy efficiency requirements, leading to further reductions in solid fuel consumption [6]. Hence, a comprehensive understanding of the mechanisms driving alterations in carbon emissions and a detailed prediction of the trends of the iron and steel industry of China bear both theoretical and practical significance. Designing effective carbon emission policies, methodologies, and pathways, along with adopting pertinent energy-saving and emission-reduction technologies, are essential steps toward achieving the goals of carbon peak and neutrality (dual carbon).

In recent years, numerous models have been developed to understand the dual-carbon pathway of the iron and steel industry. Based on the modeling principles, they can be classified into three categories: Top-down models, bottom-up models, and hybrid models. The top-down models are dominated by computable general equilibrium (CGE). Zhu et al. [7] employed a CGE model to evaluate the economic and environmental impacts of energy-intensive sectors, including cement, iron, steel, and construction. They scrutinized how these impacts influenced the implied carbon emissions of the construction industry. Zhang et al. [8] used a dynamic CGE model to simulate the peak time of carbon emissions in China under two scenarios: Single policy and hybrid policy. It has been found that the hybrid policy has a better emission reduction effect than the single policy, so policy makers should scientifically adjust the carbon tax and carbon trading system to fully utilize the synergistic effect of economy and environment. However, these models mainly analyze energy changes from an economic perspective and cannot start from the technical level, which underestimates the technical potential. The long-range energy alternatives planning system (LEAP) model, on the other hand, as a common bottom-up model, has a detailed portrayal of technologies, ignores a certain degree of sectoral linkages, and analyzes changes in the energy environment in more detail. Duan et al. [9] integrated life-cycle theory into the LEAP model and predicted carbon emissions in the iron and steel industry of Jilin Province. Their study included the energy and ore mining stage to the steel end-of-life recycling stage. The findings revealed that the steel production stage accounted for over 80% of total carbon emissions, with the ironmaking system being the highest emitter within this stage. Ates et al. [10] explored energy efficiency and emission reduction potentials in the Turkish iron and steel industry using the LEAP model. Results indicated significant reductions in energy consumption and GHG emissions through the adoption of energy-saving technologies and enhanced energy system management. The NEMS model developed by the U.S. Department of Energy and the hybrid IIASA-WECE3 model developed by Austria in conjunction with the World Energy Council are complex models that are difficult to manipulate, although they can provide an exhaustive picture of changes in the national energy sector [11]. To assess the economic advantages of diverse energy-saving and emission-reduction measures, Zhang et al. [12] evaluated 35 technologies within the iron and steel industry and constructed energy-saving supply curves. Dong et al. [13] introduced a logarithmic form of marginal emission reduction cost function to analyze the emission reduction costs and potentials of various technologies while fostering the low-carbon transformation of the iron and steel industry.

Numerous theoretical studies and empirical analyses on carbon emissions in the iron and steel industry focusing on energy, environmental, and economic aspects could be found. This study examined the current status of low-carbon transformation in the iron and steel industry. A comprehensive carbon neutrality and carbon peak model for the iron and steel industry of China was established using the LEAP model, which is based on the choice of the technology and scenario analysis while considering the emission history, driving factors, and policy analyses. The research period was from 2020 to 2060. Special attention was given to analyzing the impacts and advantages of production structure adjustments and energy efficiency technologies in emission reduction. This analysis offers valuable insights for policymakers aiming to facilitate the green and low-carbon transition of the industry.

2. Overview of Low-Carbon Transition in the Iron and Steel Industry of China

2.1. Current Status of Dual-Carbon Policies in the Domestic and International Iron and Steel Industry

Considering the efforts for energy conservation and emission reduction in the iron and steel industry of China, the evolution of the industry can be divided into three key stages: The formative years from 1949 to 1999, the period of rapid growth spanning 2000 to 2014, and the current phase of maturity and stability since 2015 [14] (Figure 1). Until 2020, the industry had managed to annually reduce comprehensive energy consumption per ton of steel to 545 kgce and carbon emission intensity per ton to 1.79 t [15]. Despite these achievements, the increase in crude steel production posed challenges in reducing the overall carbon emissions growth rate within the industry. As the economy continued to grow, policy directives in the iron and steel sector shifted from guidance and support to stringent measures such as controlling total output, reducing excess capacity, phasing out outdated production facilities, and prioritizing high-quality development within the industry since 2020. China set forth the ambitious dual-carbon goal while introducing more stringent policies that prioritize scientific and technological innovation, coordinated development, intelligent manufacturing, green and low-carbon practices, quality control, and the research and development of high-precision products within the industry [16]. These policies have been incorporated into the overarching framework for achieving carbon peak and carbon neutrality while forming the foundational 1 + N policy system for the dual-carbon efforts of the industry [17]. Figure 2 illustrates the release dates and principal contents of significant policies in the steel industry post-2000.

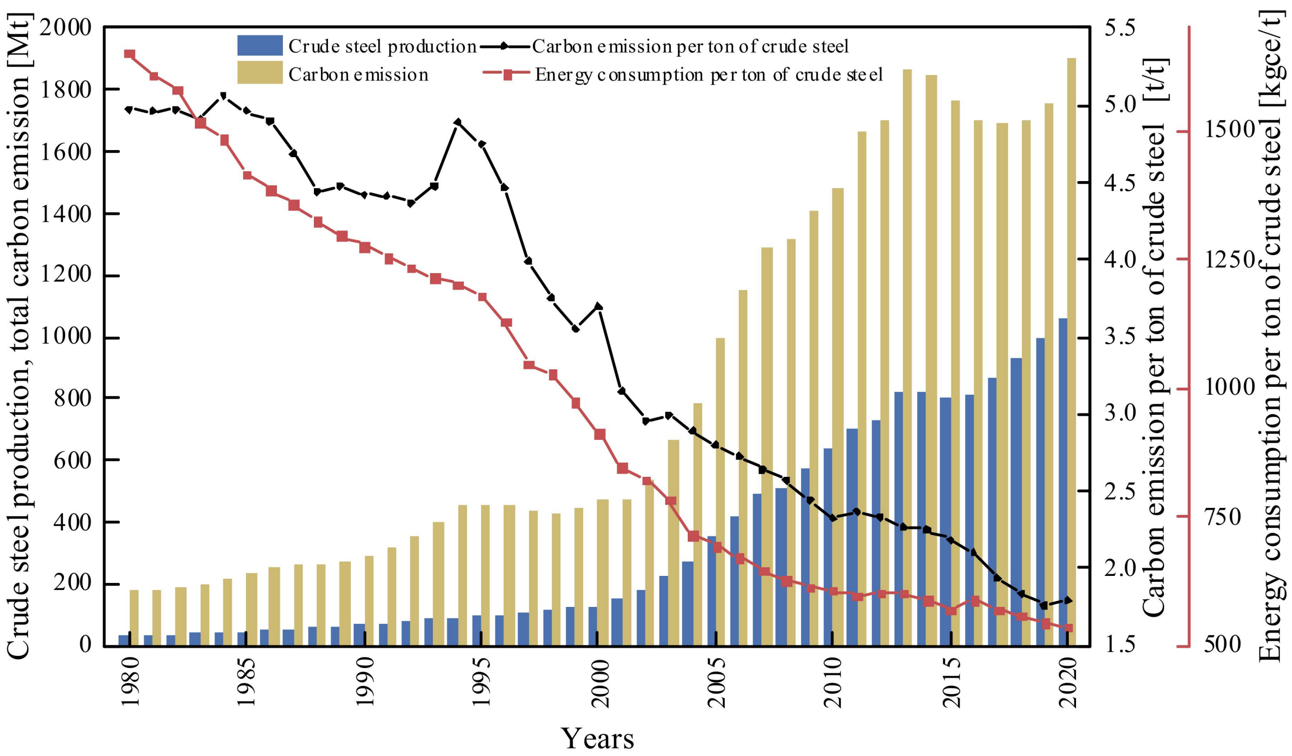

Figure 1. Evolution of crude steel production, carbon emissions, and energy consumption per ton of crude steel in the iron and steel industry of China [14,15].

Figure 2. Major policies and contents of the iron and steel industry of China in the 21st century [18–22].

The Carbon Border Adjustment Mechanism (CBAM), approved by the Council of the European Union (EU) on 23 April 2023, and scheduled for launch on 1 October during the transition phase, is designed to prevent carbon leakage and decrease emissions by levying a surtax on imports with high carbon emissions, such as steel products [23]. The gradual reduction of free quotas under CBAM, coupled with the carbon border tax, compensates for the implied carbon emissions in the EU and the carbon disparity between importing nations. A comparative analysis of carbon trading market prices in China and Europe, along with the carbon emissions intensity per ton of steel, indicates that the domestic steel industry will confront substantial emission reduction costs and transformational challenges [24].

2.2. Current Research Status on Dual-Carbon Pathways in the Iron and Steel Industry

In response to the domestic dual-carbon objectives and international carbon tariff policies of China, the iron and steel industry is proactively advancing three pivotal initiatives: Capacity replacement, ultra-low emissions, and extreme energy efficiency [25]. These efforts drive the industry towards greener low-carbon practices. Table 1 presents the dual-carbon roadmaps unveiled by key entities such as Baosteel and Shougang, as well as the China Iron and Steel Association (CISA). These roadmaps outline the implementation phases for the iron and steel industry of China, which include proactive carbon peaking by 2030, deep decarbonization spanning from 2030–2040, intense carbon reduction from 2040–2050, and striving for carbon neutrality by 2050–2060 [26]. The implementation strategies of the iron and steel industry revolve around two core approaches: Source reduction and sink enhancement. Key factors include crude steel production, process structure, energy intensity and composition, utilization of green hydrogen, and carbon capture, utilization, and storage (CCUS). The scale factor was found to be the primary driver for the rising carbon emissions of the industry, as indicated by the decomposition analysis utilizing the two-phase log-averaged Diophantine index method. Additionally, energy intensity emerged as the most significant inhibitory factor [27]. To adapt to the growing worldwide challenges and align with evolving development requirements, the focus of energy conservation and carbon reduction efforts within the iron and steel industry must shift. This shift involves transitioning emphasis from total quantity to intensity control and progressively moving from dual-energy consumption control to dual carbon emission control. In this context, enhancing energy efficiency will be essential for achieving energy savings and emission reductions before reaching their peak.

Table 1. Peak carbon neutral routes and implementation paths for major steel companies/industry in China.

<table>
<tr><th>Major Steel Companies/Industry</th><th>Dual-Carbon Route Planning</th><th>Implementation Pathway</th></tr>
<tr><td>Baowu Group</td><td>(1) Low Carbon Metallurgy Roadmap Released in 2021
(2) Strive to achieve carbon peaking by 2023
(3) Process technology capability for 30% carbon reduction by 2025
(4) Strive for 30% carbon reduction by 2035
(5) Strive to achieve carbon neutrality by 2050</td><td rowspan="3">(1) Fine-tuning energy management, enhancing overall system efficiency
(2) Recycling metallurgical resources, collaborative carbon reduction across multiple industries
(3) Process optimization, promoting low-carbon smelting technologies
(4) Breakthroughs in near-zero smelting technologies, green hydrogen and electricity facilitate “zero-carbon” smelting
(5) Upgrading green and low-carbon products, achieving carbon reduction throughout the entire lifecycle
(6) Carbon capture, storage, and utilization for energy-carbon decoupling, ensuring carbon neutrality in the steel industry</td></tr>
<tr><td>Shougang Group</td><td>(1) Publishing a “dual-carbon” work program in 2022
(2) Strive to achieve carbon peak by 2025
(3) Strive to reduce carbon emissions by 30% from the peak by 2035
(4) Become the first tier of large-scale iron and steel enterprises to achieve carbon neutrality by 2050–2060.</td></tr>
<tr><td>Ansteel Group</td><td>(1) Low Carbon Metallurgy Roadmap Released by the End of 2021
(2) Achieve carbon peaking by 2025
(3) Large-scale application of deep carbon reduction processes by 2030
(4) Reduce total carbon emissions by 30% from the peak in 2035
(5) First batch of carbon neutral enterprises in the iron and steel industry by 2050</td></tr>
</table>

Table 1. *Cont.*

Major Steel Companies/Industry	Dual-Carbon Route Planning	Implementation Pathway
Jianlong Group	(1) Publishing a roadmap for green development of the iron and steel sector in 2022 (2) Peak total carbon emissions in 2025 (3) Reduce total carbon emissions by 20% from the peak in 2033, and reduce carbon emission intensity by 25% from the 2020 level (4) Achieve carbon neutrality by 2060	
CISA	(1) Ensure carbon peaking in 2030 and reduce total carbon emissions by 15% compared with 2020 (2) Reduce the total carbon emissions of the industry by 40% in 2040 compared with that in 2020 (3) Reduce total industry carbon emissions by 85% in 2050 compared with 2020 (4) Achieve carbon neutrality by 2060 and reduce total industry carbon emissions by 95% compared with 2020	

Numerous scholars use energy efficiency and carbon emission intensity as important indicators to reveal the energy conversion and carbon emissions in the production process of the iron and steel industry. The former is mainly established based on the first and second laws of thermodynamics, including thermal efficiency and hydronic efficiency, which are widely used nowadays, and the carbon emission intensity indicator is the carbon emission per unit of product or service [28,29]. Energy efficiency in the iron and steel industry is directed towards reducing the consumption of the first and second energy carriers and recovering secondary energy wherever possible [30]. Table 2 summarizes the assessment methods for energy efficiency and carbon emissions in the steel industry. The research focus on energy efficiency and carbon emission reduction in the iron and steel industry has gradually shifted from the initial stage of energy saving in single equipment and processes to system energy saving and coupled energy-material flow optimization, aiming at exploring the relationship between material, energy, and carbon emissions in the iron and steel production process in a transparent, systematic, and integrated way.

Table 2. Methodology for assessing energy efficiency and carbon emissions in the iron and steel industry.

Names	Research Methodology	Characteristic	Level
Costa et al. [31]	Exergy analysis method	Taking a single unit as the research object	Facility level
Wu et al. [32]		Comprehensive assessment of the steel industry network and its impact on power generation, energy, and CO_2 emissions	Facility/process level
Sun et al. [33]	Stochastic Frontier Analysis	Evaluating GHG efficiency at the industrial level in China and revealing the potential for industry to reduce emissions	Industry level
Na et al. [34]	Methodology for evaluating energy efficiency in the process industry	Considers not only energy consumption and energy recovery, but also includes energy utilization for the entire process (e.g., heat of reaction, heat of phase change, etc.)	Facility/process/system level
Zhang et al. [35]	Carbon flow analysis in material and energy flows	Propose an integrated material-energy-carbon center for transparent carbon flow tracking and carbon accounting in the iron and steel industry	Facility/process/system level

2.2.1. Extreme Energy Efficiency Model

The *Extreme Energy Efficiency Project* is not merely a cost reduction initiative; rather, it constitutes a comprehensive industry-wide endeavor. This involves the rapid adoption of mature technologies, collaborative research and development to address shared technological challenges, and the implementation of various policies, regulations, and standards.

These efforts leverage national governance capabilities as well as the self-regulatory capacities of the industry to optimize steel production efficiency significantly. This strategic approach aims to bolster the low-carbon competitiveness of the iron and steel industry. And this project aims to enhance the overall process energy efficiency, representing the primary focus for carbon reduction in the iron and steel sector. Figure 1 illustrates a 67.6% reduction in comprehensive energy consumption per ton of steel and a 15–20% decrease in energy intensity in the steel industry over the last 40 years [34]. Therefore, crucial strategies involve focusing on innovating and applying waste heat and energy recovery methods, enhancing interfacial energy efficiency, optimizing process operations, utilizing optimal technologies, and integrating emerging advanced technologies. Limiting thermodynamic energy consumption levels under theoretical conditions represents a fundamental step towards achieving carbon peak and carbon neutrality in the iron and steel industry.

The extreme energy efficiency model is established based on the energy–mass balance relationship (Figure 3), and the specific relationships are presented in Equations (1) and (2).

$$H_{in} + E_{in} = H_{out} + E_{out} \tag{1}$$

$$H_{material} + H_{auxiliary} + E_{energy} = H_{product} + H_{byproduct} + E_{recovery} + E_{loss} \tag{2}$$

where, $H_{material}$ is the energy carried by the input raw materials of the process, $kJ/t_{product}$; $H_{auxiliary}$ is the energy carried by the input auxiliary materials of the process, $kJ/t_{product}$; E_{energy} is the energy contained in the input energy medium of the process, including energy mediums such as coal, gas, and diesel, as well as energy-consuming substances such as electricity, steam, heat, compressed air, and water, $kJ/t_{product}$; $H_{product}$ and $H_{byproduct}$ are the energies carried by the products and by-products of the process, respectively, $kJ/t_{product}$; $E_{recovery}$ is the energy recovered from the process; and E_{loss} is the loss of energy from the various implementations within the process, including facility losses and environmental heat dissipation, $kJ/t_{product}$.

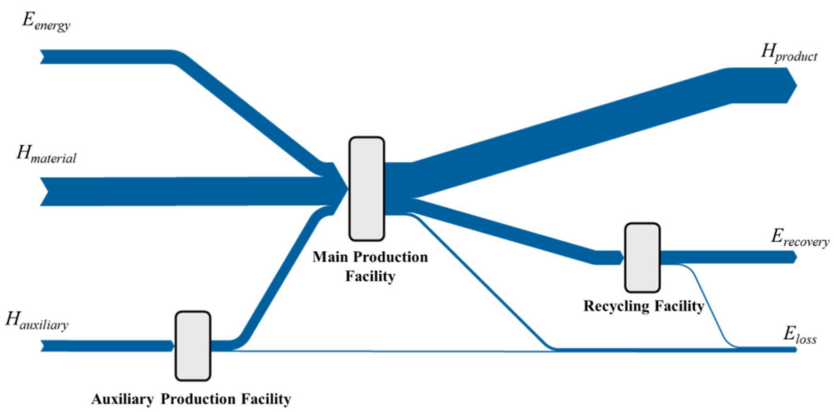

Figure 3. Extreme energy efficiency model.

Consequently, the actual energy consumption of the production process equals the disparity between the energy contained in the utilized energy medium and the recovered energy. The second expression can be deduced from the energy–mass balance relationship of the process (Equation (2)), as demonstrated in Equation (3).

$$\begin{aligned} E_{actual} &= E_{energy} - E_{recovery} \\ &= H_{product} + H_{byproduct} + E_{loss} - H_{auxiliary} - H_{material} \end{aligned} \tag{3}$$

where, E_{actual} is the energy consumption during the actual production process, $kJ/t_{product}$.

Equation (4) illustrates the extreme energy consumption of the production process. The enthalpy difference between the raw and auxiliary materials and the product signifies the essential energy requirement for product manufacturing, primarily dictated by material production characteristics. Simultaneously, the enthalpy of the product and by-products directly influences the high energy consumption of the process. Meticulous recovery of residual energy from products and by-products, along with minimizing environmental losses in process facilities, emerges as the principal strategies to curtail extreme energy consumption.

$$E_{extreme} = H_{product} - H_{auxiliary} - H_{material} \quad (4)$$

where, $E_{extreme}$ is the limit of energy consumption.

2.2.2. Energy Efficiency Improvement

The appellate model underscores the essence of the energy efficiency improvement pathway in steel production, emphasizing the reduction in enthalpy in $H_{byproduct}$, E_{loss}, and raw and auxiliary materials from upstream to downstream. Consequently, pathways to achieve extreme energy efficiency in the steel industry can be classified into three primary groups, as illustrated in Figure 4.

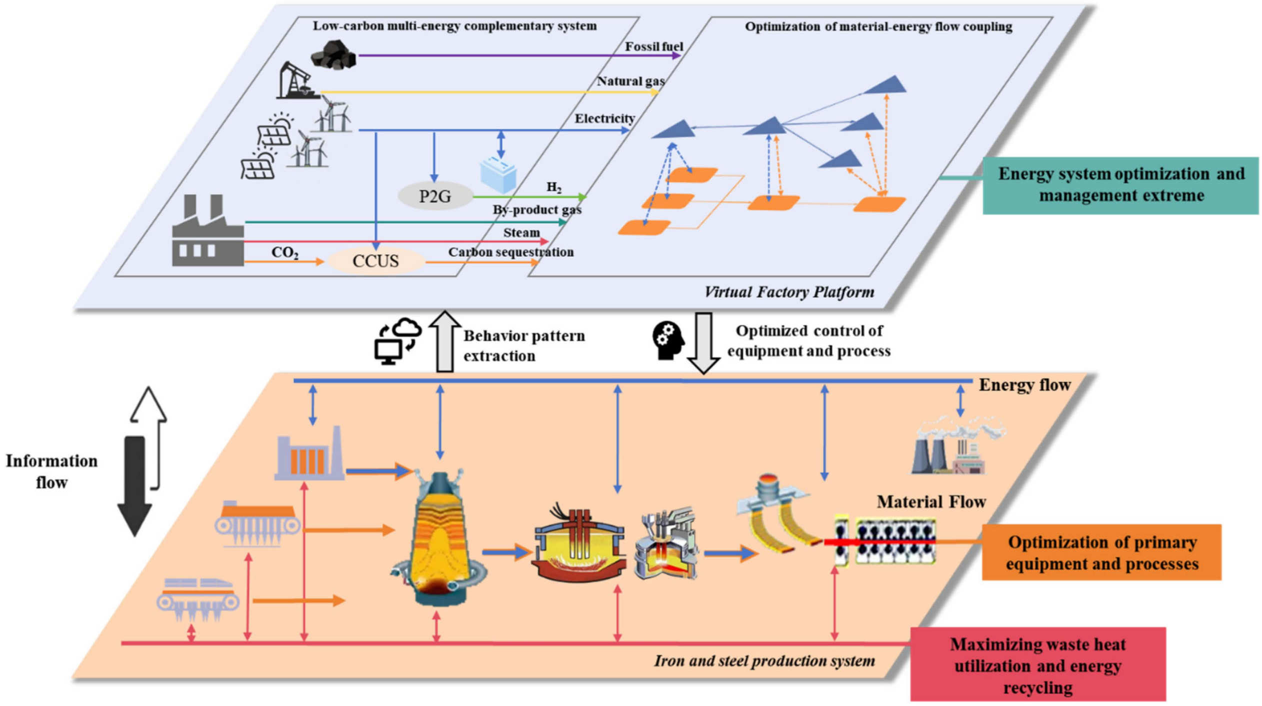

Figure 4. Optimization of low carbon steel production system by multi-energy complementary coupling and energy efficiency improvement pathway.

(1) Maximizing waste heat utilization and energy recycling

Harnessing the potential of waste heat and energy: Enhancing in-depth recovery and utilization of medium- and low-temperature waste heat resources. Currently, only 30–50% of the energy consumption of iron and steel production processes can be effectively utilized. Specifically, waste heat recovery in the ironmaking process stands at only 10%, with a primary focus on high-temperature waste heat [36]. Therefore, conducting a meticulous analysis of the metallurgical process is imperative, with a focus on medium- and high-temperature energy sources as catalysts. This approach facilitates the optimal reintegration of waste energy into the original process or peripheral energy systems while enhancing the energy grade. Consequently, regional energy self-balance could be achieved while substituting external energy inputs and curbing overall process energy consumption.

(2) Optimization of primary equipment and processes

The iron and steel industry needs to encourage capacity replacement, optimize the iron and steel process structure, and initiate modifications in the primary processes. The efficiency of the primary process requires a minimum energy consumption threshold. The transformation and upgrade of outdated equipment is characterized by low energy efficiency, inadequate cleanliness, and high emission intensity into advanced, efficient equipment. Interface technology has to be developed to achieve the compactness and continuity of metallurgical production while minimizing avoidable losses during the process. Concurrently, the industry needs to expedite the development of near-zero metallurgical technologies, including hydrogen-rich blast furnaces and hydrogen-based shaft furnaces, aiming to achieve the low-carbon transformation of the iron and steel industry at the fundamental process level.

(3) Integrated energy systems optimization and management for the iron and steel production process

This study optimized and controlled the integrated energy system while significantly enhancing the overall energy efficiency of the process. The study focuses on synergistic mechanisms of material flow, energy flow, and information flow in the iron and steel industry. The analysis of key energy mediums (gas, steam, and electricity) is crucial while considering the dual role of the iron and steel industry as a significant energy consumer and producer, diverse energy sources, and enhancing optimal scheduling. Furthermore, developing the ability for multi-energy complementarity with emerging sources such as wind and photovoltaic energy is essential for energy conservation. Optimizing the interconnection of material flow, energy flow, and information flow could enable the active involvement of flexible loads within the steel industry in system regulation and result in a comprehensive enhancement in the energy efficiency of the entire steel system.

In summary, the iron and steel industry primarily emphasizes strategies related to total volume, energy utilization, and structural adjustments within production processes. These measures aim to achieve significant reductions in unit energy consumption and carbon emission intensity in the industry. Existing research and policies comprehensively indicate that achieving peak carbon neutrality in the iron and steel industry at the present stage hinges on three main factors: Changes in overall production volume, optimization of the production structure, and enhancement of energy efficiency. Consequently, the subsequent section delves into these three facets and analyzes the trajectory and developmental trends toward carbon neutrality in the iron and steel industry of China. This analysis considered the viewpoints of energy consumption, carbon emissions, and economic costs.

3. Research Design

3.1. Crude Steel Production Forecast in the Iron and Steel Industry

The rise in iron and steel consumption is closely linked to societal development, population growth, and economic prosperity. The close connection between steel production, gross domestic product (GDP), and population has been documented, which is often represented by an inverted U-shaped curve [37]. Jia et al. [38] indicated that the steel consumption elasticity coefficient of China had a robust positive correlation with the GDP growth rate before 2008. Following the financial crisis and the implementation of capacity replacement methods, this correlation turned negative, leading to an annual average reduction in steel consumption intensity of 4.4% after 2010. Current policies and development plans in the iron and steel industry of China have acknowledged that crude steel production has reached its peak on the arc while considering the substantial GDP growth of China. Moreover, the intensity of crude steel per unit GDP is projected to decline. Consequently, production is expected to gradually rise before reaching its peak and subsequently decline. The decline rate of crude steel intensity per unit of GDP during each period of the national five-year development plan has been determined by Xue et al. [39]. The GDP projections for the next 40 years are based on the findings of Liu et al. [40]. Table 3 represents specific data, including the projected crude steel output at the end of each five-year planning period.

Table 3. Forecast parameters and crude steel production at the end of the five-year plan [39,40].

Year	GDP Growth Rate/%	Crude Steel Intensity per GDP/%	Forecast of Crude Steel Production/10^8 t
2021–2025	5.5%	−5.0%	10.77
2026–2030	4.5%	−6.0%	9.85
2031–2035	3.8%	−7.0%	8.48
2036–2040	3.4%	−5.2%	7.67
2041–2045	3.2%	−4.0%	7.33
2046–2050	2.8%	−4.0%	6.86
2051–2055	2.8%	−3.2%	6.69
2056–2060	2.5%	−2.6%	6.63

3.2. Production Structure of the Iron and Steel Industry

In pursuit of carbon neutrality, the iron and steel industry must undergo a profound production structure transformation. Promoting the adoption of the short process for scrap steel and increasing the utilization of pelletized ore represent effective strategies for carbon reduction. The recyclability of steel resources facilitates resource recycling and sustainable development through the processing of scrap steel for re-smelting. Utilizing scrap steel for the production of 1 t of crude steel could conserve 1.65 t of iron ore, lower energy consumption by approximately 350 kgce, reduce CO_2 emissions by about 1.4 t, and minimize solid waste by about 3 t [14]. The significant disparity in short-process smelting ratio of China compared to developed nations is closely tied to the evolution of its iron and steel industry. The iron and steel stockpile of China had surpassed 500 million tons by 2002, predominantly comprising new stockpiles, with end-of-life recycling being a future consideration [41]. Simultaneously, China holds a prominent position in the global long-process production route. The energy intensity of this process is only 5% lower than Germany, 9% lower than the United States, and 13% lower than South Korea. Key Chinese steel enterprises, including Baowu and Shougang, have achieved advanced technological proficiency across multiple operational facets [42]. The theoretical limit for CO_2 emissions from producing a ton of crude steel is 1.37 t after considering all energy losses [43]. The development of short-process smelting takes center stage in the double control of energy consumption and the double control of carbon emissions initiatives of China.

Apart from emission reductions in the steelmaking process, adjustments in the proportion of ore production within the furnace require attention. Furnace-generated ore is typically classified as sintered or pelleted. Sintered ore production suffers from process and equipment defects, leading to a high leakage rate and low energy efficiency. Conversely, pellet ore production units are well-sealed, boasting low leakage rates and enabling comprehensive waste heat utilization, ensuring high energy efficiency. Pellet mines exhibit approximately half the process energy consumption and carbon emissions of sinter mines. The measured data from Hesteel reveal that sinter mine units emit 0.2824 t of carbon, while pellet mine units emit only 0.1412 t [44,45]. Currently, sintered ore constitutes around 80% of the blast furnace charge of China, with pelletized ore comprising approximately 15%. In contrast, the United States and the EU utilize over 90% pelletized material in their blast furnace charges. The Swedish Steel AB plant in Sweden exclusively employs pelletized ore with a ratio of 100%. Elevating the proportion of pelletized ore in the furnace not only curtails carbon emissions in the iron pre-process but also furnishes raw materials for direct iron reduction. A dedicated effort to boost pelletized ore production could foster high-quality producers and hold immense significance for future hydrometallurgical advancements. Transforming the production process and enhancing the proportion of short processes is crucial for efficient resource utilization and mitigating the security risks associated with the heavy reliance on foreign iron ore of China. The production structure change scenario primarily focuses on steelmaking processes and artificial ore production structures. The detailed parameters are presented in Table 4.

Table 4. Parameters of production structure change scenarios [46].

Scenario	Proportion of EF Steel Production	Proportion of Pellet Production
Baseline scenario	2030: 15%, 2040: 25%, 2060: 40%	2030: 20%, 2040: 28%, 2060: 50%
Production structure change scenario	2030: 20%, 2040: 35%, 2060: 75%	2030: 24%, 2050: 50%, 2060: 70%

3.3. Energy Efficiency Improvement in the Iron and Steel Industry

Enhancing energy efficiency is the primary technical approach to curbing carbon emissions in existing production conditions. This study systematically categorized energy efficiency improvement technologies within the steel industry based on their sequential processes. These methods decrease energy consumption by enhancing production conditions, productivity, and energy utilization. Additionally, they elevate energy efficiency by harnessing waste heat and energy reuse. Technical parameters and market penetration data were obtained from the Guide to Advanced and Applicable Technologies for Energy Conservation and Emission Reduction in the Iron and Steel Industry (First Batch) as well as relevant research [15,47–50]. A comprehensive screening process identified 31 distinct technologies, as listed in Table 5. Under the current baseline scenario, the penetration rate of energy efficiency improvement technologies is expected to increase gradually. However, when the industry confronts stringent environmental constraints, this rate will dramatically increase. Figure 5a,b illustrates the penetration rates of these technologies under the respective scenarios.

Table 5. Energy savings and market share of energy efficiency upgradation technologies [15,47–50].

No.	Process	Technology	Energy Saving/kgce	Penetration Rate/%
T1	Coking	High-temperature and high-pressure dry coke quenching	7.19	14
T2		Coal moisture control	6.07	9
T3		Coke oven waste gas sensible heat recovery	11.97	15
T4	Sintering	Low temperature sintering	2.50	60
T5		Thick layer sintering technology	24.89	80
T6		Reduced sintering air leakage rate technology	2.00	70
T7		Small ball sintering technology	5.50	70
T8		Sintering flue gas waste heat recovery technology	7.14	20
T9	Pelletizing	Pellet ore sensible heat recovery technology	8.00	70
T10	BF	High-efficiency coal injection for blast furnace	9.04	40
T11		Blast furnace dehumidification blast technology	10.80	5
T12		Dual preheating technology for hot blast furnace flue gas	8.55	5
T13		Blast furnace top gas dry residual pressure power generation	5.16	83
T14		Blast furnace gas recovery technology	3.92	94
T15		Blast furnace slag heat recovery	12.50	0
T16	Continuous casting	High-efficiency continuous casting technology	14.01	75
T17		Integrated continuous casting and rolling technology for strip steel	13.43	20
T18	BOF	Converter gas sensible heat recovery technology	18.53	40
T19		Converter dry de-dusting technology	11.10	20
T20		Converter flue gas efficient utilization technology	7.40	15
T21		Converter slag heat recovery	5.33	5
T22	EAF	Scrap preheating technology	7.49	10
T23		Optimized power supply technology for electric furnaces	2.46	15
T24		Electric furnace flue gas waste heat recovery technology	5.53	10
T25	Rolling	Low temperature rolling technology	7.51	10
T26		Regenerative combustion technology for heating furnaces	17.88	40
T27		Process control technology for hot rolling mills	9.85	80
T28		Continuous casting billet hot loading and hot delivery technology	12.88	80
T29		In-line heat treatment technology	11.76	55
T30		Automatic monitoring and identification system	9.25	55
T31		Preventive maintenance technology	18.91	40

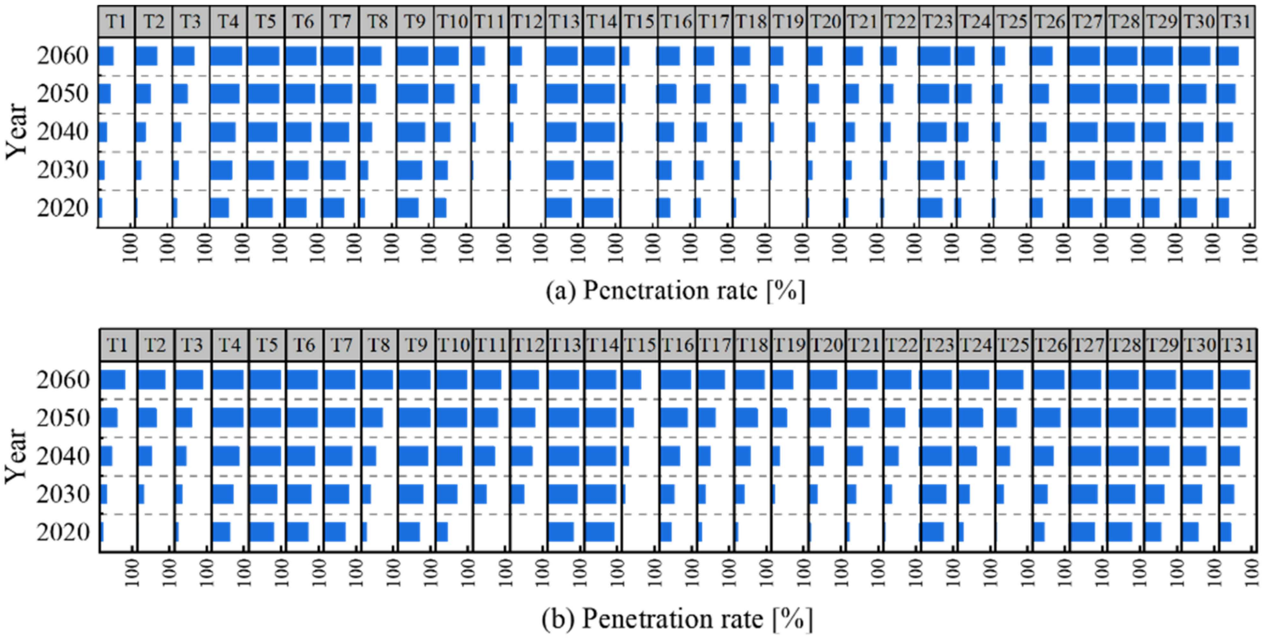

Figure 5. Technology penetration rate under the baseline and energy efficiency improvement scenario.

3.4. Abatement Costs in the Iron and Steel Industry

The Marginal Abatement Cost Curve (MACC) stands as the predominant method for evaluating the costs associated with diverse measures within intricate systems. Considering the iron and steel industry, this approach extensively assesses the potential for energy savings and emission reductions. This could be accomplished by neglecting the investment cost, energy replacement, and emission reduction benefits of each technology to its yearly service life [50]. This methodology has been adopted widely for evaluating various technologies in the iron and steel industry (Equations (5)–(8)).

$$CESER = \frac{ACC + \Delta O\&M - EAB - ERB}{ER} \quad (5)$$

$$ACC = CC \times \frac{d}{(1-(1+d)^{-n})} \quad (6)$$

$$ERB = ER \times PC \quad (7)$$

$$EAB = EA \times PE \quad (8)$$

where, *CESER* is the marginal energy saving and emission reduction cost of the technology, yuan/t(CO_2). *ACC* is the annualized cost of investment, yuan/t. $\Delta O\&M$ is the annualized operation and maintenance cost, yuan/t. *CC* is the fixed investment cost, yuan/t. d is the discount rate, which is considered to be 15% in this paper. n is the payback period, which is uniformly assumed to be 20 years. *EAB* and *ERB* are the energy-saving benefit and emission-reduction benefit, respectively. EA and ER are the energy savings and carbon emission reductions, kgce and t(CO_2). The *PE* and *PC* are the energy replacement price and carbon price, which are considered to be 0.91 yuan/kgce [50] and 60 yuan/t, respectively.

By utilizing the integrated database of the LEAP platform and incorporating the aforementioned marginal abatement cost analysis, a model for analyzing the energy demand and environmental impact of the iron and steel industry of China was established, in which for the environmental impact analysis, this paper only discusses the impact of CO_2 emissions. The primary calculation methods are presented in Equations (9)–(13).

1. Sectoral production

$$P = \sum_i P_i \quad (9)$$

where, P is the total output of the iron and steel industry, t; and P_i is the output of the ith process, t.

2. Energy demand

$$E = \sum_i \sum_j \sum_n e_{n,j,i} \times P_{j,i} \quad (10)$$

where, E is the total energy demand of the iron and steel industry, tce. $e_{n,j,i}$ is the total amount of energy of type n consumed for the production of equipment j in process i, tce.

3. Environmental impact

$$C = \sum_i \sum_j \sum_n ef_{n,j,i} \times e_{n,j,i} \times P_{j,i} \quad (11)$$

where, C is the total carbon emissions of the iron and steel industry, t and $ef_{n,j,i}$ is the CO_2 emission factor, which is the carbon emissions of the n-type unit of energy consumed by the production of equipment j in process i, tCO_2/tce.

4. Energy saving and emission reduction potential

$$ESP = \frac{E_0 - E_a}{E_0} \quad (12)$$

$$CMP = \frac{C_0 - C_a}{C_0} \quad (13)$$

where, ESP is the energy-saving potential, %; E_a is the energy consumption of scenario a, tce; E_0 is the energy consumption of the baseline scenario, tce; CMP is the emission reduction potential, %; C_a is the carbon emissions of scenario a, t; and C_0 is the carbon emissions in the baseline scenario, t.

Based on the preceding scenario analysis, this study categorizes the future into three sub-scenarios (the baseline scenario, the production structure change scenario, and the energy efficiency improvement scenario) and two composite scenarios (the baseline scenario and the energy-saving and emission-reduction scenario). In the baseline scenario, the current developmental trajectory continues without imposing stringent greenhouse gas control measures. With the reduction in crude steel output, technologies are upgraded in line with current policy requirements, and the proportion of electric furnace steel is adjusted accordingly. This scenario alters production methods and energy consumption structures while focusing on a limited set of factors influencing carbon emissions. The production structure change scenarios delve deeper into energy-saving and carbon reduction potentials, emphasizing the increase in short processes and pellet ore usage. The energy efficiency improvement scenario concentrates on scaling up the adoption of mature energy-saving technologies prevalent in the industry and hastening their widespread application. A comprehensive energy-saving and emission-reduction scenario merges these three influential factors cohesively.

Therefore, this paper combines the actual situation and the results of the previous study. The model construction process is shown in Figure 6, which is mainly divided into the following steps:

(1) Determine the object of analysis as the iron and steel industry of China, and analyze energy consumption, carbon emissions, and marginal abatement costs, with a time horizon of 2021–2060.
(2) Determine the main influencing factors, including production, technological progress, and policy measures.
(3) Establishing a bottom-up steel production model based on the LEAP model according to the actual production of the iron and steel industry of China.
(4) Establishing different scenarios based on the industry's development status, the 14th Five-Year Plan, the Outline of Vision 2035, and other relevant policy documents.

(5) Compare and analyze the trend of energy consumption and carbon dioxide emissions under different scenarios, and combine them with the marginal abatement cost curve to find the implementation path of low-carbon development in the industry.

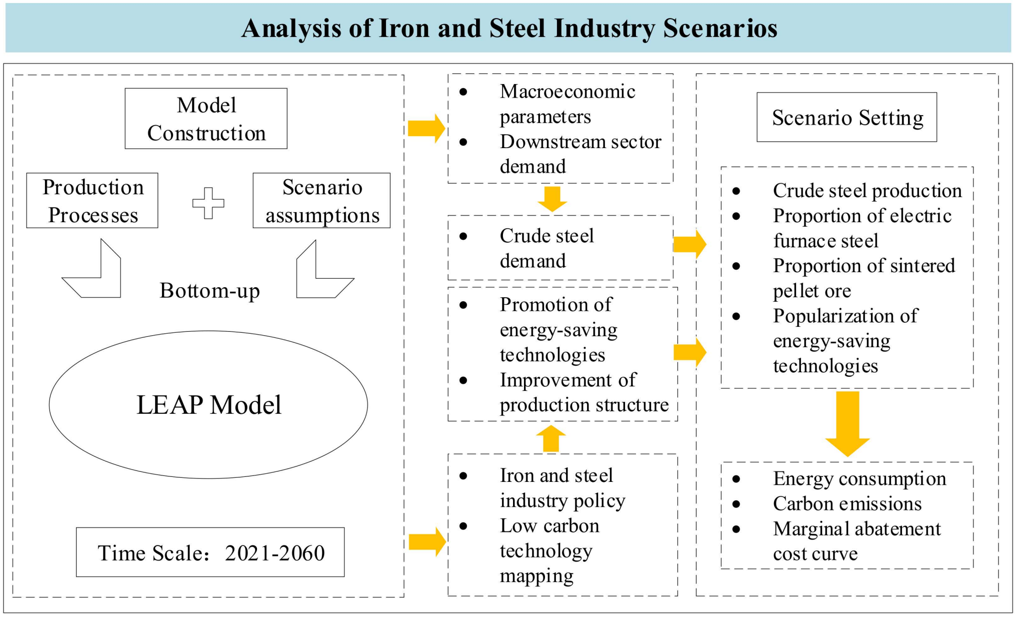

Figure 6. Flowchart of carbon emission modeling of the iron and steel industry of China based on the LEAP model.

4. Discussion

4.1. Total and Structural Energy Consumption

Figure 7 illustrates the energy consumption trend in the iron and steel industry of China from 2020 to 2060. In 2020, the energy consumption of the industry stood at 570 Mtce. Both energy consumption and crude steel production exhibit a consistent decline. Under the baseline scenario, crude steel production will experience gradual growth until 2025. However, due to the increased adoption of electric furnace steelmaking and the implementation of energy-efficiency improvement technologies, the industry achieved peak energy consumption in 2020. The consumption will slowly decrease to 564.69 Mtce in 2025 and to 271.09 Mtce in 2060. The energy-saving and emission-reduction scenario, driven by the accelerated promotion of production processes and energy-efficiency improvement technologies, results in more significant declines in energy consumption, reaching 271.09 Mtce in 2060. By 2025, energy consumption will reduce significantly, totaling 193.93 Mtce in 2060, marking a 28.5% decrease from the baseline scenario. In 2060, energy consumption per ton of steel will be 408.9 kgce and 292.5 kgce, respectively. It is crucial to note that crude steel output significantly influences energy consumption fluctuations. Assuming a crude steel output of 1.09 billion tons in 2025, total energy consumption in the iron and steel industry will continue an upward trend even in the baseline scenario. Therefore, curbing the disorderly growth of crude steel production is of priority.

The primary energy inputs for the steel industry include coal, coke, natural gas, electricity, hydrogen, gasoline, and diesel. A simplification is conducted to neglect the conversion of hydrogen, gasoline, and diesel to standard coal since their ratio in the primary energy inputs is small. As these values exhibit minimal changes across different scenarios, they are excluded from the sub-category of energy consumption. Figure 8 illustrates the alterations in the main energy sources from 2020 to 2060. The findings reveal coal and the predominant share of coke, constituting approximately 90% of total energy consumption in the baseline year. The shift in energy source distribution in the baseline scenario is marginal, which will stay at 87%, 85%, 85%, and 86% from 2030 to 2060, respectively. The share of coal could diminish slightly, reaching 87.4%, 85.8%, 84.2%, and 81.7% from

2030 to 2060. Under the energy-saving and emission reduction scenario, coal-based energy could significantly decrease, comprising 86.7%, 84.3%, 80.3%, and 72.9% from 2030 to 2060. This decline could result from a higher proportion of short-process steelmaking, leading to a significant rise in electricity consumption from 8.9% in 2020 to 19.1% in 2060. The future environmentally friendly and low-carbon progression of the iron and steel industry of China hinges on steel electrification levels and the degree of decarbonization of the electrical industry. These approaches fundamentally curtail reliance on coal-based energy, either through the development of all-scrap short processes or direct iron reduction through water.

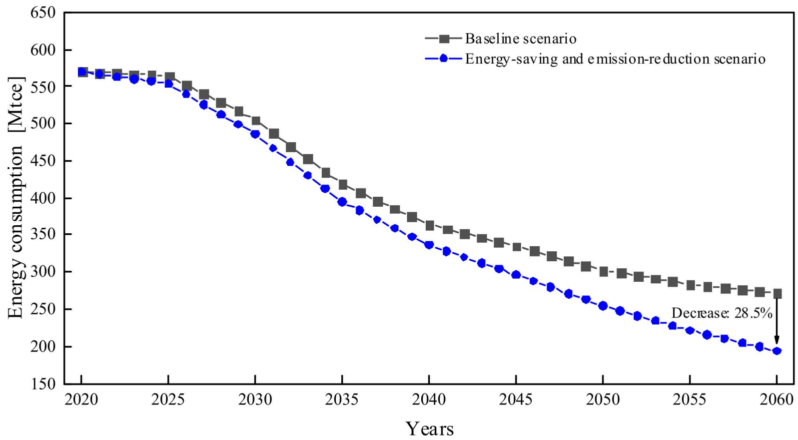

Figure 7. Total energy consumption in the iron and steel industry of China from 2020 to 2060.

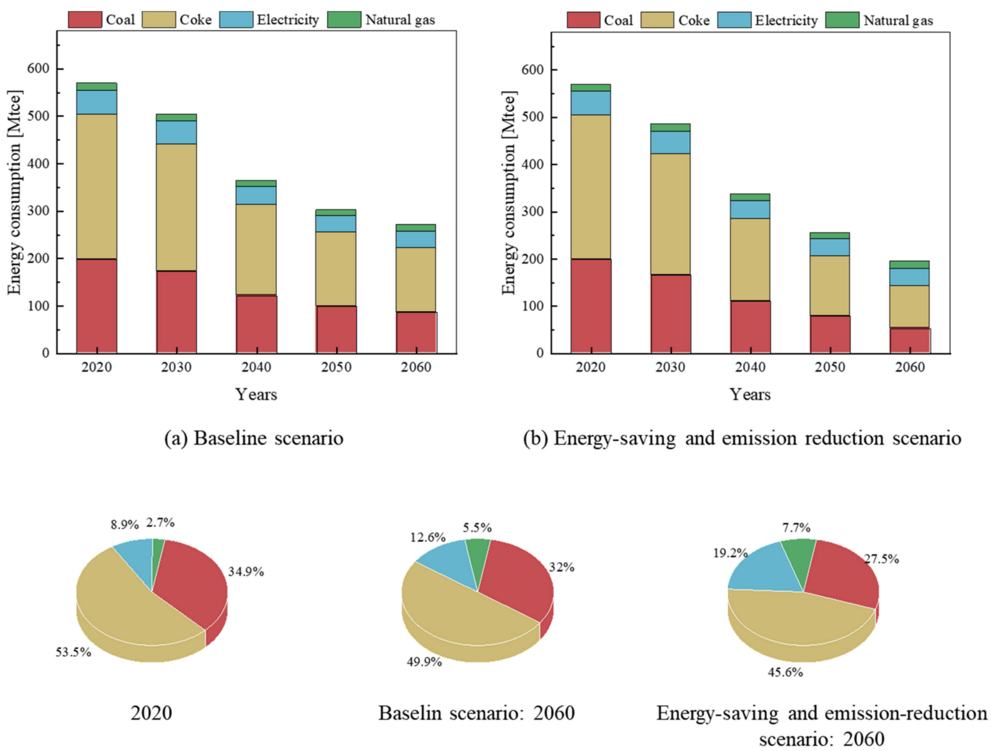

Figure 8. Changes in the structure of energy consumption by category under different scenarios.

4.2. Total Carbon Emissions and Intensity

The iron and steel industry will transition from dual-control of energy consumption to dual-control of carbon emissions in the future. The total carbon emissions of the industry will shift from relative constraints to absolute constraints. This shift is crucial for decision-makers, providing an intuitive basis for judgment when compared to total energy consumption. The iron and steel industry of China emitted 1786 Mt of carbon in the base year. Figure 9 illustrates total carbon emissions and the change in carbon emissions per ton of steel across comprehensive scenarios. Carbon emissions exhibit a downward trend in both scenarios, peaking in 2020. Under the baseline scenario, the industry will emit 863 Mt of carbon in 2060, a 51.7% decrease from the baseline year. However, the decline in carbon emissions tends to plateau over time. Despite existing emission reduction measures and technological advancements, the carbon emissions of the industry will remain high during the *Carbon Neutral Year*. Therefore, more stringent carbon emission control policies are required. The low-carbon scenario reduces emissions by 27.2% compared to the baseline scenario, reaching 629 Mt. This is accomplished by optimizing production structures and by the adoption of energy-efficiency technologies. Under the carbon-neutral scenario, new technologies in the energy structure could result in 120 Mt emissions in 2060, an 86.1% decrease from the baseline scenario. However, achieving net-zero emissions is unattainable for the steel industry under all these scenarios. Even the most efficient carbon-neutral scenario still emits 100 million tons of carbon. Therefore, the industry must adopt options such as purchasing carbon emission rights to attain carbon neutrality. Figure 9b illustrates carbon emissions per unit of crude steel produced under the three scenarios: 1301.1 $kgCO_2/t$ of steel in 2060 for the baseline scenario, 947.5 $kgCO_2/t$ of steel for the low-carbon scenario, and 254.7 $kgCO_2/t$ of steel for the carbon-neutral scenario.

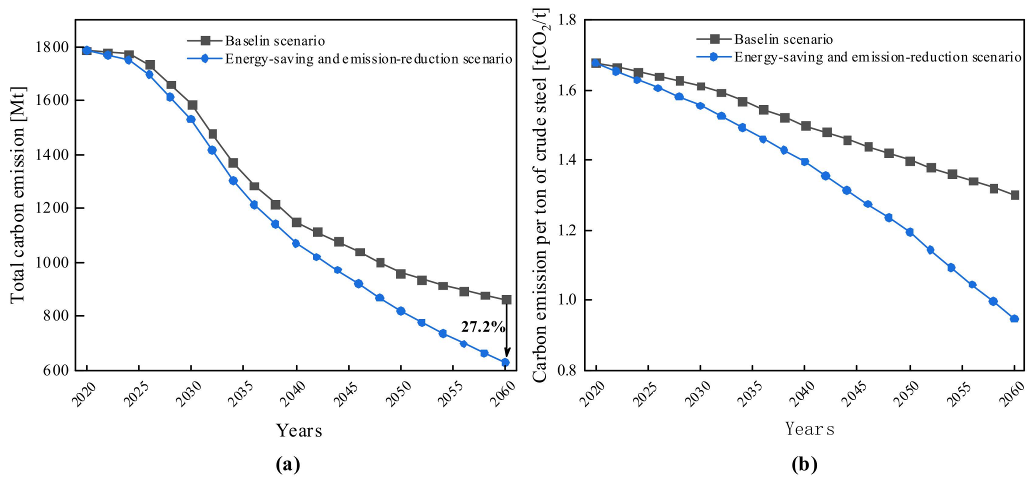

Figure 9. Changes in (**a**) total carbon emission and (**b**) carbon emission per ton of steel from 2020 to 2060.

The trend of carbon emission changes in the iron and steel industry of China under each sub-scenario is illustrated in Figure 10. Considering only the natural change in crude steel output due to economic development, the iron and steel industry in China is projected to reach the carbon emission peak in 2025 while emitting 1803 Mt. This peak in carbon emissions aligns with the peak of output, occurring simultaneously. By 2060, carbon emissions are expected to decrease to 1089 Mt, with a 60.8% contribution from the reduction in output. This finding is consistent with previous studies, emphasizing the substantial impact of output changes on carbon emissions. The production structure change scenario further reduces carbon emissions by 36.9% based on the decline in production, reaching 666 Mt in 2060. However, the contribution of energy efficiency and emission reduction technologies in the iron and steel industry remains relatively low (2.3%). This is primarily because the energy efficiency improvement technologies considered in this paper are highly mature and easily promotable. Some of them had significant applications by 2020 and are anticipated to reach their promotion limits by 2040. Additionally, the decline in production and changes in production structure diminish the emission reduction potential of energy efficiency improvement technologies.

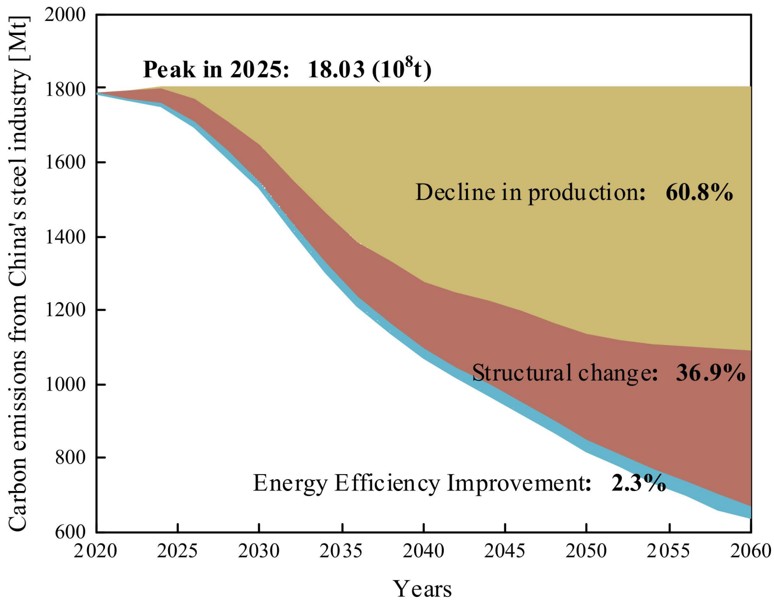

Figure 10. Carbon emissions and emission reduction contributions from the iron and steel industry of China.

4.3. Abatement Costs in the Iron and Steel Industry

Figure 11 illustrates the cumulative emission reductions resulting from 31 energy efficiency improvement technologies, which have a total emission reduction potential of 780 Mt under the energy efficiency improvement scenario. The coking process yields the smallest cumulative emission reductions. This is primarily due to the limited consideration of coke-making plants within the iron and steel enterprises of the model, resulting in a lower activity level compared to other processes. Technologies in the blast furnace process offer slightly higher cumulative emission reductions than other processes. High-efficiency coal injection in the blast furnace, dehumidification blast technology, and double preheating of flue gas in the hot blast furnace all contribute to cumulative emission reductions of over 50 Mt. Market penetration significantly influences cumulative emission reductions. For instance, technologies such as dry residual pressure power generation from the blast furnace roof gas and gas recovery from the blast furnace for T13 and T14 exhibit lower cumulative emission reductions. Other technologies demonstrate varied cumulative emission reductions based on their penetration rate, inherent energy saving, and emission reduction potential. Energy efficiency improvement technologies applied to converters, electric furnaces, and rolling processes also offer substantial opportunities for emission reductions.

As depicted in Figure 12, the marginal abatement cost of each technology can be calculated using Equation (5) while utilizing the accumulated emission reduction data. Within the energy efficiency improvement scenario, the iron and steel industry of China exhibits an average unit energy saving and emission reduction cost of 27.0 yuan, amounting to a total carbon emission reduction cost of 21.02 billion yuan. Scrap preheating technology significantly enhances scrap recycling efficiency by elevating scrap temperature and, thereby, could reduce carbon dioxide emissions at the source, equating to an energy-saving and emission-reduction benefit of 885.2 yuan/t. Additionally, alterations in pellet mine and short-flow production structure could contribute to a substantial 36.9% reduction in emissions by 2060. However, due to the cost implications associated with these production structure changes, the unit energy-saving and emission reduction cost related to these structural modifications is 702.7 yuan [13]. This cost considerably surpasses the unit energy-saving and emission reduction cost associated with energy efficiency enhancement, posing a significant challenge to the large-scale transition of the iron and steel industry to short-flow steelmaking. The financial challenge serves as a major impediment to the shift of the industry to short-process steelmaking. Therefore, the iron and steel sector must be formally integrated into the carbon trading market. The anticipated future increase in carbon trading prices is expected to reduce the abatement cost associated with production structure changes. The iron and steel industry should seize this opportunity and focus on energy efficiency improvement as the core technology for abatement. Gradual promotion of the transition to short-process steelmaking is recommended while aiming at reducing the overall carbon intensity of the iron and steel industry and facilitating the green and low-carbon transformation.

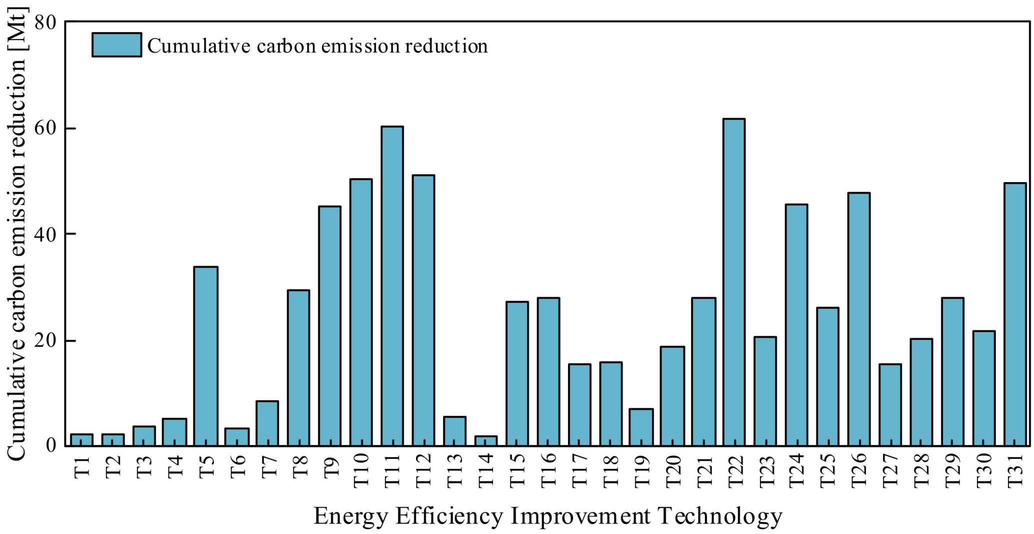

Figure 11. Cumulative emission reduction from 31 energy efficiency enhancement technologies.

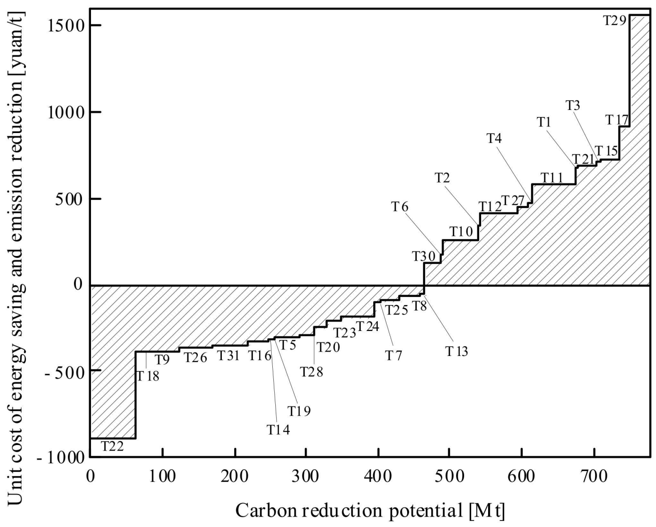

Figure 12. Carbon emission reduction potential and abatement costs of energy efficiency improvements in the iron and steel industry.

5. Conclusions

This study employed the LEAP model to project the future trajectory of the iron and steel industry of China. The analysis integrated data on energy consumption, carbon emissions, and marginal abatement costs across diverse scenarios. The findings provided essential policy recommendations to facilitate the transition of the iron and steel industry towards carbon peak and carbon neutrality.

1. It is imperative to curtail the unregulated surge in crude steel output and phase out outdated production capacities. Crude steel production stands as the primary driver of carbon emissions. Over the last two decades, the unprecedented rise of the industry

in carbon emissions has indicated a sharp increase in crude steel production. With the economic growth of China, the focus of the iron and steel industry should shift towards the production of high-quality and multi-purpose steel. The iron and steel industry has already achieved carbon peaking at the current production level with the assumption that crude steel production does not exceed 1070 Mt.

2. The green and low-carbon transformation of the iron and steel industry can be achieved by controlling the production of crude steel and employing energy efficiency improvement technologies in all processes of the iron and steel industry. Under the comprehensive scenario, the future total energy consumption and carbon emissions of the industry exhibit a consistent downward trajectory. The baseline scenario represents the most gradual decline, whereas the energy-saving and emission-reduction scenario accelerates the adoption of advanced production processes and technologies, resulting in significantly reduced carbon emissions of 947.5 kg per ton of steel, as opposed to 1301.1 kg. Once the influence of crude steel production is mitigated, structural changes in production are poised to be pivotal in emission reduction in the long term. Although energy efficiency improvement technology plays a relatively minor role, its potential for emission reduction by 2030 should not be underestimated.
3. Stringent external regulations must be implemented to foster the growth of environmentally conscious enterprises. At this stage, the average unit energy saving and emission reduction cost of energy efficiency improvement in the iron and steel industry of China is 27.0 yuan, and the total emission reduction cost is 21.02 billion yuan. The unit abatement cost of production structure change due to the price of scrap and pellet ore is 702.7 yuan. The abatement cost limitation has become an obstacle to promotion at this stage. The iron and steel industry must be integrated into the carbon trading market system while leveraging market constraints to enhance the industry-wide reduction of carbon emission intensity. Tailored incentives must be offered to enterprises employing cutting-edge technologies while compensating for the augmented production costs incurred due to green and low-carbon practices. Furthermore, widespread industry investment in research and development must be encouraged.

Author Contributions: Conceptualization, Y.G.; data curation, B.T.; formal analysis, B.T. and C.P.; investigation, W.L. and B.W.; methodology, Y.G. and C.P.; resources, B.W. and X.Y.; software, B.W.; validation, B.W. and X.Y.; visualization, B.T.; writing—original draft, Y.G. and C.P.; writing—review and editing, Y.G., W.L., X.Y. and C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Industry and Information Technology Public Service Platform Project for Industrial Technology Foundation in 2021, grant number 2021-H029-1-1.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

Glossary

LEAP	Long-range energy alternatives planning system
GHG	Greenhouse gas
CBAM	Carbon border adjustment mechanism
EU	European Union
CCUS	Carbon capture, utilization, and storage
CISA	China Iron and Steel Association
GDP	Gross domestic product
BF	Blast furnace

BOF	Basic oxygen furnace
EAF	Electric arc furnace
$MACC$	Marginal abatement cost curve
H_i	The energy carried by material
E_i	The energy contained in the energy medium
$CESER$	Marginal energy saving and emission reduction cost of the technology
ACC	Annualized investment cost
$\Delta O\&M$	Annualized operation and maintenance cos
CC	Fixed investment cost
ER	Carbon emission reductions
EA	Energy savings
EAB	Energy-saving benefit
ERB	Carbon emission reduction benefit
PE	Energy replacement price
PC	Carbon price
d	Discount rate
n	Payback period
P	Output of the iron and steel industry
P_i	Output of the ith process
E	Energy demand of the iron and steel industry
$e_{n,j,i}$	Amount of energy of type n consumed for the production of equipment j in process i
$ef_{n,j,i}$	CO_2 emission factor
ESP	Energy saving potential
CMP	Emission reduction potential
C	Carbon emissions

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