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Review

Recent Status of Production, Administration Policies, and Low-Carbon Technology Development of China's Steel Industry

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Abstract: In 2023, China's crude steel production amount reached 1.019 billion tons, and the energy consumption of China's steel industry amount reached 561 million tons of coal. China's steel industry, with its dominant reliance on coal for energy and the primary use of blast furnaces and converters in production processes, as well as its massive output, has become the main field for achieving China's "carbon peaking" and "carbon neutrality" goals. Firstly, this article summarizes the current production status of the steel industry and the situation of carbon emissions in the steel industry. Secondly, it discusses the dual-carbon policies based on the national and steel industry levels and outlines the future directions for China's steel industry. Subsequently, it analyzes the current state of research and application of mature and emerging low-carbon technology in China's steel industry and details the low-carbon plans of China's steel companies using the low-carbon technology roadmaps of two representative steel companies as examples. Finally, the article gives policy suggestions for the further carbon reduction of China's steel industry. The purpose of this paper is to show the efforts and contributions of China's steel industry to the early realization of its "carbon peaking" and "carbon neutrality" goals.

Keywords: steel industry; carbon peaking; carbon neutrality; low-carbon technology; low-carbon policy

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1. Introduction

The increase in greenhouse gas emissions, such as carbon dioxide and methane, caused by human industrial, energy, and other activities is the main cause of global warming. Global warming leads to climate problems, such as rising sea levels and increasing extreme weather, and indirectly causes conflicts and economic issues. China currently possesses the world's most comprehensive and largest-scale steel industry system, equipped with the world's most advanced equipment and technology [1]. This industry can provide the most abundant iron and steel products. As an important basic industry, the steel industry contributes to the material foundation and material security of national economic development. However, the steel industry has been under significant pressure due to its environmental impact [2]. The steel industry is a resource-intensive and energy-intensive industry, while it is a high-energy-consumption and high-emission industry [3]. China's crude steel production is about 1.019 billion tons, ranking first globally. The steel industry's carbon emissions account for 15% of China's carbon dioxide emissions, and it is the second largest emitting industry [4]. Therefore, the steel industry faces enormous pressure to reduce carbon emissions.

China announced it will strive to reach peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 [5]. As a major contributor to China's carbon emissions, the steel industry has received increasing attention recently. The Chinese government, large steel enterprises, universities, research institutions, and others have all carried out relevant work. On 24 December 2021, the Chinese government issued the "Working Guidance for

Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy" [6]. It pointed out the formulation of action plans for carbon peaking in the energy, steel, and other industries to accelerate low-carbon technological development in the industrial sector. On 20 January 2022, the Chinese government issued "The Guiding Opinions on Promoting the High-Quality Development of the Steel Industry" [7]. It pointed out that innovative development, total quantity control, low-carbon development and overall co-ordination are the basic principles to achieve high-quality development in the steel industry. On 18 November 2021, Baowu Steel Group established a Low-Carbon Metallurgy Innovation Center and completed the construction of a Hydrogen-enriched Carbonic oxide Recycling Oxygenate Furnace (HyCROF), providing support for the progress of low-carbon metallurgical technology [8]. In December 2022, through the implementation of the "Hegang Low-Carbon Product Plan", Hegang Group promotes the innovation of low-carbon technologies with upstream and downstream industries by using carbon reduction technologies such as biomass energy substitution and carbon capture utilization and storage (CCUS) [9]. In 2021, Capital Engineering & Research Incorporated was approved to establish the Low-Carbon Technology Research Institute (Beijing) of China Metallurgical Corporation, which provides a solid foundation for future low-carbon technology research and development. Northeastern University, University of Science and Technology Beijing, Chongqing University, North China University of Science and Technology, and other universities have established low-carbon metallurgical research departments based on their advantageous disciplines of metallurgy and focus on the key technologies for low-carbon steelmaking to help China's steel industry to achieve low-carbon development.

Although many scholars have discussed carbon emissions and low-carbon technologies in China's steel industry [10,11], few have discussed low-carbon policies for the steel industry and steel enterprise's carbon reduction technologies. To fill this gap, firstly, this article overviews the development status of China's steel industry. Secondly, it discusses the dual-carbon policies based on the national and steel industry levels. Subsequently, it analyzes the current state of research on low-carbon technology in China's steel industry and details the low-carbon plans of China's steel companies. Finally, the article gives suggestions for further carbon reduction in China's steel industry. It is aiming to provide a reference for China's steel industry to achieve carbon peaking and carbon neutrality as soon as possible.

2. Current Production Status of China's Steel Industry

2.1. Variations of Crude Steel Production Amount

China's crude steel production amounts from less than one-thousandth of the world's production amount when the People's Republic of China was established, to 53.9% of the global crude steel production amount by 2023; this growth rate sets a new historical record for humanity [12]. Before 2000, China's crude steel production amount showed relatively stable growth. However, starting in 2001, with China's accession to the World Trade Organization and the subsequent surge in trade, China's crude steel production amount began to surge. It increased from 150 million tons in 2001 to 1.019 billion tons in 2023, and the trend is shown in Figure 1 [13,14]. According to data from the National Bureau of Statistics of China, the country's steel exports amount to 91.201 million tons, accounting for 8.94% of the production amount in 2023. This indicates that China's steel production primarily aims to meet domestic demand, and the economic condition heavily influences the crude steel production level.

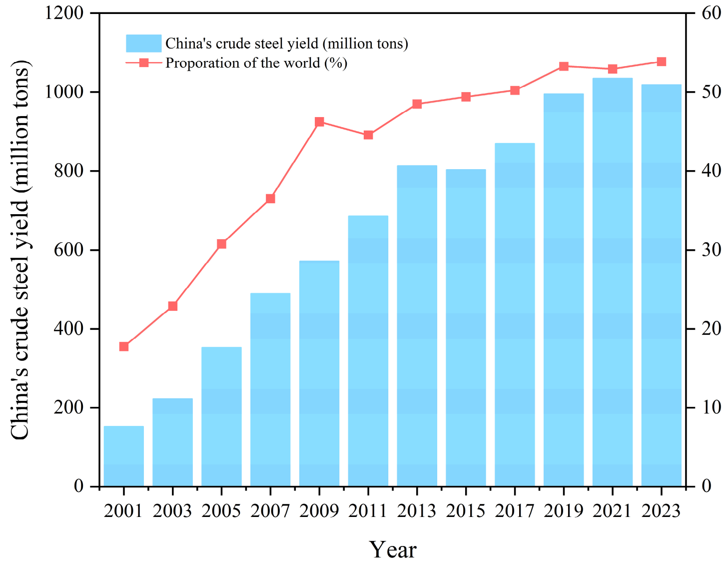

Figure 1. China's crude steel yield and the proportion of the world in recent years.

2.2. Overview of Carbon Emissions and Challenges Ahead

Currently, the carbon emissions from the Chinese steel industry account for approximately 15% of the country's carbon emissions. The primary use of blast furnaces and converters in production processes in China's steel industry contributes to the high level of carbon emissions because this process relies on coal and coke as the reducing agent and source of heat. The energy consumption of various major processes and carbon emission factors of the main raw materials are given in Table 1 and Figure 2 [15–17]. In recent years, the carbon dioxide emission from the Chinese steel industry has continued to increase, and the trend is shown in Figure 3. Until 2022, the carbon dioxide emissions from the Chinese steel industry had reached 1.823 billion tons [18–21].

Table 1. Process energy consumption of steel enterprises in 2023.

	Sintering Process	Pellet Process	Coking Process	Blast Furnace Process	Converter Process	Rolling Process
kgce/t	54.95	24.35	90.26	376.40	−12.27	54.75

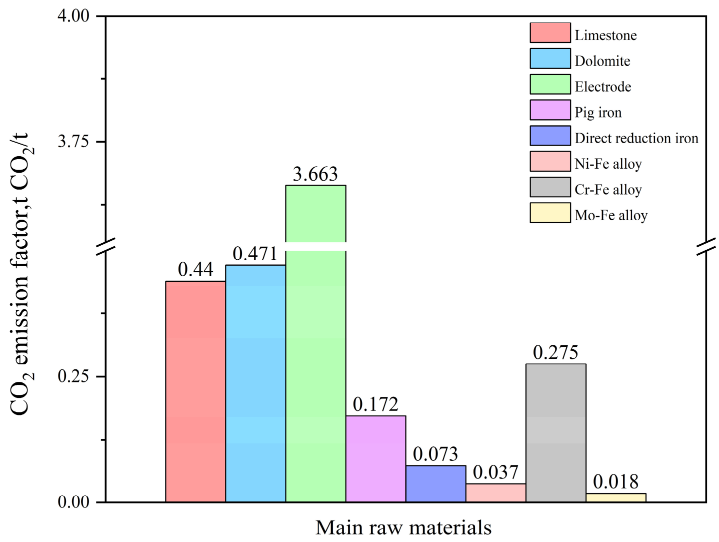

Figure 2. Carbon emission factors of main raw material.

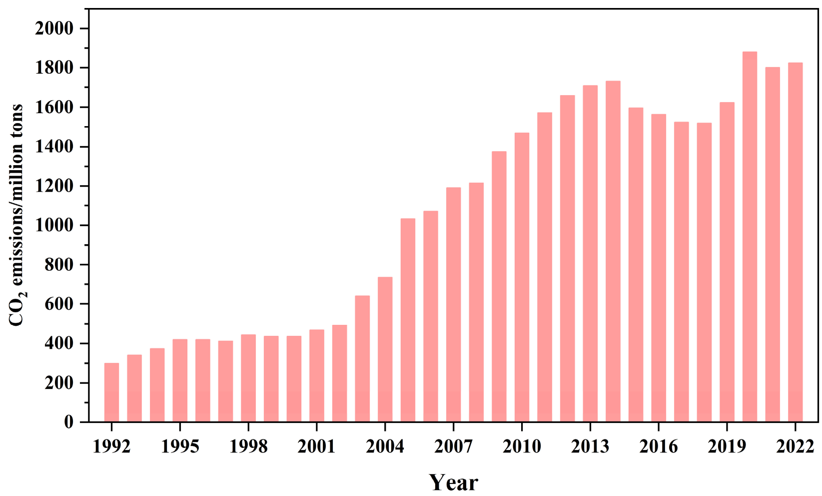

Figure 3. Changes in carbon emissions of China's steel industry in different years.

The Chinese steel industry faces several challenges in reducing carbon emissions [1,22–24]: (1) Increasingly stringent carbon emission regulations. Since 2021, the Chinese government and relevant departments have introduced a series of policies requiring steel enterprises to reduce carbon emissions. For example, "The Guiding Opinions on Promoting the High-Quality Development of the Steel Industry" emphasizes the need for the steel industry to achieve carbon peaking before 2030. (2) Imbalanced low-carbon technology levels among enterprises. Some leading steel companies have already reached or are close to world-class levels in terms of equipment and key technologies. However, some companies still have relatively outdated equipment and technologies, leading to high energy consumption and emissions. This imbalance hinders carbon reduction efforts in China's steel industry. (3) Lack of unified national low-carbon technology research and application plan. The Chinese steel industry has made significant progress in low-carbon technology recently. However, the development is still unbalanced. It is necessary to prioritize applying and developing universally applicable low-carbon technology. Mature and highly applicable low-carbon technology should be promoted and widely adopted as soon as possible.

2.3. Predictions on China's Steel Production Amount and Regional Distribution Changes

Whether or not the carbon emission can peak quickly depends on the amount of crude steel production. Although the crude steel production amount in China started to decline in 2022 and may enter a sustained slow decline, however, to support the sustainable development of emerging economies and China's urbanization process, the steel industry will still maintain a large production amount in the future. It is projected that, by 2050, China's crude steel production amount will decrease to 600 million tons; the trend is shown in Figure 4 [25]. To realize the sustainable development of China's steel industry, we must focus on developing low-carbon and zero-carbon technology. It can contribute to national carbon neutrality goals by achieving carbon neutrality within itself.

The future production layout of crude steel in China will primarily depend on factors such as the place of crude steel consumption and ore production, the costs of hydrogen energy, transportation, and carbon capture and storage (CCS). Under deep decarbonization, the Chinese steel industry will mainly be concentrated in the northern regions by 2050 [26]. The crude steel production amount has significantly increased in Xinjiang and Qinghai due to the development of hydrogen and other renewable energy sources. On the other hand, regions that lack abundant renewable energy resources and have limited application of CCS technology will experience a noticeable reduction in the crude steel production amount. Therefore, for southern regions like Guangxi and Hunan, as well as major energy-consuming areas in eastern China, electric furnace steelmaking processes should be considered more.

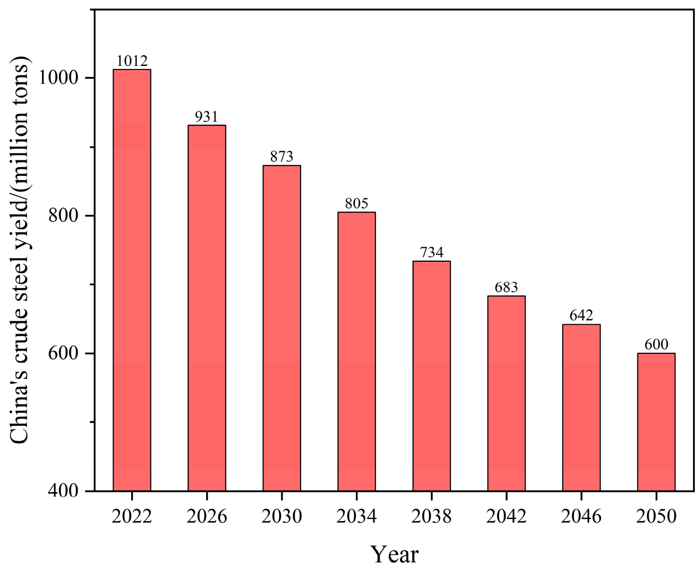

Figure 4. Forecast of China's crude steel production.

3. Low-Carbon Policies Related to China's Steel Industry

To actively implement the dual-carbon goals proposed by President Jinping Xi at the 75th United Nations General Assembly, China's government and ministries related to the steel industry have successively issued a series of relevant documents in recent years, which have provided guidance and principles for China's dual-carbon work.

3.1. National-Level Dual-Carbon Policies

On 26 October 2020, the Chinese government issued "Proposals for Formulating the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives through the Year 2035" [27]. It emphasized the need to accelerate the promotion of green development, strengthen legal and policy guarantees for green development, expedite the development and utilization of clean energy, reduce carbon emissions, support eligible regions in achieving carbon peaking at an earlier stage, and formulate an action plan to achieve the goal of carbon emissions peak before 2030.

On 24 October 2021, the Chinese government issued an "Action Plan for Carbon Dioxide Peaking before 2030" [28]. Over the 14th Five-Year Plan period, notable progress should be made in the adjustment and optimization of the industrial structure and the energy structure, and new improvements will be made in the R&D and broad application of low-carbon technology, making the goal to reach peak carbon emissions permeate the whole process and every aspect of economic and social development. Particular focus will be placed on implementing ten carbon-peaking actions: promote structural optimization for the steel industry and the substitution of clean energy, vigorously promote demonstrations of non-blast furnace technology, drive the application of advanced and appropriate technologies, and squeeze out all available potential for saving energy and cutting carbon emissions.

On 18 October 2021, the Chinese government released "Several Opinions on Strict Energy Efficiency Constraints to Promote Energy Conservation and Carbon Reduction in Key Areas" [29]. The document aims to gradually promote carbon reduction efforts in critical industries, fully utilizing the technological resources of domestic research institutes, universities, and leading enterprises. It seeks to expedite the development of cutting-edge low-carbon technology and promote the greening and high efficiency of key domestic enterprises' equipment. By 2025, the document requires the proportion of the standard-level production amount exceeding 30% in the steel industry through the implementation of energy conservation and carbon reduction actions.

3.2. China's Dual-Carbon Policies for Steel Industry

3.2.1. Enhance Innovation Capabilities of Steel Industry

The Chinese government issued the "Guiding Opinions on Promoting the High-Quality Development of the Steel Industry". This includes the following: achieving breakthroughs in cutting-edge technologies, such as hydrogen metallurgy and non-blast furnace ironmaking; and highlighting the importance of enhancing the industry's innovation capabilities. Additionally, the document specifies the main research directions for key common technologies and all-purpose and specialized equipment, establishes co-operation mechanisms for key areas, and builds industrial alliances; and encourages qualified localities to plan and build regional innovation platforms in the steel sector and actively strive to create national-level innovation platforms.

3.2.2. Strictly Control Iron and Steel Production Amount

To curb the continued increase in steel production amount, the "Guiding Opinions on Promoting the High-Quality Development of the Steel Industry" emphasizes the need to intensify efforts to prevent the blind implementation of smelting projects, and additional capacity in processing, casting, ferroalloys, etc., is prohibited; strictly avoid the resurgence of low-grade steel and strengthen penalties for violations; and increase the investigation of new steel production amounts in breach of regulations and use a legal way to effectively address the issue of overcapacity in the steel industry.

3.2.3. Develop Electric Arc Furnace Steelmaking in an Orderly Manner

Compared to long-process steelmaking, electric arc furnace short-process steelmaking no longer requires ore as the raw material. It mainly consumes electricity as energy, significantly reducing CO_2 emissions. The "Guiding Opinions on Promoting the High-Quality Development of the Steel Industry" states that it encourages eligible enterprises to prioritize the transformation of electric arc furnace steelmaking. It also suggests establishing small- and medium-sized electric arc furnace steelmaking enterprises in central cities and urban clusters, and it can synergistically dispose of urban waste; and encourages regions with advantageous conditions to establish electric arc furnace steelmaking demonstration zones and explore and develop new technologies and equipment.

3.2.4. Promote Restructuring of Steel Enterprises

The steel industry is an essential sector of China's national economy. The restructuring of steel enterprises can enhance the industry concentration, which, in turn, has several significant effects. Firstly, the increased concentration could reduce carbon emissions through regulated economies. Secondly, it helps in controlling the overall industry capacity. In 2020, the concentration ratio of China's steel industry was 39.2%, an increase of a five-percentage-point compared to the end of the 13th Five-Year Plan. However, the concentration level of Chinese steel enterprises remains relatively low, with a notable gap compared to other countries worldwide. Since 2005, the Chinese government has supported restructuring steel enterprises. A noteworthy example is the establishment of China Baowu Steel Group in 2016, which became the first steel conglomerate in China with an annual production amount exceeding 100 million tons.

3.2.5. Deepen Co-operation in Low-Carbon Technology Development

The "Guiding Opinions on Promoting the High-Quality Development of the Steel Industry" deepens the promotion of low-carbon technology development as the main task; emphasizes supporting the construction of low-carbon metallurgical innovation alliances; establishes a data management system for carbon emissions in the production process, and formulate action plans for hydrogen metallurgy; and actively promotes the coupled development of steel, electric power, chemicals, and other industries.

4. Development Status of Low-Carbon Technology in China's Steel Industry

4.1. Quantitative Assessment of Carbon-Reducing and Energy-Saving Capacity of Different Low-Carbon Technologies

A quantitative assessment of the energy-saving and carbon-reducing capacity of steel industries is useful for the rational use of fuel, energy resources, and raw materials, and the improvement of the technological structure of production. A number of energy-modeling approaches have been used to analyze future trends and to assess the capacity for energy-saving and emissions reduction [30]. These can be categorized into two types: top-down and bottom-up models [31–33]. Most of the methods of assessment for low-carbon technologies in the steel industry use bottom-up analyses [34]. The advantage of the bottom-up analysis method is that it can simulate the development of technologies from a micro level, and forecast the energy-saving potential [35]. Some scholars divide 20 types of low-carbon technologies into four categories—coal-saving technology, electricity-saving technology, comprehensive energy-saving technology, and linkage technology—according to the energy-saving effect of the different technology on energy varieties, and construct a bottom-up model to analyze the carbon-reducing and energy-saving capacity under three different scenarios—the baseline scenario (BS), policy scenario (PS), and strengthened policy scenario (SPS). In terms of carbon reducing, the contribution of comprehensive energy-saving technology is highest; the emission reduction in 2030 is 129 million tons CO_2 ($MtCO_2$) and 130 $MtCO_2$, in the PS and SPS. In terms of energy saving, the contribution of coal-saving technology is highest; the ratios of coal saving in 2030 is 12.6% and 13.6%, in the PS and SPS [35].

4.2. Application Status of Typical Low-Carbon Technology

With the continuous development of China's steel industry in recent years, many carbon reduction technologies have reached leading levels and have been implemented in large domestic enterprises [36,37].

(1) Coal Moisture Control

In this technology, the coking coal is dried before being loaded into the coke oven through direct or indirect heating. The moisture content of the coking coal is stabilized at around 6% before the coking process begins. This technology significantly reduces the heat consumption during cooking, resulting a in lower energy consumption and notable emission reduction effects. Additionally, it helps achieve a more uniform particle size distribution of the coke and improves its quality. In China, the coal moisture control saves approximately 0.06 $GJ \cdot t^{-1}$ and reduces CO_2 emissions by about 1.47 $kg \cdot t^{-1}$. Coal moisture control technology has been widely adopted in major steel enterprises, such as Baosteel Group, Taiyuan Group, and Magang Group [38].

(2) Coke Dry Quenching

This method cools discharged coke from the oven with a cold, inert gas. It has significant advantages in recovering sensible heat from the discharged coke and optimizing operational conditions. It offers benefits such as improving coke quality and reducing energy consumption. In China, the coke dry quenching saves approximately 0.37 $GJ \cdot t^{-1}$ and reduces CO_2 emissions by about 42.54 $kg \cdot t^{-1}$. Over 330 sets of coke dry quenching equipment have been put into operation in China, with a processing capacity of approximately 46,000 $t \cdot h^{-1}$. The adoption rate of coke dry quenching in the national coking industry has exceeded 60% [39].

(3) Top Pressure Recovery Turbine

This technology uses gas expansion to drive a turbine, which generates electricity. The top pressure recovery turbine does not consume any fossil fuels, and it does not produce any pollutant gas emissions, resulting in significant emission reduction benefits. In China, the top pressure recovery turbine saves approximately 0.12 $GJ \cdot t^{-1}$ and reduces CO_2 emissions by about 22.66 $kg \cdot t^{-1}$. According to statistics from the China Iron and Steel

Industry Association, by 2010, over 600 blast furnaces were equipped with 597 sets of Top Pressure Recovery Turbine (TRT) equipment. For example, two 5500 m^3 blast furnaces with TRT technology in the Jingtang Steel Plant achieved a maximum power generation of 31,323 kW·h and a maximum daily average of 29,536 kW·h [40,41].

(4) Converter Dry Dedusting System

In this technology, the hot gas in the flue is cooled to about 200 °C, and then the cooled gas is treated with an electrostatic precipitator. This technology significantly reduces the emission of dust particles, achieves zero wastewater discharge, and offers advantages such as long service life and low operating costs [42]. In China, the converter dry dedusting system saves approximately 0.14 $GJ{\cdot}t^{-1}$ and reduces CO_2 emissions by about 5.77 $kg{\cdot}t^{-1}$. Major Chinese steel companies such as Baotou Steel, Taiyuan Iron and Steel, and Laigang Steel have used converter dry dedusting system technology since around 2005.

(5) Sinter Plant Heat Recovery

Sinter Plant Heat Recovery technology is primarily used to improve the energy utilization efficiency and reduce energy consumption during the sintering process. In the Chinese steel industry, the energy consumption of the sintering process is second, accounting for 10% to 20% of the production energy consumption, only to the ironmaking process. Therefore, the recovery and utilization of waste heat generated during the sintering process hold significant importance for the low-carbon development of the steel industry. In China, the sinter plant heat recovery technology saves approximately 0.35 $GJ{\cdot}t^{-1}$ and reduces CO_2 emissions by about 14.77 $kg{\cdot}t^{-1}$. There are 1200 sintering machines in operation in China, with a waste heat recovery utilization rate ranging from 20–30%; the sintering area is about 126,000 m^2 [43]

(6) Blast Furnace Injection of Natural Gas/Coke Oven Gas

In blast furnace injection of natural gas/coke oven gas, the reducing gases such as natural gas and coke oven gas were injected into the blast furnace, partially replacing the injection of coal and coke. Countries with abundant natural gas resources, such as Russia and the United States, have used natural gas injection in blast furnaces since the 1970s. The technology of blast furnace injection of natural gas is relatively mature. In 2019, at the No. 7 blast furnace (4800 m^3) in Indiana Harbor operated by ArcelorMittal in the United States, the natural gas injection rate was 50 kg/t, and the fuel rate was 480 kg/t [44]. Injecting hydrogen-rich gases into the blast furnace not only generates certain economic benefits through coke saving but also helps improve the company's economic performance by reducing CO_2 emissions. In China, the blast furnace injection of coke oven gas saves approximately 0.35 $GJ{\cdot}t^{-1}$, and reduces CO_2 emissions by about 14.77 $kg{\cdot}t^{-1}$. Jinnan Steel has conducted coke oven gas and hydrogen injection tests in three 1860 m^3 blast furnaces [45,46].

(7) High Percentage of Pellet/Lump Ore in BF Burden

The energy consumption of pellet ore in blast furnace iron production is half that of sinter ore. Pellet ore has advantages such as having a high grade, good reducibility, and lower emissions during the production process. Lump ore is a natural mineral and is cleaner [23]. Carbon emissions can be effectively reduced by increasing the proportion of pellet and lump ore in production. Ganbao Plant achieved a high level of 21.5% lump ore utilization in 2019 [47].

(8) High-efficiency Continuous Casting

High-efficiency continuous casting focuses on a high casting speed and is based on the production process being high-quality and defect-free. It aims to achieve high casting rates and high operation rates. The widespread adoption of high-efficiency continuous casting technology has increased the output of continuous casting machines and improved the surface and internal quality of cast slabs, leading to the production of defect-free billets. In China, the high-efficiency continuous casting saves approximately 0.39 GJ/t, and reduces

CO_2 emissions by about 27.49 kg/t. Chinese steel companies such as Wuhan Iron and Steel Group and Meigang Group have implemented various new technologies related to high-efficiency continuous casting in multiple stages of their production processes [48–50].

4.3. Research Status of New Low-Carbon Technology in China

In recent years, China has conducted extensive research on low-carbon technology [51–53], which has extensively promoted the development of low-carbon ironmaking technologies in the country. This article provides an overview of the development status of low-carbon technology in China, focusing on representative examples such as hydrogen-enriched carbonic oxide recycling oxygenate furnaces, coke oven gas zero-reforming shaft furnace direct reduction technology, HIsmelt technology, CO_2 steelmaking, and steel–chemical coproduction.

(1) Hydrogen-enriched Carbonic oxide Recycling Oxygenate Furnace

The Hydrogen-enriched Carbonic oxide Recycling Oxygenate Furnace is a modification of traditional metallurgical processes, where hydrogen replaces carbon, significantly reducing greenhouse gas emissions during the smelting process and, ultimately, achieving carbon neutrality for the entire smelting process. In July 2020, Baowu Group completed the construction of the world's first 430 m^3 hydrogen-enriched carbonic oxide recycling oxygenate furnace. In June 2021, the injection of the Ouye shaft furnace decarbonized gas at the tuyere was achieved. In July 2021, the hydrogen-rich metallurgical industrial experiments were completed, with a blast oxygen content of 50%, and the injection of coke oven gas and decarbonized gas at the tuyere was achieved. In 2022, the goal of full oxygen smelting was achieved, and the injection of decarbonized heating gas and coke oven gas was completed at the tuyere and furnace stack [54–56]. Baowu Group's experimental team has completed industrial production tests under conditions ranging from 35% oxygen to 50% oxygen [57]. In 2023, Baowu Group plans to construct a 2500 m^3 hydrogen-enriched carbonic oxide recycling oxygenate furnace.

(2) Coke Oven Gas Zero-Reforming Shaft Furnace Direct Reduction Technology

This technology primarily involves the reduction and deoxidation of oxidized pellets using a reducing gas consisting mainly of H_2 and CO, and accompanied by reactions such as the self-reforming of coke oven gas and carburization [58]. After self-reforming, the H_2/CO ratio in the coke oven gas can reach above 8:1, becoming the highest hydrogen content in the gas-based shaft direct reduction process currently used. In December 2022, Hebei Iron and Steel Group completed the construction of the world's first project for the coke oven gas zero-reforming shaft furnace direct reduction technology. This project can reduce carbon emissions by approximately 70% compared to traditional metallurgical processes, reducing carbon emissions by approximately 0.5 kg/t [59].

(3) HIsmelt Technology

Compared to traditional blast furnace ironmaking, the HIsmelt process enables the direct use of non-coking coal powder and ordinary ore powder for smelting, eliminating the reliance on coking coal and simplifying the entire ironmaking process. The innovation of HIsmelt technology includes the use of a rotary kiln instead of a fluidized bed to reduce equipment failure rates, the replacement of refractory materials to optimize cooling systems and extend equipment lifespan, the development of high-life mixed injection lances, and the optimization of operations to achieve flexible iron output. Through continuous research and adjustments, in 2017, Shandong Molong achieved continuous production of HIsmelt and, in 2018, achieved 157 consecutive days of stable output [60].

(4) Carbon Dioxide Steelmaking Technology

Carbon dioxide has stability, non-burning-supporting properties, and the ability to undergo reactions at high temperatures. These characteristics enable CO_2 to play roles in stirring, cover protection, and dilution within the steelmaking process [61]. Beijing University of Science and Technology has invented several CO_2-related technologies, including

CO_2-O_2 dust reduction, CO_2 phosphorus removal, CO_2 nitrogen removal, CO_2 oxygen control, and CO_2 bottom blowing. In April 2022, the O_2-CO_2-CaO bottom-blowing technology was tested in an industrial setting at Shougang Jing-Tang Iron and Steel Company, achieving a CO_2 emission reduction of 30 kg/t [62].

(5) Steel–Chemical Coproduction

This technology, using blast furnace gas, converter gas, and coke oven gas of iron and steel enterprises as raw materials, involves extracting components such as carbon dioxide, carbon monoxide, and hydrogen through a series of purification and refinement processes, and then making methanol, ethanol, liquefied natural gas, and other high-value-added products after chemical processing [63,64]. Steel–chemical coproduction reduces carbon emissions from the source and achieves the coupling development of the chemical and steel industries. Numerous Chinese companies have begun the large-scale production of chemical products using exhaust gases, such as methanol, ethanol, ethylene glycol, and formic acid. In 2018, the first set of natural gas ethylene glycol projects was successfully tested by Xinjiang Tianying Petroleum Chemical [65].

4.4. Representative Steel Enterprises' Low-Carbon Technology Roadmap

4.4.1. Baowu Group's Low-Carbon Technology Roadmap

In 2021, Baowu Group released its low-carbon technology roadmap, as shown in Figure 5 [66]. It plans to achieve carbon peaking in 2023, can reduce carbon emissions by 30% in 2025, strives to achieve a 30% emission reduction in 2035, and strives for carbon neutrality in 2050. Its low-carbon goals are realized primarily by deploying six technologies: extreme efficiency, HyCROF, terminal manufacture, metallurgical resource recycling, hydrogen-based shaft furnace, and carbon recovery and utilization. From 2020 to 2035, the deployment of extreme efficiency, metallurgical resource recycling, terminal manufacture, and HyCROF will be completed. From 2035 to 2050, the deployment of hydrogen-based shaft furnace and carbon recovery and utilization technologies will be completed. The emission reduction targets for each technology category are as follows: extreme efficiency (3–5% reduction), metallurgical resource recycling (10–20% reduction), terminal manufacture (5–10% reduction), HyCROF (30–50% reduction), hydrogen-based shaft furnace (50–90% reduction), and carbon recovery and utilization (30–50% reduction).

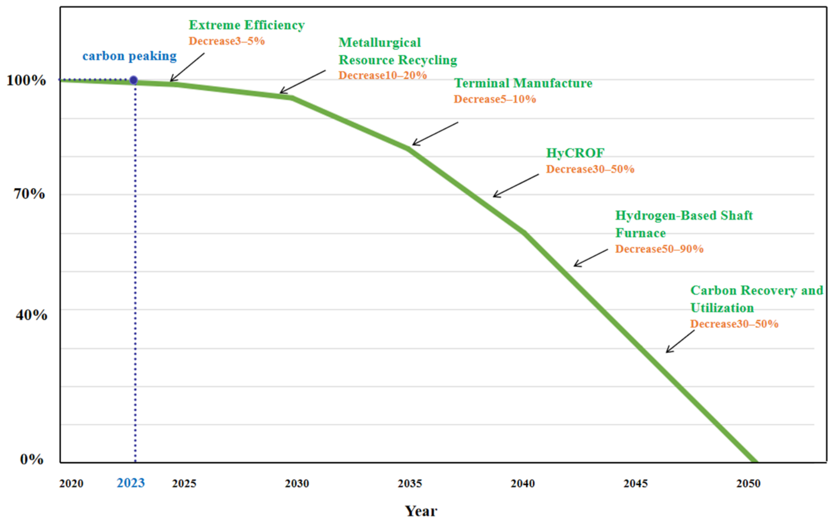

Figure 5. Baowu group's low-carbon technology roadmap.

4.4.2. Hebei Iron and Steel Group's Low-Carbon Technology Roadmap

In 2022, Hebei Iron and Steel Group released its low-carbon technology roadmap, as shown in Figure 6 [67]. The roadmap outlines three phases of low-carbon development: "Peak Carbon Platform Period (2022–2025), Steady Decline Period (2025–2030), and

Deep Decarbonization Period (2031–2050)". Through implementing six major technology pathways, Hebei Iron and Steel Group aims to achieve a reduction in carbon emissions of over 10% compared to peak levels by 2025, over 30% by 2030, and carbon neutrality by 2050. The six major technology pathways include optimizing iron and steel resources, process optimizing and restructuring, improving system energy efficiency, optimizing energy structure, technological transformation for low-carbon, and collaborative decarbonization across industries. By 2050, it is projected that optimizing iron and steel resources will result in a 13% carbon reduction, process optimizing and restructuring will result in an 18% carbon reduction, improving system energy efficiency will result in a 34% carbon reduction, optimizing energy structure will result in an 11% carbon reduction, technological transformation for low-carbon will result in a 17% carbon reduction, and collaborative decarbonization across industries will result in a 7% carbon reduction [68].

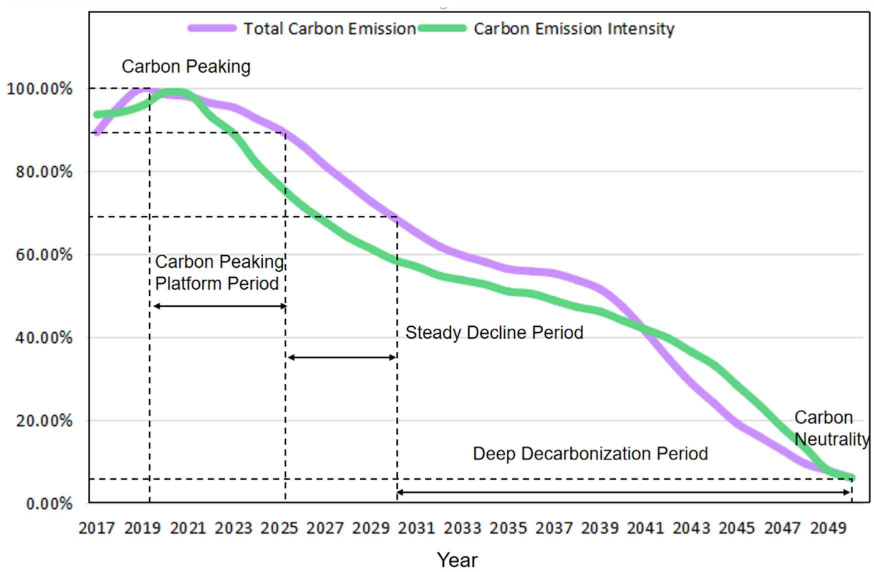

Figure 6. Hebei iron and steel group's low-carbon technology roadmap.

5. Suggestions for Further Reduction of Carbon Emission in China's Steel Industry

(1) Unify organization and implementation

On the one hand, we uniformly consider the demand for steel in the country's economic and social development, utilizing both domestic and international steel supply, under the premise of meeting the basic domestic steel demand, scientifically planning and forecasting of the trend of China's steel production, and scientifically leading China's steel materials and related industries towards high-end and volume reduction to ensure the economic competitiveness of the iron and steel industry. On the other hand, combined with the changes in China's scrap production and import volume, as well as the progress of decarbonization of the power system, we guide the development of electric arc furnace short-process steelmaking in a timely manner. The steel industry should formulate carbon neutrality targets in stages based on completing the above two works and clarifying the corresponding stages' key tasks and implementation paths.

(2) Establish national industrial experimental platform

Low-carbon technology research is a large, high-risk, and time-critical task that is difficult for individual organizations to afford. In the foreseeable future, steel materials will continue to serve as the essential foundation for developing the social economy. Therefore, the steel industry's low-carbon development is society's responsibility. It is necessary to provide financial and policy support for the research of low-carbon technology from the national level and to promote the study of low-carbon technology by establishing a national-level industrialization experiment platform.

(3) Select key technologies for research by process

Long processes currently dominate China's iron and steel smelting, but the proportion of short processes will significantly increase, eventually forming a complementary situation. Therefore, research on low-carbon technology in the steel industry should be carried out using long and short processes. The development of carbon reduction technologies based on long processes is of great significance to the carbon peaking and initial carbon reduction of China's steel industry, while the development of low-carbon technologies based on short processes is of decisive importance to realizing carbon neutrality in China's steel industry.

(4) Establish new research co-operation model

China's government attaches great importance to the goal of carbon peaking and carbon neutrality, so the relevant departments should play a leading role in the research of low-carbon technology. The research of low-carbon technology in the steel industry should be aimed at engineering applications, and enterprises, design institutes, and engineering companies in the leading position in the industry play an important role in the research of low-carbon technology. The research on low-carbon technology must rely on the proposal of original technology, which comes from a large amount of basic research. Therefore, it is inseparable from the active participation of universities and research institutes. The research work requires a large amount of workforce and material resources, and it is also essential to ensure the stability of funding channels and balance the relationship between inputs and benefits. Organizational models used in the European Union (EU) and Japan for metallurgical process development, such as Ultra Low CO_2 Steelmaking (ULCOS), CO_2 Ultimate Reduction in Steelmaking process by innovative technology for cool Earth 50 (COURSE50), etc., can be referenced, with efforts to mobilize more positive factors.

6. Conclusions

(1) China's steel industry faces significant pressure to reduce carbon emissions with its massive production, its dominant reliance on coal for energy, and the primary use of blast furnaces and converters in production processes. The Chinese steel industry has limited potential to reduce process energy consumption alone to achieve carbon peaking and carbon neutrality. It relies on technological innovation and continues investing in low-carbon technology research.

(2) China's steel industry prioritizes dual-carbon goals, and companies and research institutions are taking significant action to achieve them. However, the development of high-efficiency carbon reduction technologies in China is in its early stages and relatively behind compared to other countries. It has yet to reach the level of industrial application, and there is still a significant gap in obtaining world-class carbon reduction technologies.

(3) Many Chinese steel companies have not proposed clear dual-carbon plans, and more unified research activities are needed at the industry level. Companies should establish their dual-carbon plans, co-operate with relevant universities and research institutions in collaborative research, and strive to achieve dual-carbon goals as soon as possible.

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