ENERGY AND INNOVATION AT IFP ENERGIES NOUVELLES

IFPEN ECONOMIC PAPERS

IFP SCHOOL - IFPEN N° 159 APRIL • 2024

RESEARCH

DECARBONIZING CHINA'S IRON AND STEEL INDUSTRY: POLICY INCENTIVES AND TECHNOLOGICAL PATHS

This article develops a mixed integer programming model to explore how the Chinese iron and steel industry can efficiently manage the simultaneous phasing out of blast furnaces and promotion of advanced steelmaking technologies.

Yang Liu
Yuchen Zhang
Xiaoli Zhao
Rongda Zhang
Arash Farnoosh

Pour toute information complémentaire
For any additional information

Victor Court

IFP School
Centre Economie et Management de l'Energie
Center for Energy Economics and Management
victor.court@ifpen.fr
Tél +33 1 47 52 73 17

Decarbonizing China's Iron and Steel Industry: Policy Incentives and Technological Paths

Yang Liu [1], Yuchen Zhang [2], Xiaoli Zhao [1], Rongda Zhang [1], Arash Farnoosh [3]

[1] School of Economics and Management, China University of Petroleum, Beijing, China

[2] School of Economics, Nankai University, Tianjin, China

[3] IFPEN, IFP School, 92852 Rueil-Malmaison, France

Abstract

As the largest industrial carbon-emitting sector in China, the iron and steel industry heavily relies on blast furnace capacity with a short operational lifespan, posing significant challenges in terms of high sunk costs during decarbonization transition. To address these challenges, this paper develops a mixed-integer programming model to explore how the Chinese iron and steel industry can efficiently manage the simultaneous phasing-out of blast furnaces and promotion of advanced steelmaking technologies. The aim is to achieve decarbonization goals while minimizing the transition costs. The findings indicate: (1) Stricter decarbonization targets do not necessarily mean higher transition costs; (2) There are significant interactive effects among different technological paths for decarbonizing the steel industry. For instance, opting for earlier blast furnace phase-outs may hinder the deployment of zero-carbon technologies, thereby impeding the achievement of ultimate decarbonization goals; (3) The carbon pricing mechanism plays a crucial role in determining the decarbonization transition path for the steel industry. Introducing carbon emissions trading can significantly reduce the costs of achieving the 1.5°C target compared to carbon neutrality goals. A hybrid carbon pricing approach that combines carbon taxes and emissions trading performs better in balancing the decommissioning of blast furnaces and the deployment of zero-carbon technologies than a single carbon pricing mechanism. Finally, this paper provides policy recommendations on how China's iron and steel industry can achieve cost-efficient decarbonization transition.

1. Introduction

Climate change is a major challenge facing human society, and it has become a global consensus to deal with it. Paris Agreement established the long-term goal of temperature control to maintain the stability of the earth, human beings, and ecosystems (Schleussner et al.,2016). Therefore, it requires the world to achieve net zero emissions around 2050 (Tollefson, 2018）. Up to now, more than 130 countries have set the goal of carbon neutrality (Zhao et al., 2022). China promises to achieve peak carbon dioxide emissions and carbon neutrality in 2030 and 2060 respectively. The steel industry accounts for about 15% of China's CO2 emissions, and China's carbon-neutral target has brought enormous pressure on the steel industry to reduce emissions (An et al., 2018). Therefore, it is urgent to explore the carbon neutral path of China's steel industry.

Many studies have discussed the low-carbon development of steel industry. Among them, part of the literature is carried out at the factory level. For example, the energy-saving supply curve is used to evaluate the carbon dioxide emission reduction potential of various energy-saving technologies (Wang et al., 2020); to develop the material-energy-carbon hub model to track the flow of carbon dioxide (Zhang et al., 2022); and to evaluate the environmental impact of steel plant life cycle (Liang et al., 2020). Some literatures discussed the U-shaped relationship between different environmental supervision measures (command-based, market-based, and public-based regulations) and energy and environmental performance of iron and steel industry from the industry level (Wu and Lin, 2022); Causality between economic growth, environmental regulation, and CO2 emission reduction in steel industry has also been analyzed (Yu et al., 2015). There are also some literatures that study the combination of low-carbon technologies to achieve the 2°C-temperature control target and 1.5°C temperature control target in the steel industry from the bottom up (Tian et al., 2018; Sun et al., 2022) and the decommissioning strategy of blast furnace (Vogl et al., 2021; Wang et al., 2021）. However, there is a lack of research on how to achieve the goal of decarbonization of the whole steel industry at the lowest economic cost under different policy combinations.

Therefore, in this paper we develop a model to minimize the transformation cost of iron and steel industry, and examine 39 policy scenarios consisting of: three kinds of decarbonization targets (2060 carbon neutral, 2050 carbon neutral, 1.5 degree temperature control target), decommissioning strategy of blast furnace, four kinds of carbon pricing methods (direct carbon tax (DC) , indirect carbon tax (IC) , carbon right (CR) , indirect carbon tax + carbon right (IC&CR)) and two kinds of low-carbon technology packages (low-carbon technology packages with or without CCS technology participation). Specifically, this paper aims to answer the following three questions: (1) How does carbon tax, carbon emission trading and combined carbon pricing affect the choice of low-carbon technology in steel industry? (2) How different decarbonization targets match which carbon pricing method can realize the transformation path of the steel industry with the lowest economic cost? (3) Which low-carbon technologies play a key role in the transformation path of steel industry and the interaction between different technologies?

The overall layout of this paper is as follows. Section 2 reviews the literature related to decarbonization of steel industry. Section 3 introduces the model construction, data, and scenario design. Section 4 explains the results of the model, including the choice of different decarbonization targets, carbon pricing methods, the time of blast furnace decommissioning based on the technological path in the process of steel industry transformation, and finally the cost difference of different low-carbon technology packages in achieving decarbonization targets. At the end in section 5 we give the conclusion and policy recommendations of this research work.

2. Literature review

Existing research has evaluated the carbon dioxide emission reduction potential of steel industry from different levels. In terms of methods, part of the research is based on index decomposition (Du and Lin, 2018), vector autoregression(Yu et al., 2015) and quantile regression models(Xu and Lin, 2016) to discuss the effects of economic growth, technology expenditure, investment rate and labor productivity on carbon dioxide emissions in steel industry. These studies describe the driving factors of carbon dioxide from the macro level. Others have analyzed the carbon dioxide emission reduction potential of steel industry under different technology combinations from the bottom-up perspective. For example, by analyzing the emission reduction supply curves of 24 advanced technologies in China's steel industry, the effects of various technologies were evaluated (Wu et al., 2016). The emission reduction potentials of 21 energy-saving technologies in 2020 and 2050 were evaluated by using the saving supply curve and quadrant method (Wen et al., 2019). A bottom-up cost minimization model was established to simulate the impact of emission reduction measures such as elimination of backward production capacity, energy-saving technological transformation and clean energy utilization. The intrinsic potential of CCS technology was investigated to contribute to the goal of 2-degree temperature control (Tian et al., 2018). The feasibility of decarbonizing the steel industry was discussed by using inherent waste stream to achieve the goal of temperature control of 2 degrees (Sun et al., 2022). The influence of different decommissioning time nodes of blast furnace for achieving the goal of 1.5-degree temperature control was evaluated (Vogl et al., 2021; Wang et.al., 2021). In other words, focusing on the feasible path of carbon neutrality in the steel industry, the bottom-up method has greater flexibility in quantitative evaluation of emission reduction measures.

Discussions on different carbon pricing methods have been carried out in the power industry. However, the research on carbon pricing in the steel industry still stays on the impact of carbon tax level on the cost of low-carbon technology (Wu et al.,2016). Nong et al.（2020), Paul et al.(2021) and Liu et al.（2021) compare the effectiveness of carbon emission trading system and carbon tax in power industry. While in the study by Fu et al.（2021)，Cao et al. (2019) and Bi et al. 2019) the effects of mixed carbon pricing and single carbon pricing are compared. Bertram et al. (2015) evaluated which combination of emission pricing and technology policy can effectively avoid further lock-in and start the transformation required to limit the temperature rise to 2℃.

The existing research on steelmaking technology mostly focuses on incremental technology or single technology of traditional steelmaking (Ren et al, 2021; Tian et.al,2018；Li et al, 2020), and the technology selection is not comprehensive enough. Moreover, there is a lack of discussion on breakthrough steelmaking technology and the combination of different technologies. At the same time, most of the existing research have not considered the technology iteration and replacement in the next 30 years and the technology selection in different periods.

Decarburization of steel industry is a systematic process, involving many kinds of influencing factors. The existing research focuses on the technologies and costs related to carbon emission and depicts the path of emission reduction in the steel industry. It lacks in-depth exploration from the perspective of cost optimization of policy-resource-technology-emission integrated system. First, existing studies generally believe that the stricter the decarbonization target, the higher the transformation cost by ignoring the possible cost impact of matching with different carbon pricing methods. Second, the steel industry is a resource-intensive industry, and it changes in the use of steel resources (such as differences in scrap supply) may have a significant impact on the choice of decarbonization path. However, the choice of decarbonization technology path will have a negative effect on the demand of iron ore and waste materials. The supply of renewable energy has the same problem. Third, the existing research has neglected the interaction and influence of different low-carbon steelmaking technologies. Therefore, in order to comprehensively evaluate the comprehensive implementation effect of carbon neutral path in the steel industry, this study included the decarburization target, carbon pricing method, blast furnace decommissioning schedule and future feasible low-carbon technology collection of China's steel industry. We also discuss the feasible path and challenges faced by the steel industry to achieve carbon neutral. Comprehensive analysis of the above factors can provide a more comprehensive picture of the layout of carbon neutral schemes, and a more direct and accurate quantitative evaluation basis for guiding policy practice.

3. Method and Data

3.1 Model setting

A mixed integer linear programming (MILP) model is built to calculate the technical path and economic cost of China's steel industry transformation before 2050 under different schemes. In this paper, MILP, as an optimization model, aims at planning the most cost-effective and minimized decarbonization path in the steel industry according to the predicted demand. It takes into account the annual capacity increase and decommissioning of different steelmaking technologies between the current date (2022) and the target date (2050). Path optimization is subject to the operational constraints of various low-carbon technologies, resource availability, and different climate policy objectives.

The objective function of the model is to minimize the sum of the following costs: (1) The initial investment cost of a newly-built steelmaking plant (IIC); (2) Operating cost of newly-built steel mills (OMC), including fixed operating cost and energy consumption cost; (3) Carbon dioxide emission cost of newly-built steel mills (ECT).

$$Min\ TC = IIC + OMC + ECT$$

Among them, the total investment cost is

$$IIC = \sum_{Tech(A1-5;B2-9)} CAPEX_{Tech} \cdot (1-\beta_{st}) \cdot \sum_{t=2022}^{2050} RCAP_{Tech\,t} \cdot \frac{1}{(1+\alpha)^{t-2022}} + 340.5 \cdot (1-\beta_{st}) \cdot \sum_{t=2022}^{2050} RCAP_{B1\,t} \cdot \frac{1}{(1+\alpha)^{t-2022}} + 1903.83 \cdot \sum_{t=2022}^{2050} RCAP_{B1\,t} \cdot \frac{1}{(1+\alpha)^{t-2022}}$$

$Tech$ represents various steelmaking technologies. $CAPEX_{Tech}$ represents the unit investment cost of each technology. L_{Tech} represents the life cycle of each technology. β_{st} is 15% and represents the technical subsidy rate, and α is equal to 10% representing the investment discount rate (Zhang et al.,2019).

Table 1: Summary of Typical Low Carbon Steelmaking Technologies in Iron and Steel Industry

Comprehensive steelmaking technology category without CCS technology participation			Comprehensive steelmaking technology category with CCS technology participation		
Tech(A)	$CAPEX_{Tech}$ CNY(2020)	L_{Tech} (year)	*Tech(B)*	$CAPEX_{Tech}$ CNY(2020)	L_{Tech} (year)

A1: DRI-EAF（MIDREX-NG）	4635.78	20	B1: BF-BOF	1903.83+340.45	17
A2: DRI-EAF（MIDREX-NG+60% H2）	4635.78	20	B2: HIsarna-BOF	3673.45	17
A3: Scrap-EAF	2060.35	20	B3: BF-TGR-BOF	1904.57	17
A4: DRI-EAF（100%H2）	6425.92	20	B4: DRI-EAF（MIDREX: NG）	4820.20	20
A5: ULCOLYSIS	37516.65	20	B5: DRI-EAF（MIDREX: NG+60%H2）	4763.24	20
			B6: Scrap-EAF	2060.35	20
			B7: DRI-EAF(100%H2)	6425.92	20
			B8: ULCOLYSIS	37516.65	20
			B9: ULCORED	5015.76	20

Note: (1) BF-BOF with the participation of CCS technology represents the installation of CCS for traditional old blast furnace equipment, and its investment cost is divided into two parts: the replacement cost (1903.83 yuan) and the installation cost of CCS (340.45 yuan). BF-BOF transformation does not enjoy technical subsidy. (2) The investment cost of various technologies is calculated based on 2020.

Total operating cost is

$OMC = \sum_{Tech} OM_{Tech} \cdot \sum_{t=2022}^{2050} Y_{Tech\,t} \sum_{t=2022}^{2050} \sum_{E} P_{E\,t} \cdot C_{E\,t}$

$C_{E\,t} = \sum_{Tech} U_{Tech\,E} \cdot Y_{Tech\,t}$

OM_{Tech} represents the unit fixed operating cost of each Technology. $C_{E\,t}$represents the total consumption of each energy E in the year T (t=2022, 2023, ..., 2050). $P_{E\,t}$ represents the unit price of each energy E in the year T. $Y_{Tech\,t}$represents the total output of each technology tech in the year T. $U_{Tech\,E}$ represents the unit energy consumption of each technology.

Total emission cost（ECT）is affected by four carbon pricing methods, so it can be divided into four types.

$$ECT_{DC} = \sum_{t=2022}^{2050} TAX_{c\,t} \cdot \sum_{Tech} EM_{Tech} \cdot Y_{Tech\,t}$$

$$ECT_{IC} = 1.5 \cdot C_{E1} \cdot \sum_{t=2022}^{2050} TAX_{c\,t} \cdot \sum\nolimits_{Tech} U_{Tech\,E1} \cdot Y_{Tech\,t} + 1.2 \cdot C_{E2} \cdot$$
$$\cdot \sum_{t=2022}^{2050} TAX_{c\,t} \sum\nolimits_{Tech} U_{Tech\ E2} \cdot Y_{Tech\,t}$$

$$ECT_{CR} = \sum\nolimits_{t=2022}^{2050} TAX_{c\,t} \cdot \sum_{Tech} (968 - EM_{Tech}) \cdot Y_{Tech\,t}$$

$$ECT_{IC\&CR} = 1.5 \cdot C_{E1} \cdot \sum_{t=2022}^{2050} TAX_{c\,t} \cdot \sum\nolimits_{Tech} U_{Tech\,E1} \cdot Y_{Tech\,t} + 1.2 \cdot C_{E2}$$
$$\cdot \sum_{t=2022}^{2050} TAX_{c\,t} \sum\nolimits_{Tech} U_{Tech\ E2} \cdot Y_{Tech\,t}$$
$$- \sum\nolimits_{t=2022}^{2050} TAX_{c\,t} \cdot \sum_{Tech} (968 - EM_{Tech}) \cdot Y_{Tech\,t}$$

$TAX_{c\,t}$ represents the carbon tax in the t year, EM_{Tech} represents the emissions per ton of steel of various technologies, C_{E1} represents the carbon emission coefficient of coal and finally C_{E2} represents the carbon emission coefficient of natural gas.

For the calculation method of indirect carbon tax, we refer to the method of Fu et al (2021), and levy taxes based on the carbon emission coefficient of energy, which is 1.5 times of ECT in the case of direct carbon tax on coal and 1.2 times of ECT in the case of direct carbon tax on natural gas. As for the calculation method of carbon right, according to the benchmark and credit method (World Bank, 2021), we issue an emission permit (0.968 tCO2/t) for each ton of crude steel according to the target of 1.5°C, and allow it to trade freely, in which the carbon price is implemented according to ECT in direct carbon tax.

The model includes five constraints: carbon emission constraint, operation constraint, supply and demand balance constraint, renewable energy constraint and raw material constraint.

The emission constraints are affected by the setting of decarbonization targets, which are divided into 2060 carbon neutral targets and 2050 carbon neutral 1.5-degree temperature control targets. Therefore, the emission constraints under different decarbonization targets are:

$$\sum_{Tech} EM_{Tech} \cdot Y_{Tech\ 2050} \leq Goal_{2060}$$

$$\sum_{Tech} EM_{Tech} \cdot Y_{Tech\ 2050} \leq Goal_{2050}$$

$$\sum_{2022}^{2050} \sum_{Tech} EM_{Tech} \cdot Y_{Tech\ t} + *2050.23 \leq \sum_{2022}^{2050} P_{old\ t}\ Goal_{1.5}$$

$P_{old\ t}$ represents the output of the old blast furnace that has not been retired in the year t. According to an energy sector roadmap to carbon neutrality in China (IEA, 2021), the carbon neutrality target is set as a point target in this paper, which only restricts the carbon emissions in 2050, while the 1.5°C temperature control target restricts the cumulative carbon emissions from now until 2050.

Operation constraints are

$$CAP_{Tech\ t} = \sum_{2022}^{t} RCAP_{Tech\ t} [\frac{t-m-1}{n} + 1.96]$$

m=t

When, n=16 $LT_{Tech} = 15$

When, n=18 $LT_{Tech} = 17$

When, n=21 $LT_{Tech} = 20$

$CAP_{Tech\ t}$ represents the active annual production capacity (t=2022, 2023, ... 2050) of various technologies in year T, and $RCAP_{Tech\ t}$ represents the new annual production capacity (t=2022, 2023, ... 2050) of various technologies in year T. Since BF-BOF, HIsarna-BOF, BF-TGR-BOF are all old blast furnace transformation technologies, the sum of the new annual production capacity of the three technologies in the year t should not exceed the decommissioning capacity of the traditional old blast furnace in that year.

$$\sum_{Tech=B1,B2,B3} RCAP_{Tech\ t} \leq Re_{Blast\ t}$$

$Re_{Blast\ t}$ represents the decommissioning capacity of the traditional old blast furnace in the year t.

According to the *Opinions of China's Development and Reform Commission on Doing a Good Job in Resolving Excess Capacity of Steel and Coal Industry in 2017 to Realize Development from Difficulties*, the new annual production capacity of new steelmaking technology should be greater than 195,000 tons, and the new annual production capacity of new steelmaking technology should be an integer multiple of 10,000 tons. Therefore,

If $RCAP_{Tech\,t}>0$ Then $RCAP_{\mathrm{Tech}\,t}>195000$（expect B1, B2,B3）($RCAP_{\mathrm{Tech}\,t}$（expect B1, B2,B3） takes an integer multiple of ten thousand）

$$Y_{Tech\,t} = \gamma_{Tech} \cdot CAP_{Tech\,t}$$

γ_{Tech}Stands for capacity utilization rate, set at 85% (Vogl et al, 2021).

The constraint of supply and demand balance of new technical capacity every year is as follows

$$\sum_{Tech} Y_{Tech\,t} \geq D_t$$

We subtract the annual output of traditional old blast furnaces in service from the domestic crude steel demand in 2022-2050 predicted by IEA(2020) to get the annual output demand of new technologies. Among them, the annual output of in-service blast furnaces comes from the research of Tong et al (2019). They calculated the annual output of traditional old blast furnaces from 2020 to 2050.（D_t

The renewable energy constraints include the supply constraints of green electricity and green hydrogen, which are

$$\sum_{Tech} Y_{Tech\,t} \cdot U_{Tech\,E3} \leq S_{E3\,t}$$

$$\sum_{Tech} Y_{Tech\,t} \cdot U_{Tech\,E4} \leq S_{E4\,t}$$

$\mathrm{S}_{\mathrm{E3}\,\mathrm{t}}$ represents the supply of green electricity (t=2022, 2023, ... 2050) in the year t and $\mathrm{S}_{\mathrm{E4}\,\mathrm{t}}$ represents the supply of green hydrogen (t=2022, 2023, ... 2050) in the year t.

As the main raw material of electric arc furnace steelmaking and the auxiliary material of blast furnace steelmaking, the supply of scrap steel is in great shortage (). According to McKinsey report, scrap steel is divided into three categories: self-produced scrap steel, processed scrap steel and depreciated scrap steel. Among them, self-produced scrap steel and processed scrap steel are produced in the production process of steel mills, and they are the most accessible scrap resources. Steel mills usually meet the demand of scrap steel in blast furnace production first. Depreciation scrap is the scrap formed by the society after a certain number of years of use. For example, scrap steel obtained from scrapped automobiles, machinery and equipment, airplanes, ships, containers, containers, daily-use articles, etc., is difficult to recover, and is the main source of scrap steel for new electric arc furnace technology in the future.

$$Y_{\mathrm{A1,A2}\ t} \cdot 1100 \leq S_{scrap,t}$$

$S_{scrap,t}$ represents the supply of scrap steel for EAF steelmaking (t = 2022,2023, ..., 2050). The calculation method is as followng:

If $Scrap_{Home,t} + Scrap_{Prompt,t} - (P_{old\ t} + \sum_{Tech=B1,B2,B3} Y_{Tech\ t}) \cdot 130 \leq 0$, *then* $S_{scrap,t} = Scrap_{Obsolete,t} + Scrap_{Home,t} + Scrap_{Prompt,t} - (P_{old\ t} + \sum_{Tech=B1,B2,B3} Y_{Tech\ t}).130$; *conversely*, $S_{scrap\ t} = Scrap_{Obsolete,t}$

3.2 Scenario Setting

We set a total of 39 scenarios, as shown in Table 2. The policy level includes the selection of three kinds of decarbonization targets (2060 carbon neutral /2050 carbon neutral /1.5 degree temperature control target), four kinds of carbon pricing methods (direct carbon tax (DC)/ indirect carbon tax (IC)/ carbon right (CR)/ indirect carbon tax + carbon right (IC&CR)) and three kinds of blast furnace decommissioning time points (early decommissioning (ER)). Furthermore, we have matched two kinds of low-carbon technology packages available in the steel industry in the future, mainly by examining the optional low-carbon steelmaking technology set (NonCCS/CCS) with or without CCS technology.

Table 2 Scenario Setting

		Decarbonization target							
		260 carbon neutralization		250 carbon neutralization		1.5°C temperature control target			
Carbon pricing		DC	IC	DC	IC	DC	IC	CR	IC&CR
Retirement	ER	(Non)	Non	(Non)	Non	(Non)	Non	(Non)	(Non)

time		CCS	CCS	CCS	CCS	CCS	CCS	CCS	CCS
	MR	(Non)	Non	(Non)	Non	(Non)	Non	(Non)	(Non)
		CCS	CCS	CCS	CCS	CCS	CCS	CCS	CCS
	LR	(Non)	Non	(Non)	Non	(Non)	Non	(Non)	(Non)
		CCS	CCS	CCS	CCS	CCS	CCS	CCS	CCS

According to the APS(Announced Pledges Scenario) in IEA Report (2021), we set the 2060 carbon neutral target and 2050 carbon neutral target. The first scenario is 2060_DC with six blast furnace decommissioning strategies, which aims to reflect the impact of different blast furnace decommissioning strategies on the transformation of steel industry. They provide a benchmark for evaluating the impact of the change of decarbonization target and the choice of carbon pricing method. The second scenario is three strategies of decommissioning blast furnace under 2060_IC, which can reflect the impact of the change of carbon pricing mode on the transformation of iron and steel industry compared with 2060_DC. In the third and fourth scenarios we only changed the decarbonization target to 2050 carbon.

In order to better explore the influence of different decarbonization targets and carbon pricing methods on the transformation of iron and steel industry, a temperature control target of 1.5℃ is introduced here, and two additional carbon pricing methods different from the carbon neutral target are designed for it: carbon emissions trading, carbon emissions trading & indirect carbon tax. Referring to the research of Wang et al. (2021), we calculated and set the temperature control target of 1.5℃. Among them, the 1.5_DC scenario and the 1.5_IC scenario not only provide a richer discussion on the impact of the change of decarbonization target, but also provide a benchmark for finding the best carbon pricing method under the target of 1.5℃. According to the report of the World Bank (2021), in the 1.5_CR scenario, based on the temperature control target of 1.5℃, we designed a carbon emission trading method by adopting the method of benchmark and credit. The 1.5_IC&CR scenario adds indirect carbon tax on the basis of the 1.5_CR scenario. Except indirect carbon tax, there are six strategies for decommissioning of blast furnace. The transformation of blast furnace under indirect carbon tax is not feasible, so there are only three strategies for decommissioning blast furnace.

4. Result

4.1 Transition costs and greenhouse gas emissions under the goal of carbon neutrality and the route of technology development

Firstly, we evaluated the cost path of technological transformation in steel industry under the scenario of 2060_DC_NonCCS. The core features of the minimum cost path are as follows: the traditional blast furnace technology will be retired from the mid-term (2027) and completely withdrawn from steel production by 2042; DRI-EAF and Scrap-EAF will expand their production capacity from now (2022) to cope with the supply reduction caused by the mid-term decommissioning of blast furnace; Until 2039, electrolysis technology was introduced. By 2050, the cumulative output of DRI-EAF, Scrap-EAF and electrolysis technology will account for 14.2%, 60.9% and 24.9% respectively, and the total transformation cost will be 17,203.88 billion yuan. Considering that some large steel enterprises in China have announced that they will achieve carbon neutrality ahead of schedule in 2050.[1], We investigated the transformation path of the steel industry under the scenario of 2050_DC_NonCCS. The transformation cost of 250_DC_NonCCS is still the lowest when the blast furnace was retired in the middle stage, which is 17205 billion yuan, which is 1.38 billion yuan higher than that of 2060_DC_NonCCS. However, electrolysis technology was used earlier, and the steelmaking technology based on fossil raw materials will completely withdraw from the market before 2050.

[1] Since 2021, China's Baowu, Hesteel, Angang Steel, Baotou Steel and other super-large steel enterprises have successively released carbon peak and carbon neutrality targets, of which the carbon peak time point is basically controlled before 2025, and carbon reduction will be achieved by 30% by about 2030, and carbon neutrality will be achieved by 2050.

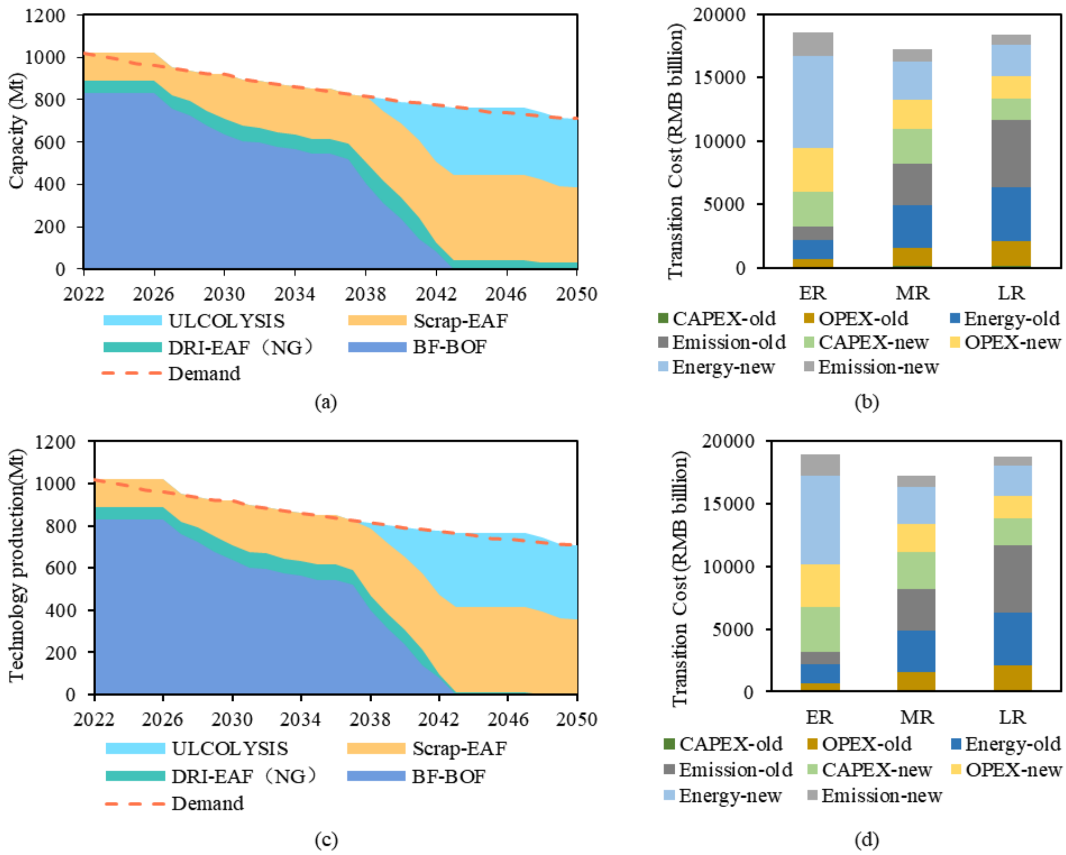

Fig.1 Comparison of Technology Path and Cost of Iron and Steel Industry under 2060 and 2050 Carbon Neutralization Goals

Compared with the mid-term decommissioning of blast furnace, the transformation cost brought by early decommissioning is the highest. On the one hand, the early retirement of blast furnace leads to high investment cost of new equipment. On the other hand, early retirement is not conducive to the matching between low-carbon steelmaking technology and raw material supply. In particular, in the future, the expansion of electro-metallurgy scale and the growth of renewable power and scrap steel supply will increase the transformation cost. (Photo: Total cost, transformation & old blast furnace). Specifically, when the blast furnace is decommissioned in the early stage. This is because the electric arc furnace technology has the most cost advantage and it is the most important low-carbon steelmaking technology to supplement the decommissioning capacity of the blast furnace in the early stage. However, the capacity expansion of early EAF was limited by the supply of scrap steel, so DRI-EAF with the second lowest cost was needed as a supplement.

At this time, renewable power supply can meet the power demand of these two low-carbon steelmaking technologies. However, from 2025, the total operating cost per ton of steel of electrolysis technology (including fixed operating cost, emission cost and energy consumption cost) began to be lower than that of natural gas shaft furnace, and gradually had cost advantage. By 2039, the total operating cost per ton of steel of electrolysis technology will be even lower than that of electric arc furnace, making it the most cost-effective technology in the medium term. However, as a large number of newly added electric arc furnaces and DRI-EAF capacity have not been retired in the early stage, the renewable power supply required by electrolysis technology is squeezed out, making it impossible to expand the capacity. Even in the late stage, high-cost hydrogen-based steelmaking technology has to be adopted to meet the requirements of carbon neutrality. In contrast, the mid-term decommissioning of blast furnace reserves renewable power space for the capacity expansion of electrolysis technology and avoids the excessive transformation cost caused by the mismatch of technology and resources. The transformation cost of blast furnace under late retirement is between early retirement and medium retirement. Although the late retirement saves the investment cost of new equipment, the emission cost increases faster, so it is uneconomical for the transformation of the whole steel industry.

4.2 Impact of direct carbon tax and indirect carbon tax on technology path selection under carbon neutral target (comparison between the choices of carbon pricing methods under different decarbonization targets)

Compared with the direct carbon tax to tax the steel industry's terminal emissions, the indirect carbon tax (taxing the energy consumption end) can more effectively restrain the use of fossil raw materials and further encourage the steel industry to adopt renewable energy steelmaking technology. The results (as shown in the figure) show that when the indirect carbon tax is applied to the steel industry, the impact on technology path selection is consistent although the minimum transformation cost increases by about 1040 billion yuan (6.1%) compared with the direct carbon tax in 2060_NonCCS and 2050_NonCCS scenarios respectively. First, the choice of low-carbon technology is similar; Second, the development scale of various new steelmaking technologies will remain unchanged in the future. The difference is that, compared with 2060_DC_NonCCS, in the situation of 2060_IC_NonCCS, the steel industry adopted electrolysis technology to replace natural gas shaft furnace earlier and on a larger scale. This is because indirect carbon tax only levies taxes on fossil raw materials, but not on renewable electricity. While not increasing the operating cost of zero-emission technologies such as electrolysis technology, it also increases the operating cost of fossil raw materials steelmaking technology, which can stimulate the steel industry to transform to zero emission more than direct carbon tax. However, due to the relatively small proportion of zero-emission technologies, indirect carbon tax will eventually lead to an increase in the total transformation cost. Compared with the 2060_NonCCS scenario, when the indirect carbon tax is adopted in the 2050_NonCCS scenario, the time point and scale of technology introduction have not changed, and only the overall transformation cost has been reduced. The results also show that indirect carbon tax has higher emission reduction requirements than direct carbon tax, and the implementation of indirect carbon tax under the 2060 carbon neutral target can guide the steel industry to achieve the 2050 carbon neutral target independently. In addition, as shown in figs. 2(a) and 2 (b), when indirect carbon tax is used, the order of transformation costs corresponding to different decommissioning time of blast furnace is: MR < ER < lR. Under the direct carbon tax scenario, the transition cost of late retirement of blast furnace is between early retirement and medium retirement. This means that, compared with the direct carbon tax, the indirect carbon tax significantly increases the transformation cost after the late decommissioning of blast furnace by increasing the emission cost, so it can more forcefully urge the transformation of fossil raw material technology to renewable energy technology in the steel industry.

4.3 Exploring the policy conditions with more emission reduction effects and cost

advantages (transition costs and greenhouse gas emissions under the temperature control target of 1.5℃ and the route of technological development)

Studies have pointed out that China's carbon neutrality target in 2060 is basically the same as the global temperature control target of 1.5℃, but the latter is more stringent (Duan et al.,2021). We evaluated the technological path of steel industry under the scenario of 1.5_DC_(Non)CCS. The results show that the technical path in this scenario is completely consistent with the 2060_DC_(Non)CCS scenario. However, it should be noted that under the goal of carbon neutrality in 2060, the blast furnace must be retired from now on, so as to ensure the goal of 1.5℃, which is consistent with the conclusion of Vogl et al.(2021). We also investigated the impact of 1.5_IC_(Non)CCS scenario on the transformation path, and the conclusion is consistent with that of 2060_IC_(Non)CCS. Further, if the carbon tax is changed to carbon emission trading, the results show that the technological path has not changed much, but the transformation cost has obviously decreased. Because carbon emission trading does not add extra cost to the steel industry like carbon tax, the overall transformation cost is not high, and it is the most economical carbon pricing method (see Figure 2(c)). However, it transfers the cost between fossil raw material technology and renewable energy technology（Duan et al.,2021）.

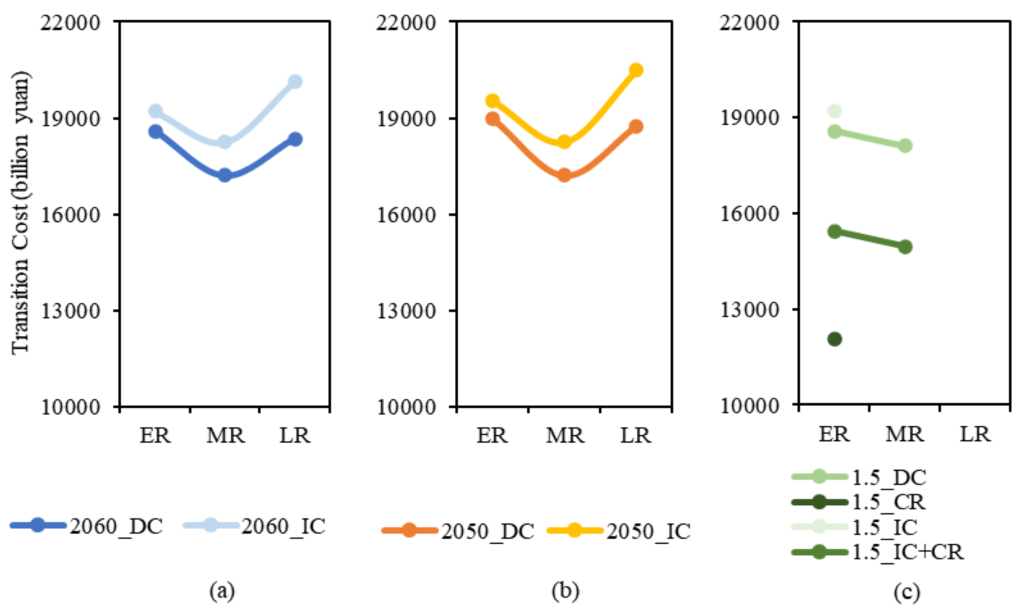

Fig.2 Impact of Different Carbon Pricing Methods on Transformation Cost of Iron and Steel Industry

Now, let's examine the combination carbon pricing method (carbon right + indirect carbon tax) with more incentive to reduce emissions. Compared with single carbon pricing, 1.5_IC&Cr_NonCCS subsidizes low-carbon steelmaking technologies through carbon trading. It reduces the unit operating cost of these technologies and further narrows the cost gap between renewable energy steelmaking technologies and fossil raw materials steelmaking technologies. As shown in Figure 2(c), under the temperature control target of 1.5°C, the combined carbon pricing method brings less transformation cost than other carbon pricing methods (except carbon rights trading), even less than the transformation to achieve the 2050/2060 carbon neutrality target. Therefore, the strictness of the decarbonization target can't completely determine the transition cost, and it is also very important to choose the appropriate carbon pricing method.

4.4 Impact of key low-carbon technologies on transformation costs and emissions of steel industry (the future development potential and importance of different steelmaking technologies and the corresponding relationship with different policy conditions)

Firstly, we compared the transformation path of steel industry with CCS and NonCCS and found that CCS technology can reduce the transformation cost and carbon emissions at the same time by improving the problem of overcapacity. This can't be achieved simply by using low-carbon steelmaking technology, setting decarbonization target and carbon pricing method. The reason is that the introduction of CCS technology provides additional decarbonization space for the steel industry, which is reflected in the following two aspects: First, CCS technology makes it possible to further decarbonize the blast furnace and improves the flexibility of decommissioning the blast furnace; Secondly, the carbon emission per ton of steel of low-cost technologies (BF-TGR-BOF, DRI-EAF-NG, DRI-EAF-60%H2) is reduced.

In the end, the advantages of CCS in the above two aspects led to a significant decrease in the total transformation cost. Specifically, in the scenario of 2060_DC_CCS, the core features of the technical path are as follows: The optimal decommissioning node of blast furnace will be advanced to 2022, and it will be completely withdrawn from steel production by 2038. BF-TGR-BOF(CCS), DRI-EAF(NG, CCS) and Scrap-EAF, as the three technologies with the most cost advantages (investment and operation costs) to meet the emission limit per ton of steel, will expand their production capacity from now on. By 2050, the cumulative output of the three technologies will account for 47.7%, 11.2% and 41.1%. Under this scenario, the total transformation cost is 14617 billion yuan, which is 3968 billion yuan less than that of 2060_DC_NonCCS. Similarly, compared with the absence of CCS technology, the cost of 1.5_DC_CCS, 1.5_IC_CCS, 1.5_CR_CCS and 1.5_IC&CR_CCS are also reduced by 3635 billion yuan, 3993 billion yuan and 1734 billion yuan respectively.

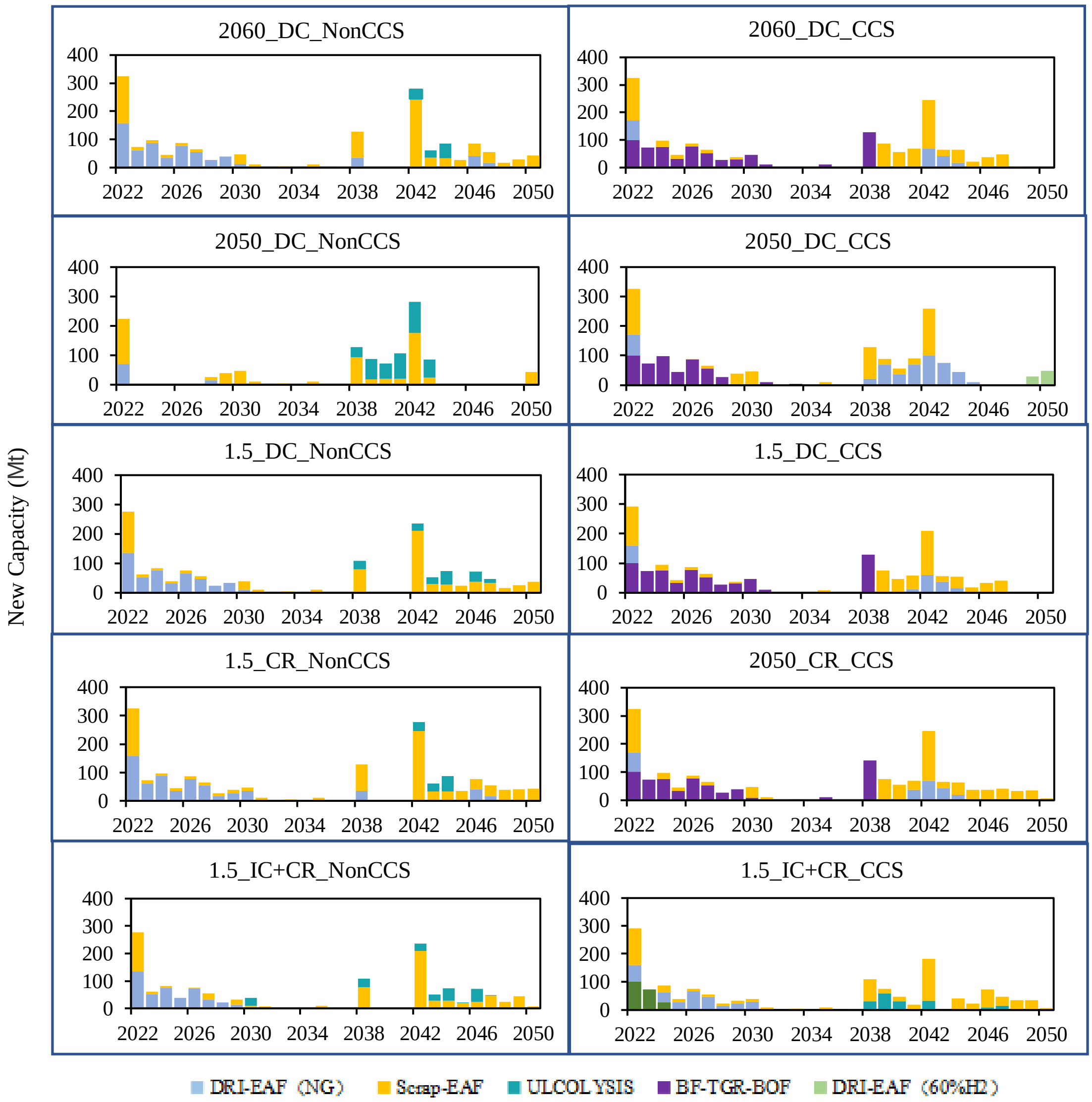

Fig.3 Compare the change trend of new capacity of low-carbon steelmaking technology in iron and steel industry with the participation of Non-CCS and CCS

Secondly, we found that electrolysis technology is always a necessary option in various scenarios. In order to further analyze the impact of electrolysis technology on cost and emission, we removed electrolysis technology and kept only the other four technologies in the scenario of 2060/2050_DC/IC_CCS/Non-CCS. We found that the goal of 2060 carbon neutrality can be achieved without electrolysis technology, but the goal of 2050 carbon neutrality is not achievable. The main reason is that the only low-carbon steelmaking technologies that can meet the emission limit of 2050 are electrolysis technology and hydrogen-based steelmaking technology. However, the hydrogen-based steelmaking technology can't play the same role as electrolysis technology due to the shortage of hydrogen supply, so it can't meet the emission reduction requirements of carbon neutrality in 2050. Similarly, under the target of 1.5℃, we examined the importance of electrolysis technology to reduce the total transformation cost and cumulative emissions. The results show that the lack of electrolysis technology will lead to the increase of the total transformation cost and accumulated carbon emissions of the steel industry to achieve the goal of 1.5℃. This result shows the importance of electrolysis technology in the low-carbon transformation of the steel industry.

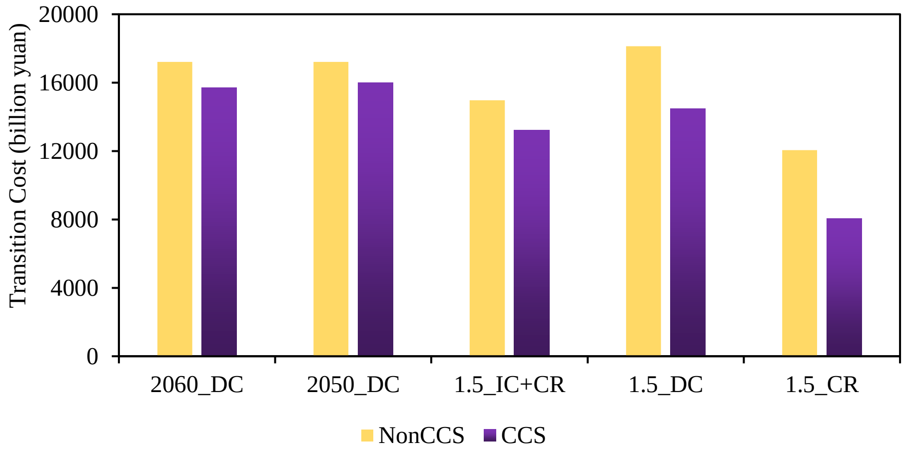

Fig.4 Cost comparisons of scenario transformation between Non-CCS and CCS.

Compared with 2060_DC_CCS, the technology used in 2050_DC_CCS is more diversified, especially when the hydrogen-based steelmaking technology is added. The main reason is that although the high hydrogen cost makes the unit operating cost of this technology higher than other low-carbon steelmaking technologies, with the rapid decline of hydrogen cost driven by technological progress, DRI-EAF(60%H2) has narrowed the gap with other technologies in energy consumption cost at the end of the transformation. In addition, since the emission of this technology is far less than that of other technologies, the investment cost of installing CCS is lower, thus making up for the disadvantage caused by the high energy consumption cost and making it possible to adopt hydrogen-based steelmaking technology.

Finally, we also explored the internal relationship among CCS technology, electrolysis technology and hydrogen-based steelmaking technology, which is not affected by the goal of carbon neutrality, carbon pricing method and decommissioning strategy of blast furnace. When CCS is available, it is possible to reduce the carbon content of blast furnace, and the emissions of other fossil fuel steelmaking technologies have been greatly reduced. Therefore, the steelmaking technology with CCS is superior to electrolysis technology in terms of unit emissions and cost, resulting in the substitution of electrolysis technology. However, when CCS technology cannot be developed on a large scale, electrolysis technology is a key to achieve the goal of carbon neutrality. Compared with other steelmaking technologies, this technology has absolute advantages in terms of both emission and energy consumption costs. The adoption of hydrogen-based steelmaking technology is influenced by the development of CCS technology and electrolysis technology. Without the cooperation of the latter two technologies, the steel industry can't achieve the goal of carbon neutrality in advance through hydrogen-based steelmaking technology.

4.5 Sensitivity analysis

The choice of low-carbon technology path in steel industry depends largely on the changes of raw material market and technology cost. For example, with the changes of energy supply and price, scrap supply and technology maturity, the development scale of various low-carbon steelmaking technologies will also change. Discussing the dynamic changes of model constraints and key exogenous variables can deepen the forward-looking and scientific validity of this research. The main exogenous parameters of the model are as following: energy supply constraint, scrap supply constraint, energy price, equipment investment cost and capacity utilization rate. The results show that the constraints of renewable energy supply, the dynamic changes (-10%, +10%) of equipment investment cost and capacity utilization rate have weak influence on technology selection. However, a 10% increase in scrap supply constraint will increase the capacity of Scrap-EAF technology by at least 6.3% and reduce the transformation cost by 5.2%. A 10% reduction in the price of hydrogen energy will enable hydrogen-based steelmaking technology to be introduced earlier and on a larger scale in the goal of 2050 carbon neutrality and 1.5-degree temperature control, and with the transformation cost reduction of at least 15.6%.

5. Conclusion and Policy Implication

5.1 Conclusion

From the cost minimization perspective, under the multiple constraints of policy-resources-technology-emissions, this study quantitatively mapped out the technological path for steel industry to achieve the goal of carbon neutrality. Based on 39 scenarios including decarbonization target, carbon pricing method, decommissioning strategy of blast furnace capacity and technology availability, the choices and challenges faced by steel industry in achieving carbon neutrality are comprehensively expounded. Moreover, the emission reduction potential, emission reduction cost and technology development path of steel industry in each scenario are quantitatively evaluated. The main conclusions of this study are given below.

（1）The cumulative cost of various policy scenarios for steel industry to achieve carbon neutrality varies greatly. Among them, the policy arrangement with the highest cost is to realize carbon neutrality of steel industry in 2050 and adopt indirect carbon tax policy (2050_DC), and the transition cost is at least 18247 billion yuan. The policy measures with the lowest cost are: to control the temperature at 1.5℃ and implement the carbon emission trading policy (1.5_CR). This scenario reduces the cost difference between fossil-fired raw material steelmaking technology (such as blast furnace and natural gas shaft furnace) and renewable energy steelmaking technology (such as electrolysis technology and hydrogen-based shaft furnace) through carbon emission trading, without increasing the overall transformation cost, and encourages the steel industry to transform to deep decarbonization faster. Furthermore, if CCS technology is involved and the government allows the blast furnace production capacity to be delayed until 2038, the minimum transformation cost can be reduced to 8060 b illion yuan, which is at least 10187 billion yuan lower than the high-cost path.

（2）The goal of decarbonization and the way of carbon pricing are equally important to the choice of transformation path of iron and steel industry. Firstly, the decarburization target determines the type of low-carbon steelmaking technology that the steel industry needs to develop. Under the goal of carbon neutrality in 2060, the steel industry focuses on the development of Scrap-EAF and DRI-EAF(NG), BOF-TGR-BF and electrolysis technology. The 2050 carbon neutral target and the 1.5℃ temperature control target put forward higher requirements for the technical arrangement of the steel industry. When CCS technology is unavailable, electrolysis technology must be introduced earlier and on a larger scale. Secondly, compared with direct carbon tax, indirect carbon tax reduces the cost difference between traditional fossil raw material steelmaking technology and renewable energy steelmaking technology by taxing energy users, and plays a key role in the introduction of electrolysis technology and hydrogen-based steelmaking technology. Furthermore, the carbon pricing method, which combines indirect carbon tax with carbon rights, strengthens this role.

（3）CCS technology, electrolysis technology and hydrogen-based steelmaking technology are the three most critical technologies to achieve carbon neutrality in steel industry. Under the same policy conditions, CCS is the best technology to achieve the goal of decarbonization, which is reflected in two aspects. First, with the participation of this technology, the cost of deep decarbonization of blast furnace is possible, and the reduction of investment cost enables the steel industry to achieve the goal of decarbonization with minimum cost. Second, CCS technology contributes to the development of hydrogen-based steelmaking technology and is an important engine for the development of zero-carbon technology in the steel industry. When CCS technology is unavailable, electrolysis technology is the last mile for the steel industry to achieve the goal of carbon neutrality. It needs to be introduced around 2038, and the output will reach at least 20% of the total social demand. Hydrogen-based steelmaking technology is the core technology of steel industry to achieve the goal of carbon neut rality in 2050. It will become the main technology in 2048, but it still needs CCS technology and electrolysis technology.

5.2 Policy Implication

Based on the analysis and discussion of the research results, this paper puts forward the following three recommendations:

(1) The decarbonization target and carbon pricing method provide the most important constraints for the technical path planning of the steel industry. From the perspective of optimal cost, the pricing method of carbon emission trading can realize the transformation path with the lowest cost. Therefore, market means should be adopted to integrate carbon market in the steel industry, which can further promote innovation and achieve low-carbon development.

(2) Iron and steel enterprises need to plan the technological development path in advance. In the short term, they should vigorously develop electric arc furnace technology; In the medium term, they should pay attention to the deployment of DRI-EAF(NG) and BOF-TGR-BF technologies; And finally, in the long run, the development of electrolysis technology, hydrogen steelmaking technology and CCS technology is more conducive toward achieving the goal of decarbonization.

(3) Iron and steel industry needs to coordinate the relationship between carbon neutrality target and raw material safety and accelerate the formation of domestic and foreign raw material double circulation system. Appropriate subsidization of the energy transformation of the iron and steel industry can reduce the cost difference between fossil raw material technology and renewable energy technology. It can encourage iron and steel enterprises to try to speed up the reduction of external dependence on iron ore and speed up the mining of domestic iron ore. It can also provide a series of support for domestic iron ore enterprises at the level of taxation, subsidies, approval, and other market mechanisms, while ensuring long-term effective and smooth international ore network channels. For scrap recycling, a complete scrap recycling-processing-distribution network is formed by establishing a large-scale

scrap processing base.disabledIt is necessary to recycle steel into the industrial chain and improve the recovery rate of scrap steel to achieve the goal of carbon neutrality.

Reference

[1] Valentin Vogl, Olle Olsson, Björn Nykvist, Phasing out the blast furnace to meet global climate targets, Joule, Volume 5, Issue 10,2021, Pages 2646-2662.

[2] Ren M, Lu P, Liu X, et al. Decarbonizing China's iron and steel industry from the supply and demand sides for carbon neutrality[J]. Applied Energy, 2021, 298:117209.

[3] Wang P, Ryberg M, Yang Y, et al. Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts[J]. Nature Communications, 2021, 12(1):2066.

[4] Tong D, Zhang Q, Zheng Y, et al. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target[J]. Nature, 2019, 572(7769):1.

[5] State and Trends of Carbon Pricing 2021，THE WORLD BANK

[6] Fu Y, Huang G, Liu L, et al. A factorial CGE model for analyzing the impacts of stepped carbon tax on Chinese economy and carbon emission[J]. Science of The Total Environment, 2020, 759:143512.

[7] Wolfram P, Weber S, K Gillingham, et al. Pricing of indirect emissions accelerates low-carbon transition of US light vehicle sector[J]. Nature Communications.

[8] UNFCCC. Adoption of the Paris Agreement (FCCC, United Nations, 2015).

[9] IEA. An Energy Sector Roadmap to Carbon Neutrality in China,2021

[10] Wei Y M, Han R, Liang Q M, et al. An integrated assessment of INDCs under Shared Socioeconomic Pathways: an implementation of C3IAM[J]. Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards, 2018.

[11] D. Nong, T.H. Nguyen, C. Wang, Q. Van Khuc. The environmental and economic impact of the emissions trading scheme (ETS) in Vietnam[J], Energy

Policy, 140 (2020)

[12] Liu J, Bai J, Deng Y, et al. Impact of energy structure on carbon emission and economy of China in the scenario of carbon taxation[J]. Science of the Total Environment, 2021, 762: 143093.

[13] Cao J, Ho M S, Jorgenson D W, et al. China's emissions trading system and an ETS-carbon tax hybrid[J]. Energy Economics, 2019, 81: 741-753.

[14] Bi H, Xiao H, Sun K. The impact of carbon market and carbon tax on green growth pathway in China: a dynamic CGE model approach[J]. Emerging Markets Finance and Trade, 2019, 55(6): 1312-1325.

[15] Goulder L H, Schein A R. Carbon taxes versus cap and trade: a critical review[J]. Climate Change Economics, 2013, 4(03): 1350010.

[16] Lin B, Li X. The effect of carbon tax on per capita CO2 emissions[J]. Energy policy, 2011, 39(9): 5137-5146.

[17] Tian S, Jiang J, Zhang Z, et al. Inherent potential of steelmaking to contribute to decarbonisation targets via industrial carbon capture and storage[J]. Nature communications, 2018, 9(1): 1-8.

[18] Sun Y, Tian S, Ciais P, et al. Decarbonising the iron and steel sector for a 2° C target using inherent waste streams[J]. Nature communications, 2022, 13(1): 1-8.

[19] Li F, Chu M, Tang J, et al. Life-cycle assessment of the coal gasification-shaft furnace-electric furnace steel production process[J]. Journal of Cleaner Production, 2021, 287: 125075.

[20] Bertram C, Luderer G, Pietzcker R C, et al. Complementing carbon prices with technology policies to keep climate targets within reach[J]. Nature climate change, 2015, 5(3): 235-239.

[21] Schleussner C F, Rogelj J, Schaeffer M, et al. Science and policy characteristics of the Paris Agreement temperature goal[J]. Nature Climate Change, 2016, 6(9): 827-835.

[22] Tollefson J. IPCC says limiting global warming to 1.5 [degrees] C will require drastic action[J]. Nature, 2018, 562(7726): 172-174.

[23] Zhao X, Ma X, Chen B, et al. Challenges toward carbon neutrality in China:

Strategies and countermeasures[J]. Resources, Conservation and Recycling, 2022, 176: 105959.

[24] An R, Yu B, Li R, et al. Potential of energy savings and CO2 emission reduction in China’s iron and steel industry[J]. Applied energy, 2018, 226: 862-880.

[25] Wang X, Zhang Q, Xu L, et al. Water-energy-carbon nexus assessment of China’s iron and steel industry: Case study from plant level[J]. Journal of Cleaner Production, 2020, 253: 119910.

[26] Zhang H, Sun W, Li W, et al. A carbon flow tracing and carbon accounting method for exploring CO2 emissions of the iron and steel industry: An integrated material–energy–carbon hub[J]. Applied Energy, 2022, 309: 118485.

[27] Liang T, Wang S, Lu C, et al. Environmental impact evaluation of an iron and steel plant in China: Normalized data and direct/indirect contribution[J]. Journal of Cleaner Production, 2020, 264: 121697.

[28] Wu R, Lin B. Environmental regulation and its influence on energy-environmental performance: Evidence on the Porter Hypothesis from China's iron and steel industry[J]. Resources, Conservation and Recycling, 2022, 176: 105954.

[29] Yu B, Li X, Qiao Y, et al. Low-carbon transition of iron and steel industry in China: carbon intensity, economic growth and policy intervention[J]. Journal of Environmental Sciences, 2015, 28: 137-147.

[30] S. Zhang, B.W. Yi, E. Worrell, F. Wagner, W. Crijns-Graus, P. Purohit, et al. Integrated assessment of resource-energy-environment nexus in China’s iron and steel industry. J Clean Prod, 232 (2019), pp. 235-249,

[31] State and Trends of Carbon Pricing 2021

[32] An energy sector roadmap to carbon neutrality in China（IEA, 2021）

[33] Iron and Steel Technology Roadmap（2020）

[34] Duan H, Zhou S, Jiang K, et al. Assessing China’s efforts to pursue the 1.5 C warming limit[J]. Science, 2021, 372(6540): 378-385.

Find the entire collection here:
https://www.ifpenergiesnouvelles.com/article/ifpen-economic-papers

228 - 232 avenue Napoléon Bonaparte
92852 Rueil-Malmaison
www.ifpschool.com

1-4 avenue de Bois-Préau
92852 Rueil-Malmaison
www.ifpenergiesnouvelles.fr