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A Study on the Potential and Cost of Carbon Reduction from Low Carbon Technologies in the Chinese Copper Industry

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Abstract

The copper industry is a basic raw material industry, and it is also the metals with high energy consumption in production. Exploring the pathway of energy saving and emission reduction in the copper industry will help China to achieve its emission reduction commitments under the Paris Agreement. The Grey Verhulst model was used to predict copper industry production and the NSGA-II algorithm and TOPSIS method were used to determine the optimal penetration rate of low-carbon technologies under different scenarios. The abatement potential and cost of eight low-carbon technologies from 2020 to 2035 were measured for different decision preferences. The results of the study indicate that: 1) China's copper industry production shows S-shaped trend and is close to peak production by 2035; 2) by 2035, the abatement potential and costs of the spin-floating copper smelting and energy-saving technology (B3) and the crude copper auto-redox refining technology (B2) are both highly advantageous and should be promoted; 3) by 2035, eight low carbon technologies are able to achieve a total emission reduction of 9.134 million tons at a total abatement cost of 900 million CNY under the systematic decision making scenario, resulting in a 23％ reduction in emissions.

JEL classification numbers: O30, O31, O32, O33.
Keywords: Low carbon technology, Abatement potential, Abatement cost, NSGA-II algorithm.

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1. Introduction

Large amounts of carbon dioxide emissions pose a challenge to sustainable development. Many countries are actively taking action to address this issue, such as setting emission reduction targets for high energy-consuming and high-polluting industries, setting emission caps, and vigorously promoting advanced technologies, etc. In 2021, China's State Council formulated the 14th Five-Year Comprehensive Work Program for Energy Conservation and Emission Reduction, stating that it should pay attention to non-ferrous metals and other industries, and implement energy-saving reforms and pollutant management. Implementation Plan" clearly emphasizes that copper, aluminum and other industries should pay attention to the role of low-carbon technologies and increase investment and application.

Among the many industries that drive China's economic development, the copper industry is one of the key raw material industries, and China has long been the world's largest copper producer and consumer. Copper has many advantages over other metals, for example, it is widely used in electronic equipment, construction, infrastructure and transportation processes due to its good electrical, thermal and corrosion resistance[1]. Especially in the context of carbon peaking and carbon neutrality, low carbon technologies are highly expected and the promotion of high-performance, zero-carbonization technologies should be enhanced[2], and copper is an important building block for renewable energy power plants and electric vehicles. Due to the high demand for wiring harnesses and drive motors, pure electric vehicles use three times more copper than conventional gasoline-powered vehicles[3]. The same is true for renewable energy-based power plants, which consume more than twice as much copper as a typical thermal power plant for the same generating capacity in terms of heat exchangers, turbines, transformers, etc.[4]. At the same time, copper is also a highly energy-intensive metal to produce, with one study finding that CO_2 emissions from refined copper in China accounted for about 0.3% of total domestic CO_2 emissions in that year[5]. Under current policy plans, some studies suggest that China's growing demand for copper-containing products is expected to continue until 2030, which could lead to future supply problems as well as environmental issues associated with copper production[6]. Therefore, carbon emission reduction in the copper industry plays an important role in carbon peaking for the entire non-ferrous metal industry.

As one of the major contributors to CO_2 emissions, the copper industry has been included in some of the energy and climate models. The copper industry mainly consists of mining, smelting, processing and recycling segments. In the copper mining segment, energy consumption and ore taste are important sources of CO_2 emissions[7][8]. Since the copper smelting link accounts for a large proportion of carbon emissions, domestic scholars seize the main contradiction and mostly focus on this stage. For example, Wang Wei et al[9] selected a certain enterprise based on governmental documents and conducted a case study to account for the carbon emissions from copper smelting. Liu Cheng et al[10] believe that in the copper smelting process, electricity CO_2 emissions accounted for the largest proportion, reaching 2/3. further, scholars have gradually explored in-depth to help the copper industry to realize the path of emission reduction. In previous studies, the promotion of advanced technology is one of the most favored measures. Some scholars propose the selection of certain specific advanced technologies for their respective countries from a theoretical perspective. For example, Zhang Hong[11] focuses on low-carbon technologies in the copper smelting process, argues that the focus should be on fuel combustion and power generation and points out that rare-oxygen combustion technology, clean low-carbon fuels and variable frequency technology can effectively reduce carbon emissions. Wang Mancang et al[12] believe that the focus should be on photovoltaic, hydrogen and other clean energy technologies and the application of carbon capture technology. There are also scholars who assess the current emission reduction capacity of different technologies in the copper industry. For example, Irving et al[13] pointed out that the use of high-temperature tera-thermal process in copper smelting can realize 22.61% energy saving and 61.4% emission reduction. Further, some scholars have considered scenarios with a mixture of emission reduction measures. It was suggested that effective emission reduction in the copper industry requires not only increased application of low carbon technologies but also a reduction in primary production[14]. Other studies have comprehensively compared the extent to which power plant decarbonization, energy efficiency improvements, low carbon technologies and copper recycling strategies have an impact on emissions reductions in the copper industry.Ciacci et al[15] found that secondary production of copper could not meet the 50% reduction in CO_2 emissions from 2000 levels under either moderate power plant decarbonization or energy efficiency improvements, compared to the application of low carbon technologies which have a great potential for mitigating climate change. has great potential for climate change mitigation.

As mentioned above, previous studies have made positive contributions to carbon emission reduction in the Chinese copper industry. The research on the structure of CO_2 emissions and the emission reduction path of the copper industry has been relatively clear. However, there are still some limitations. First, although some scholars have studied the emission reduction potential of low-carbon technologies, they have only focused on a single technology, and very few studies have extended the scope to cover the process from copper ore extraction to copper smelting to copper processing. Second, some scholars have only considered the current development of low-carbon technologies, but have not analyzed the emission reduction potential of low-carbon technologies in China's copper industry in 2025, 2030 and 2035. Third, some scholars have analyzed the current and future emission reduction potential of the copper industry from multiple perspectives, including low-carbon technologies, copper recycling, and energy efficiency improvement. However, it is not enough to only consider the emission reduction effect; enterprises are more concerned about the cost issue while reducing emissions, and setting a double target may be a better decision. Therefore, this study attempts to fill the above research gap.

2. Methods and Data

2.1 Gray Verhulst Modeling

Copper production is closely related to CO_2 emissions from the copper industry, which illustrates the importance of scientific prediction of copper production. The gray Verhulst model is widely used to predict the production and demand of various substances, has the advantage of modeling small samples, and is able to better describe the process of approaching saturation, i.e., the S-curve [16]. In this paper, we analyze the trend of China's production of copper ore, refined copper and copper material from 2005 to 2021, and find that the trend is approximately S-shaped, and the data of the production of copper ore, refined copper and copper material are from the National Bureau of Statistics. Therefore, the gray Verhulst model is used to forecast China's production of copper ore, refined copper and copper material from 2022 to 2035. The gray Verhulst model is derived as follows:
Let $X^{(0)}$ be the original sequence,

$$X^{(0)} = (x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(n)) \tag{1}$$

Where, $x^{(0)}(k) \geq 0, k = 1,2, \ldots, n$. Let $X^{(1)}$ be an accumulative generating sequence of $X^{(0)}$.

$$X^{(1)} = (x^{(1)}(1), x^{(1)}(2), \cdots, x^{(1)}(n)) \tag{2}$$

Where,

$$x^{(1)}(k) = \sum_{j=1}^{k} x^{(0)}(j), k = 1, 2, \cdots, n \tag{3}$$

The gray Verhulst model is as follows.

$$x^{(0)}(k) + 0.5a(x^{(1)}(k) + x^{(1)}(k - 1)) = b(0.5x^{(1)}(k) + 0.5x^{(1)}(k - 1))^2 \tag{4}$$

The gray Verhulst whitening equation is as follows.

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b(x^{(1)})^2 \tag{5}$$

Solving equation (5), the time response equation of the gray Verhulst model can be obtained as follows.

$$x^{(1)}(k+1) = \frac{ax^{(1)}(1)}{bx^{(1)}(1)+(a-bx^{(1)}(1))e^{ak}} \tag{6}$$

2.2 NSGA-II Model

2.2.1 Predicting CO2 Emissions

In this paper, the carbon emission factor method is used to predict the trend of CO_2 emission in China's copper industry from three aspects: copper mining, copper smelting and copper processing, as shown in Equation (7). The data of the carbon emission factor comes from the study of Zhang, F. et al [5], and the data is summarized as shown in Table 1.

$$CE_{j,t} = PRO_{j,t} \times EF_j \tag{7}$$

Where $CE_{j,t}$ is the CO_2 emissions from production at step j in year t, $PRO_{j,t}$ is the production at step j in year t, and EF_j is the carbon emission factor.

Table 1: Carbon Emission Factors

Production Process	CO_2 Emission Factors (tCO_2/t Copper)	Source of Data
Copper Ore	2.12	Fan Zhang et.al, 2022
Refined Copper	1.98	Fan Zhang et.al, 2022
Copper	0.57	Fan Zhang et.al, 2022

2.2.2 CO2 Abatement Potential and Costs

In this paper, scenario analysis is used to select eight low-carbon technologies for the copper industry in 2020 as the baseline scenario, and the same eight low-carbon technologies in 2025, 2030 and 2035 as the future scenarios. Considering the optimal technology diffusion rate determined by three different decision-making preferences, the changes in the abatement potential and cost of implementing each low-carbon technology in the copper industry in 2025, 2030, and 2035 are investigated.The diffusion rate, investment amount, energy saving, consumption reduction, and annual abatement data of each low-carbon technology in 2020 are obtained from the Catalogue of National Key Promoted Technologies (2016-2017) and the National Industrial Energy Saving Technology Application Guidelines and Case Studies (2019-2020). Production data for copper ore, refined copper and copper material are obtained from the National Bureau of Statistics (NBS).The production forecasts for 2025, 2030 and 2035 are detailed in Section 1.1.The technology diffusion rates for 2025, 2030 and 2035 are derived from the NSGA-II and TOPSIS algorithms, which are detailed in Sections 1.2.3 and 1.3.This paper assumes that low carbon technologies are based on the 2025, 2030 and 2035 technology diffusion rates. In this paper, it is assumed that the low-carbon technologies are based on the annual investment amount of a 20-year project cycle, and the unit price of standard coal is RMB 1,000/tonne, with reference to the Catalogue of National Key Promoted Technologies (2017). The calculation of the emission reduction potential and cost of low-carbon technologies in this study refers to the research method of Zhu Shuying et al [17], and the calculation formula is as follows:

The calculation formula for the emission reduction potential of each low-carbon technology is as follows:

$$ERP_{i,t} = PRO_t \times \frac{ER_i}{PRO_{i,t}} \times TP_{i,t} \tag{8}$$

Where $ERP_{i,t}$ denotes the carbon reduction potential of technology i in year t, PRO_t denotes the production of copper ore, refined copper or copper material in year t, $PRO_{i,t}$ denotes the production of the corresponding copper ore, refined copper or copper material in year t when technology i is applied, ER_i denotes the annual carbon emission reduction of technology i, and $TP_{i,t}$ denotes the rate of diffusion of technology i in year t.

The formula for calculating the abatement cost of each low-carbon technology is as follows:

$$ERC_{i,t} = ERP_{i,t} \times \frac{INV_i}{ER_i \times N} \tag{9}$$

Where $ERC_{i,t}$ denotes the abatement cost of technology i in year t, INV_i denotes the amount of investment made by the firm in applying technology i, and N denotes the number of years of investment by the firm.

The formula for calculating the energy-saving benefit of each low-carbon technology is as follows:

$$ESB_i = ES_i \times P \tag{10}$$

Where ESB_i denotes the energy saving benefit of technology i,ES_i denotes the energy saving of technology i, and P denotes the unit price of standard coal.

2.2.3 Multi-objective Optimization Model

This paper establishes a multi-objective model of CO_2 emission and cost in the copper smelting process, in which the decision variable is the promotion rate of each low-carbon technology, and the objective function is Eqs. (11)-(14).

$$F(x) = min[f_1(x), f_2(x)] \tag{11}$$

The objective function $f_1(x)$ represents CO_2 emissions and is calculated as follows:

$$f_1(x) = CE_t - \sum ERP_{i,t} \tag{12}$$

Where CE_t represents the CO_2 emissions from the copper smelting industry in year t, and $ERP_{i,t}$ represents the carbon reduction potential of technology i in year t. The objective function $f_2(x)$ represents the cost and is calculated as follows:

$$f_2(x) = \sum PRO_t \times \frac{INV_i}{PRO_{i,t} \times N} \times TP_{i,t} \tag{13}$$

Where PRO_t denotes the output of the copper smelting industry in year t, $PRO_{i,t}$ denotes the output of refined copper in year t when technology i is applied, INV_i denotes the amount of investment made by the enterprise in technology i, N denotes the number of years of investment by the enterprise, and $TP_{i,t}$ denotes the diffusion rate of technology i in year t.

The constraint function is:

$$s.t. 0 \leq TP_{i,t} \leq 1 \tag{14}$$

When weighing the benefits of two or more objectives, multi-objective algorithms can provide decision makers with more comprehensive choices, among which the NSGA-II algorithm is fast and has good convergence [18]. Therefore, NSGA-II algorithm is used in this paper to solve the above model, and the optimization process is shown in Figure 1.

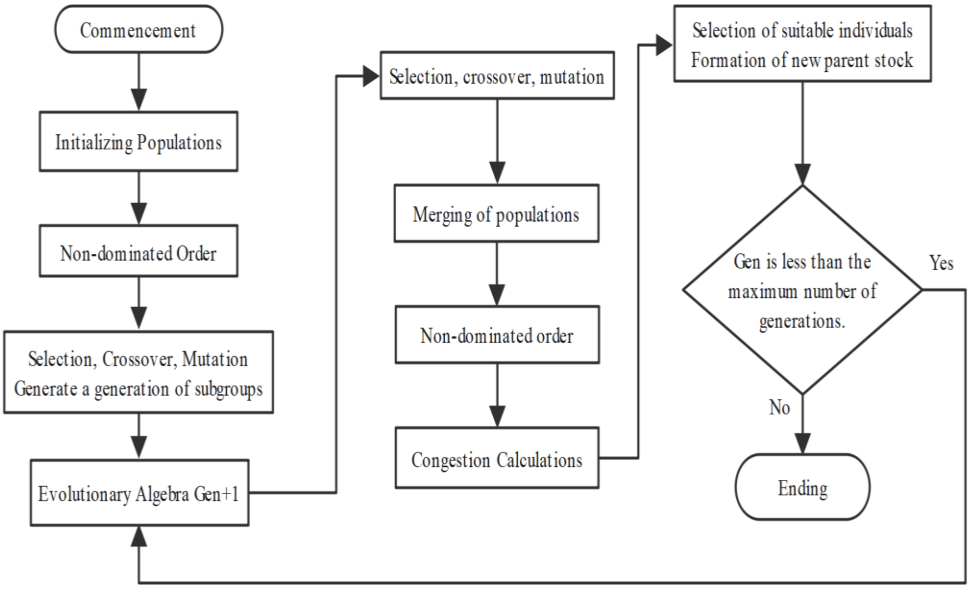

Figure 1: Flowchart of the NSGA-II Algorithm

2.2.4 TOPSIS Modeling

In order to solve the problem of selecting the optimal solution from the Pareto bounded solutions, this paper adopts the TOPSIS method to rank the similarity of the 50 ideal solutions generated by the NSGA-II algorithm. TOPSIS was firstly developed by Hwang and Yoon (1981) [19] for evaluating and filtering out the best options from a large number of available choices. It is an effective and simple, method for solving multi-objective problems with the following computational procedure:

First, let the original matrix be $A = (a_{ij})_{m\times n}$. Normalize the matrix A to construct the matrix $B = (b_{ij})_{m\times n}$,

where

$$b_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^{2}}}, i = 1, 2, \cdots, m; \ j = 1, 2, \cdots, n \tag{15}$$

Then, the positive ideal solution (b^{*}) and the negative ideal solution (b^{0}) are calculated by Eqs. (16)-(17):

$$b_j^* = \begin{cases} max_i b_{ij}, j \ is \ an \ equity\text{-}based \ property \\ minx_i b_{ij}, j \ is \ a \ cost\text{-}based \ property \end{cases} \tag{16}$$

$$b_j^0 = \begin{cases} minx_i b_{ij}, j \ is \ an \ equity\text{-}based \ property \\ maxx_i b_{ij}, j \ is \ a \ cost\text{-}based \ property \end{cases} \tag{17}$$

Let the distance between the ith evaluation object and the positive ideal solution be s_i^*, and the distance between the ith evaluation object and the negative ideal solution be s_i^0, which is calculated by Eqs. (18)-(19):

$$s_i^* = \sqrt{\sum_{j=1}^{n} (b_{ij} - b_j^*)^2}, i = 1, 2, \cdots, m \tag{18}$$

$$s_i^0 = \sqrt{\sum_{j=1}^{n} (b_{ij} - b_j^0)^2}, i = 1, 2, \cdots, m \tag{19}$$

Finally, the closeness of the ith evaluation object to the ideal solution is calculated as follows and the Pareto boundary solutions are sorted in descending order according to the magnitude of the f_i^*-value:

$$f_i^* = \frac{s_i^0}{s_i^0 + s_i^*}, i = 1, 2, \cdots, m \tag{20}$$

3. Research Findings

3.1 Development of low-carbon technologies in China's copper industry in the base period

Table 2 shows the abatement potential, abatement cost and energy-saving benefits of different low-carbon technologies in 2020.The average abatement cost of eight low-carbon technologies imposed on China's copper industry in 2020 is 99.2 yuan/tCO_2, of which the total abatement potential is 1.512 million tons, and the total abatement cost is 150 million yuan.

From the perspective of emission reduction, spin-float copper smelting energy-saving technology (B3) has the largest annual emission reduction potential of 621,600 tons. It is applicable to the copper smelting process, through strengthening the mixing of oxygen-enriched bodies and materials, and strengthening the secondary reaction of peroxide particles and sub-oxidized particles to ensure sufficient reaction and achieve the purpose of reducing energy consumption. Crude copper auto-oxidation reduction refining technology (B2) and double side-blowing shaft furnace melting pool smelting technology (B1) also have good potential for emission reduction, respectively 350,000 tons/year and 325,000 tons/year.B2 is applicable to the refining of copper, eliminating the oxidation and reduction process of the traditional thermal refining of copper and solving the problem of pollutant emission in the traditional method at the root.B1 is applicable to the melting process of copper, which is able to improve the efficiency of melting, reduce the consumption of refractory materials and reduce the consumption of refractory materials. B1 is suitable for copper smelting, which can improve the smelting efficiency and reduce the consumption of refractory materials, and has good economic benefits while saving energy. These technologies should be considered when the task of reducing emissions is urgent.

From the cost point of view, B2 has the lowest unit abatement cost of 86,000 yuan/tCO_2, followed by B3 with 97,000 yuan/tCO_2. Their abatement amount is also higher, which indicates that B2 and B3 have higher carbon abatement efficiency. From an economic point of view, these items of technology should be prioritized. However, the unit abatement cost of some low-carbon technologies is higher, such as the steam-electric double-drive coaxial compressor unit technology (B6) in the field of copper smelting, which reaches 2,358,000 yuan/tCO_2. This may be because B6 has higher technical requirements and higher upfront investment costs. In terms of energy-saving benefits, in 2020, various low-carbon technologies can realize energy savings of 779,600 tons of standard coal, bringing energy-saving benefits of 780 million yuan. Among them, the energy-saving benefit of B3 is the most obvious, which is 380,000 tons of standard coal, and should be promoted more vigorously from the perspective of energy saving.

Table 2: Introduction of Low-carbon Technology in Copper Industry

Serial No.	Segment	Low Carbon Technologies	Technology Diffusion Rate in 2020 (%)	Energy Efficiency in 2020 (×10^4tce/a)	Emission Reduction Potential in 2020(×10^4t/a)	Cost of Abatement in 2020 (×10^4yuan)
A1	Mining	Large and High Efficient Inflatable Mechanical Agitation Flotation Machine	0.3	0.01	0.01	1.41
C1	Processing	Large-scale High-efficiency Driveless Flotation Technology	0.01	0.05	0.11	8.13
B1	Smelting	Double Side Blow Shaft Furnace Melting Technology	0.03	12.32	32.53	12030.12
B2		Crude Copper Autoxidation Reduction Refining Technology	0.2	19.75	35.09	300.75
B3		Rotary Float Copper Smelting Energy Saving Technology	0.2	38.10	62.16	601.51
B4		Double-furnace Copper Continuous Blowing Energy-saving Technology	0.03	1.16	3.80	496.84
B5		Energy-saving and High-efficiency Enhanced Electrolytic Parallel Flow Technology	0.1	5.71	15.09	1122.81
B6		Dual-drive Coaxial Compressor Technology for Copper Smelting.	0.05	0.87	2.41	568.09

3.2 Scenario Analysis of Low Carbon Technologies in China's Copper Industry

3.2.1 Production Forecast

In this paper, the grey Verhulst model is fitted to predict the output of copper ore, refined copper and copper material in China from 2005 to 2035, and the results are shown in Figure 2. The accuracy test results are shown in Table 3, and all values are less than 0.35, indicating that the model can be fitted well and can be used to predict future production.

Table 3: The Results of Accuracy Test

Procedure	Copper Ore	Refined Copper	Copper
C	0.3087	0.0823	0.2106

In Figure 2, the output of copper ore, refined copper and copper material all show an S-shaped trend, in which the refined copper output was in a rapid growth stage from 2005 to 2014, increasing from 2.668 million tonnes in 2005 to 7.6437 million tonnes in 2014, with an average annual growth rate of 13.3%. During this period, China's increased investment in infrastructure led to a steep rise in demand for raw materials, and in addition to its own mineral reserves, China also needed to import a large number of copper ores for production. The growth rate of refined copper production slowed down from 7.962 million tonnes in 2015 to 9.7833 million tonnes in 2018, with the average annual growth rate dropping to 8.5 per cent. This is mainly due to the sharp expansion of production in the previous period, while the current demand for copper is slowing down, and the problem of overcapacity occurs, affected by the supply-side reform policy, the core of the development of this stage is changed from the expansion of production capacity to the control of production capacity. The growth of refined copper production in the period of 2019-2035 is slow and close to the plateau period, and the production will be about 12,256,000 tonnes in 2035, with the growth rate of between 1-2% per annum. This result is close to the one obtained by Zhang et al.'s prediction (reaching a peak in 2040 at around 14 million tonnes) [5]. This is mainly due to the utilisation of recycled copper. Metal recycling is an effective solution to the problem of limited resources and emission reduction, under appropriate conditions, the carbon dioxide emitted from secondary production is about 43% less than the primary production process [20], recycling of copper products can save 85% of the energy consumption, which has a greater advantage of emission reduction [21], therefore, in recent years, China has gradually increased the recycling of copper, and the study shows that, by 2030, the production of recycled copper will exceed that of primary copper.

Therefore, in recent years, China has gradually increased the recycling of copper, and studies have shown that by 2030, the production of recycled copper will exceed the production of virgin copper to become the main source of copper [5]. Copper ore and copper material production also shows a similar growth trend, in 2005-2013 for the rapid growth stage, 2014-2019 for the fluctuating slow growth stage, 2019-2035 for the growth platform stage.

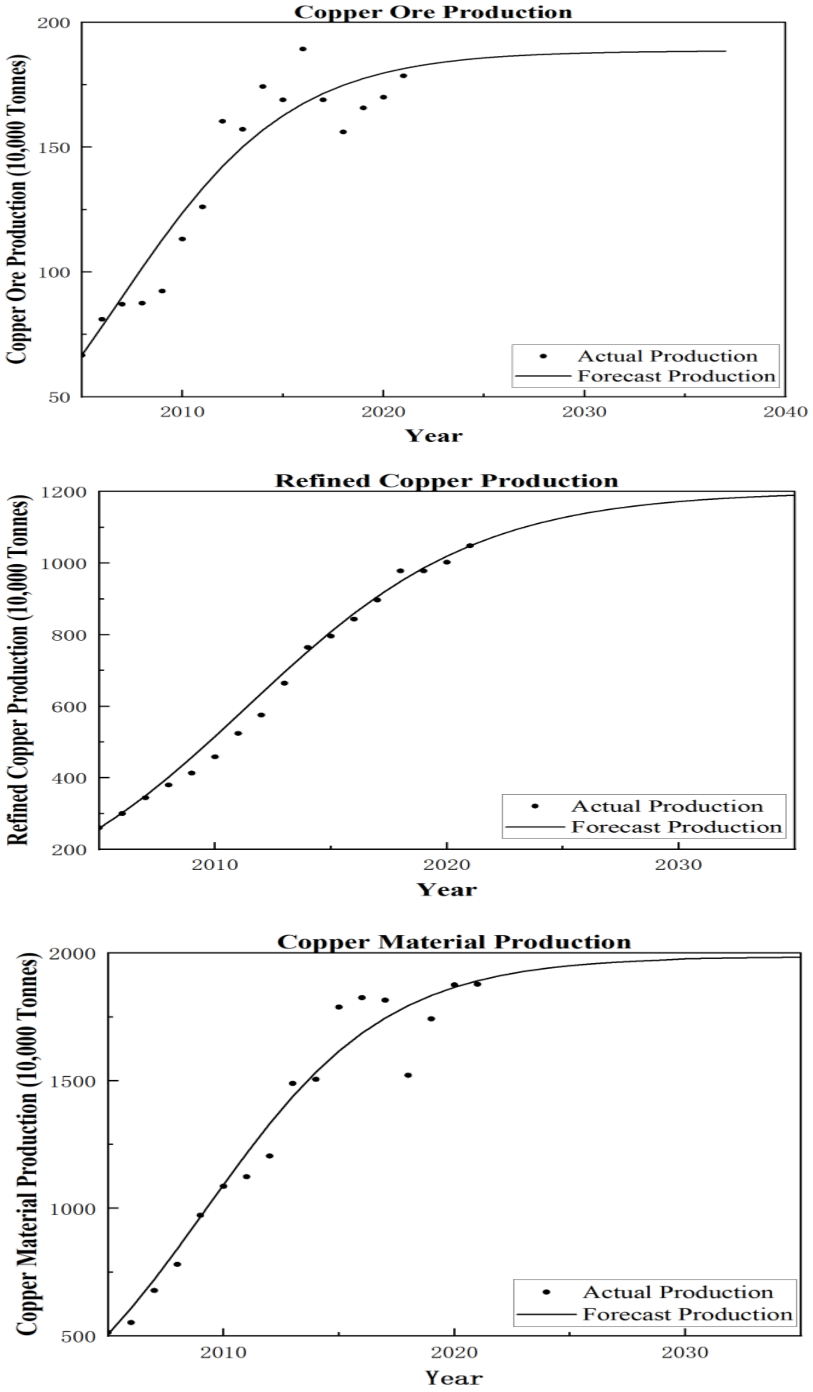

Figure 2: Forecast Results of Chinese Copper Production from 2005 to 2035

3.2.2 Optimal Technology Diffusion Rate Decision Making

Substituting each parameter into Eqs. (12), (13) and solving optimally in Matlab using the NSGA-II algorithm, the Pareto efficient frontier is obtained, as shown in Figure 3. Where $f_1(x)$ is the carbon dioxide emissions after applying low carbon technologies and $f_2(x)$ is the total cost of applying each low carbon technology. In this study, the low carbon technology diffusion rate in 2025 is the value recommended by experts in the policy document, and the low carbon technology diffusion rate in 2035 is derived by NSGA-II algorithm.

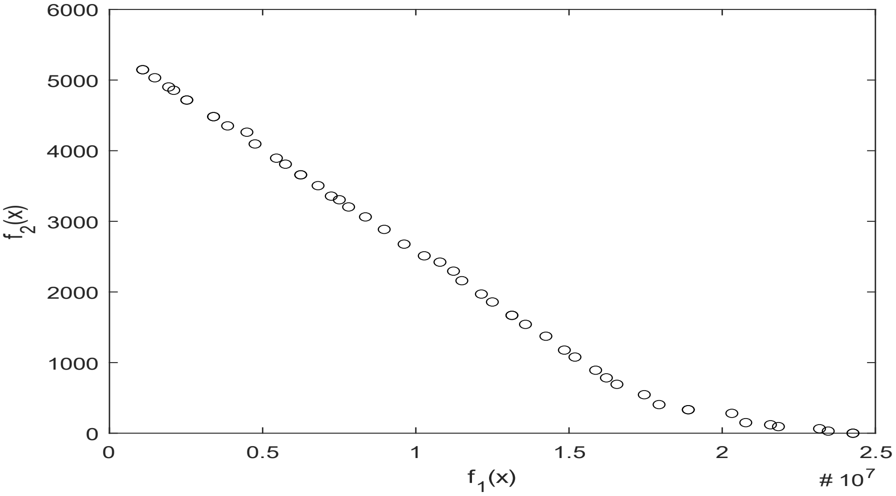

Figure 3: Pareto Optimal Front of Low-carbon Technology for Copper Smelting in 2035

In the decision preferences, this paper sets three cases of systematic decision preference (SP), emission reduction preference (AP) and economic cost preference (EP). In the set of optimal solutions derived from the NSGA-II algorithm, the optimal diffusion rate of each technology under each preference is derived using the TOPSIS method of ranking, as shown in Figure 4. There are differences in the diffusion rate of each low-carbon technology under different decision preferences. This mainly stems from the differences in the needs of enterprises, such as the pressure to reduce emissions, the economic situation and other factors, according to which the technology more suitable for the enterprise is selected. By 2035, under systemic decision-making preferences, the diffusion rates of technologies in B3 and B4 are both greater than 95 per cent, followed by B6 at 81 per cent. Under the abatement preference, B3 has the highest technology diffusion rate of 96 per cent, followed by B5 at 93.5 per cent, and B6 has the lowest diffusion rate of 23.4 per cent, which may be due to the fact that the abatement potential of the technology is more valued under this preference, whereas B6 does not have an abatement advantage at the same cost.

Under the economic cost preference, B3 has the highest technology diffusion rate of 93.8 per cent, followed by B2 at 75.1 per cent. In the previous analysis, the unit abatement cost of these two technologies is the lowest, so B2 and B3 are more favoured under the economic preference decision.

By comparing the three decision preferences, it is found that by 2035, B2 and B3 have higher technology diffusion rates, which are both greater than 75 per cent. This is due to the high potential of emission reduction and cost advantages of these two technologies. Therefore, these two technologies should be widely promoted and applied. It is worth noting that B3 is the only one of the eight low-carbon technologies selected in the Catalogue of Low-Carbon Technologies to be Promoted by the State in 2022 (the fourth batch), and after comparison, it is found that the emission reduction potential and cost of B3 have a large advantage, making it a good choice for enterprises. The technology promotion rate of B1 is lower, less than 40%. Because of its high cost, at this stage, due to the limited number of low-carbon technologies, some enterprises will adopt this technology at a specific production stage, but with technological innovation and advancement, this technology is the easiest to be replaced by 2035 when other advanced technologies appear. Due to the somewhat antagonistic nature of abatement preference and economic cost preference decision-making, the diffusion rates of some technologies have also shown opposite results. For example, under the abatement preference decision, the technology diffusion rate of B4 is 74 per cent and that of B5 is 93.5 per cent, while under the economic cost preference, the technology diffusion rate of B4 is 48.5 per cent and that of B5 is only 12.1 per cent. This is because although B4 and B5 have a high potential for emission reduction, they are also more costly and will only be considered by enterprises with urgent emission reduction needs.

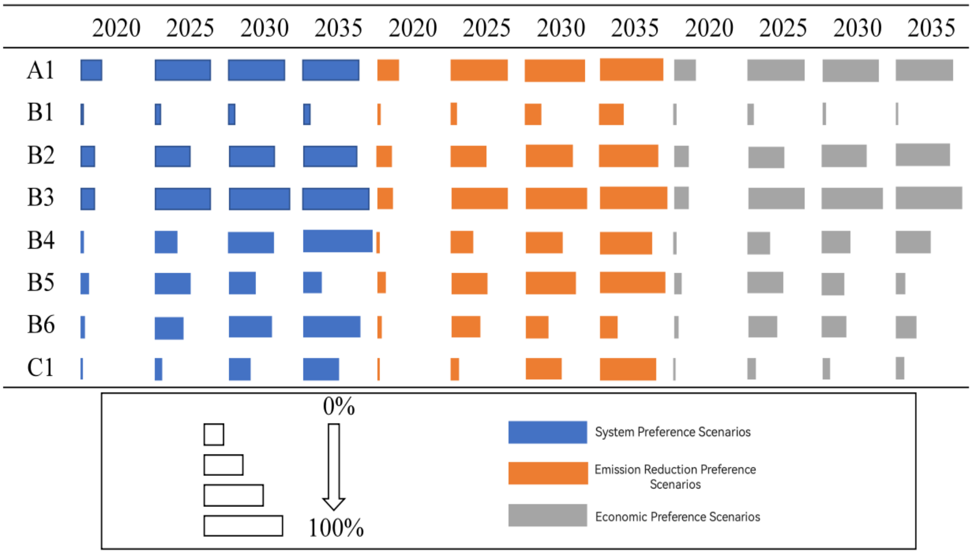

Figure 4: The Low-carbon Technology Penetration in Copper Industry

3.2.3 Analysis of Emission Reduction Potential and Cost of Emission Reduction

For each technology in Table 2, this paper takes the eight low-carbon technologies imposed in 2020 as the baseline, and calculates the total abatement potential and cost in 2025, 2030 and 2035 under different decision-making preferences on the basis of the future production and the promotion rate of each technology predicted in 2.2.1 and 2.2.2. In particular, the abatement potential and abatement cost of the eight low-carbon technologies in 2035 are shown in Figure 5, with 5(a) being the scenario under systematic decision-making preferences, 5(b) under abatement preferences, and 5(c) under economic cost preferences. The ranking of costs and emission reductions under the three decision preferences shows an opposite trend. For emission reductions, the economic cost preference decision is the smallest, followed by the system decision preference, and the emission reduction preference decision has the largest emission reductions. Specifically, under the system decision preference, the emission reductions in 2025, 2030 and 2035 are 6,391, 7,831 and 9,134,000 tonnes, respectively, and the abatement costs are 580, 750 and 900 million yuan in order, and by 2035, a 23% emission reduction is achieved. Under the abatement decision preference, the emission reductions in 2025, 2030 and 2035 are 6.391, 9.802 and 13.134 million tonnes, and the abatement costs are 5.8, 1.32 and 2.06 billion yuan in that order, and by 2035, an abatement rate of 33.17 per cent can be achieved. Under the economic cost preference, the emission reductions in 2025, 2030 and 2035 are 6,391, 6,517 and 6,460,000 tonnes, and the abatement costs are 580, 430 and 250 million yuan in order, and by 2035, it is able to reduce the emission rate by 16.32%.

A combination of the three decision preferences reveals that low-carbon technologies have some emission reduction effect, but their emission reduction is limited. Even under the emission reduction preference, it can only reach 33.17 per cent. Part of the reason is that the number of technologies covered in this study is limited and fails to include all current low-carbon technologies, and the bigger reason is that the biggest source of CO_2 emissions in the copper industry is electricity consumption, which needs to be solved by more thorough measures, such as using a zero-carbon power supply [22], increasing the share of renewable energy [23], or reducing primary production, such as expanding copper recycling to achieve a greater emission reduction Effectiveness.

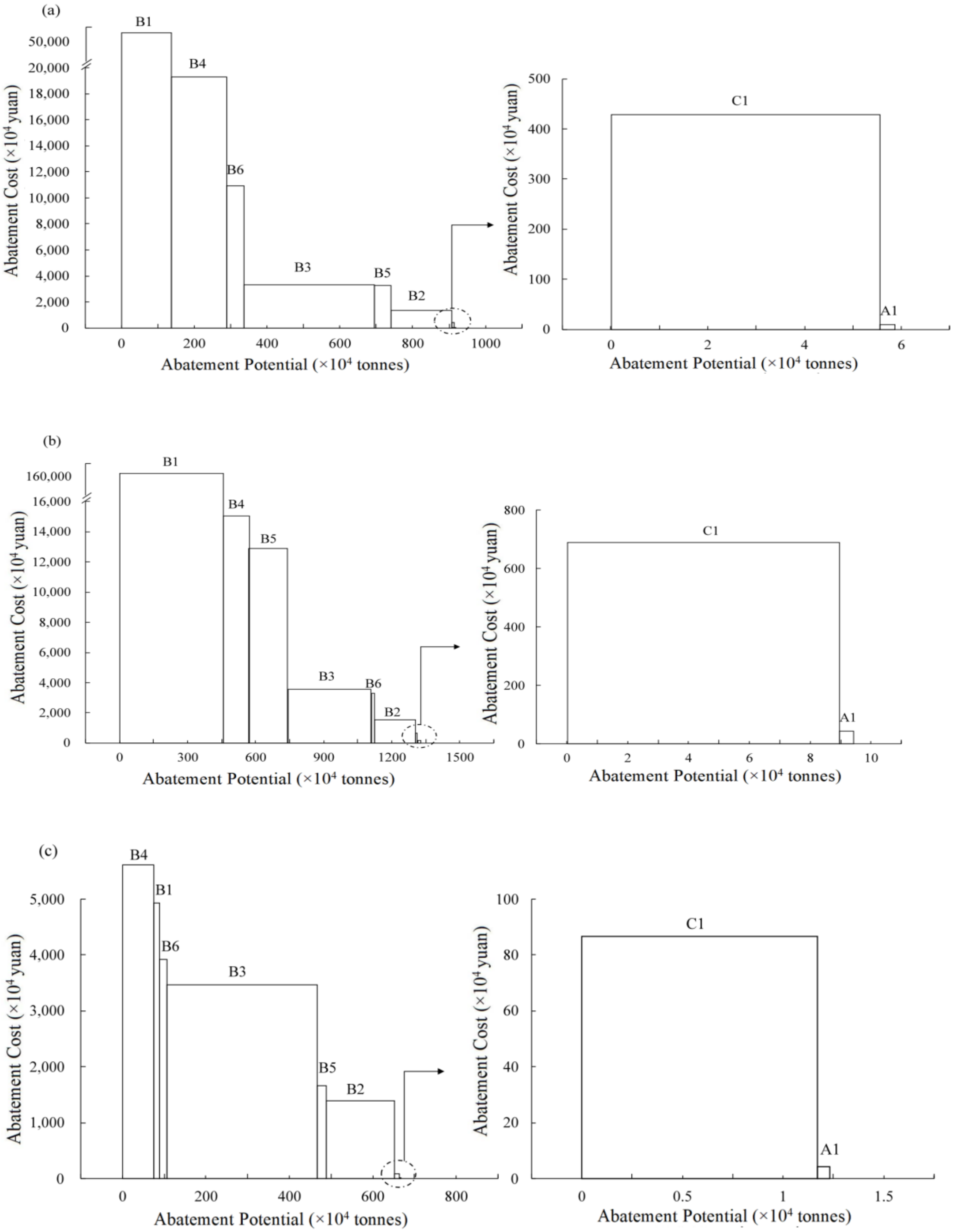

Figure 5: Carbon Reduction Costs and Potential of Low-carbon Technologies in the Copper Industry under Different Scenarios in 2035.

3.2.4 Emission Reduction Contribution of Low-carbon Technologies

Further, this paper analyses the emission reduction contribution of each technology under the three decision-making preferences in 2020-2035, as shown in Figure 6. In 2020, the three technologies with the largest emission reduction contribution have an emission reduction share of 85%. These three technologies are B3, B2 and B1, which are concentrated in the copper smelting stage. Among them, B3 has the largest emission reduction contribution of 41.11 percent. Due to the differences in process, cost and abatement potential of low-carbon technologies, the abatement contribution also changes with time and decision-making preferences. Under the systematic decision-making preference in 2035, the three technologies with the largest emission reduction contributions are B3, B2 and B4, with emission reduction contributions of 39.28%, 18.23% and 16.73%, respectively. The three technologies that contribute the most to the reduction of emissions are B1, B3 and B2, with 34.92%, 27.77% and 13.67%, respectively, under the preference for emission reduction. Under the cost preference, the three most contributing technologies are B3, B2, and B4, with emission reduction contributions of 55.19 per cent, 24.92 per cent, and 11.63 per cent, respectively. Regardless of the decision preference, B3 has a large contribution to emission reduction.

However, some technologies, such as A1 and B6, have a low contribution to emission reduction regardless of the decision preference, and both are less than 5%.The low contribution of A1 is due to the low emission reduction potential of the technology, which is applicable to the stage of copper mining, even though studies have shown that the mining of ores generates a large amount of carbon emissions, due to the resource constraints, China's copper reserves only account for 3.14% of the world's total amount of copper, and the grade is not high, so it can't support the huge demand of the country, which mainly relies on the import of copper. The low contribution of B6 is due to the high unit abatement cost of the technology (more than 200 RMB/tCO_2), which results in a low diffusion rate of the technology. Existing technologies should be further modified or related technologies should be developed to minimise economic costs.

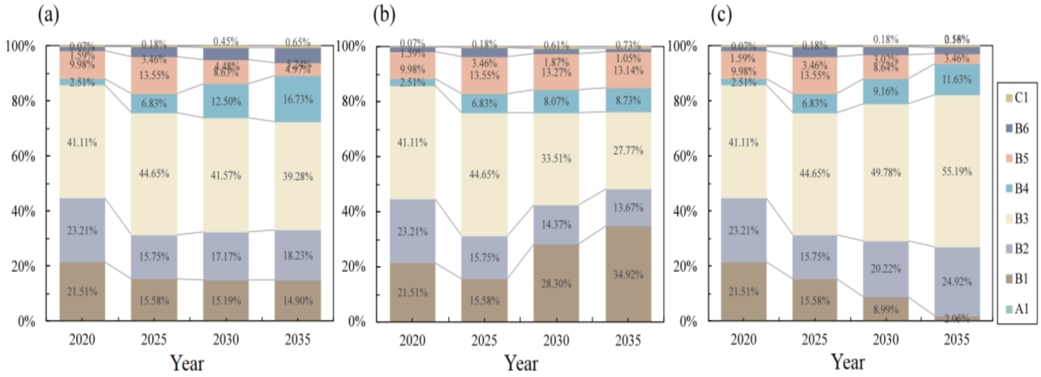

Figure 6: Contribution of CO_2 Reduction of Each Technology under Different Scenarios

4. Conclusion

This study collected eight low-carbon technologies for the Chinese copper industry from policy documents. These technologies include copper mining, smelting and processing. In this paper, a multi-objective model for emission reduction maximisation and cost minimisation was established and calculated using the NSGA-II algorithm. Based on the Pareto optimal solution set, three decision preferences (system preference, emission reduction preference and cost preference) are set, and the optimal diffusion rate of technologies under each preference is obtained using the TOPSIS method. Finally, the abatement potential, abatement cost and abatement contribution rate of each low-carbon technology under each decision preference are calculated for 2020-2035. The main results are as follows: The output of each segment of China's copper industry has become an S-shaped trend, with rapid growth since 2005, slowing down since 2015, stagnant growth near 2019, and approaching the peak of output in 2035, with the output of refined copper at around 12,256,000 tonnes; (2) By 2035, under each of the three decision-making preferences, the promotion rate of B2 and B3 technologies is greater than 75%, with a great advantage in terms of abatement potential and cost, and should be vigorously promoted. have great advantages and should be vigorously promoted; (3) the average unit abatement cost of the eight low-carbon technologies in China's copper industry in 2020 is 99.2 yuan/tCO_2. 1.512 million tonnes of abatement will be achieved in 2020, and the cost will reach 150 million yuan. By 2035, under the systematic decision-making scheme, the emission reduction volume of 9.134 million tonnes and the emission reduction cost of RMB 900 million will be able to achieve an emission reduction of 23%; under the emission reduction preference scheme, the emission reduction volume of 13.134 million tonnes and the emission reduction cost of RMB 2.06 billion will be able to achieve an emission reduction of 33.17%; under the economic cost preference scheme, the emission reduction volume of 6.46 million tonnes and the emission reduction cost of RMB 250 million will be able to achieve an emission reduction of 16.32%; (4) By 2035, under either decision-making preference, B3 has a large contribution to emission reduction, which is greater than 25%.

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