Inter-Provincial Carbon Emission Allocation and Uncertainty in China under the Carbon Peak Target

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Research Article

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Abstract

Based on China's 2030 peak carbon reduction target, allocation schemes under the equity principle, efficiency principle, and a comprehensive balance of both are explored using the input-output model, Zero Sum Game-Data Envelopment Analysis（ZSG-DEA）model, and entropy value method, respectively. Abatement costs of different allocation schemes are compared, and allocations of multiple schemes under different principles and development paths are studied separately, as are uncertainties of multiple allocation options under different principles and development paths. The study shows that abatement costs under the comprehensive scheme are more acceptable to multiple provinces, the results of multi-scheme allocation under different paths are more extreme than the uncertainty of allocation principles, and technological progress under multiple development paths can better facilitate carbon abatement. Carbon allocation policies should balance efficiency and equity, but also consider the impact of various uncertainties. This study provides a methodological reference for inter-provincial carbon emission rights allocation and uncertainty in China.

1 Introduction

To fulfill China's carbon peak target by 2030, the Chinese government has been actively implementing effective emission reduction policies and promoting orderly emission reduction in various regions. Reasonable initial regional carbon allocation is an important element in building a complete and orderly carbon market and achieving the peak carbon target. Currently, China's inter-provincial carbon allocation is facing pressure to reach the carbon peak. Considering all possible allocation results is necessary to better grasp the essential rules and inherent requirements of carbon emissions and make balanced and reasonable allocations. Therefore, the inter-provincial allocation of carbon emission rights in China under the carbon peak target should consider various principles and uncertain outcomes. Our study investigates schemes suitable for the current situation in China and analyzes uncertain allocation outcomes of the carbon peak path.

Domestic and foreign scholars have proposed various research schemes on regional carbon emission rights allocation; however, different allocation subjects and principles lead to different allocation methods, including the historical, input-output, efficiency, and comprehensive methods. The historical method is based on a target regions' emission history over time, calculating the average value of historical emissions, and setting the current emission rights. However, this method tends to ignore carbon transfer between regions, and overestimating the emissions of less-developed regions while underestimating those of developed regions is easy to do, thereby causing unfair distribution (Wang et al., 2016). The equity method is based on inter-regional equity and divides emission responsibilities by calculating carbon transfers between regions (Xia et al., 2018; Fu, 2018; Xing, 2023) or emphasizing egalitarianism in allocating provincial carbon emission allowances (Cheng et al., 2023); however, input-output table preparation is cyclical in China, and results calculated using this method have a certain lag. The efficiency method aims to improve emission reduction efficiency by reducing or increasing different carbon emission units to improve regional emission reduction efficiency values (Lins et al., 2003; Lins, 2008; Liu et al., 2020), in which the concept of a zero-sum game is incorporated into the super-efficient Slack-Based Measure model, and emission reduction efficiency values are improved by the iterative method. The efficiency method improves overall emission reduction efficiency while reducing the incentive to reduce emissions in high-emission regions (Wang & Chen, 2019). Allocation under other principles, such as including the ability to pay (Shao, 2022) and the Brazil-like proposal (Chen et al., 1999), is applicable to the comprehensive allocation of carbon emission rights internationally, but not suitable for inter-provincial carbon emission rights allocation in China because of the allocation target and measurement caliber. An allocation scheme under a single principle may lead to extreme results (Höhne et al., 2014); thus, to more reasonably allocate carbon allowances, multiple demands need to be considered to improve emission reduction efficiency while also ensuring relative equity. The integrated method combines two or more principles using the entropy value method for each principle to achieve more balanced allocation results (Wang et al., 2022; Zhang et al., 2021). Marginal abatement costs vary under different allocation methods (Huang, 2020).

Most of the abovementioned studies are based on allocation under ideal conditions and do not consider carbon emission and allocation uncertainties. Carbon emission uncertainty research has examined the relationships between government policy uncertainty and carbon emissions (Hicham et al., 2023), retailer-driven carbon taxes and inter-provincial allocation of carbon emission allowances in revenue uncertainty carbon emission reduction incentive contracts (Han, 2022). The uncertainty of inter-provincial carbon emission allowance allocation results from the uncertainty of allocation principles and carbon emission paths; however, few domestic scholars focus on the uncertainty of allocation results. The international analysis of carbon emissions and allocation uncertainty is more systematic but not applicable to China's carbon emission allowance allocation. Wang and Chen (2015) preliminarily explored carbon allowance uncertainty in each country for the global 2°C temperature rise target, Zhang et al. (2019) comparatively analyzed price and quantity-based emission reduction policy tools under uncertainty, and Den Elzen et al. (2003) reported carbon allowances in 2020 for each region based on different research findings. However, the abovementioned literature is based on global targets, and while the results of carbon emission allowance allocation by province under China's 2030 carbon peak target will also show uncertainty, few scholars have examined this issue to date.

Based on the above analysis, this study explores different inter-provincial carbon allocation scenarios and compares abatement costs under the 2030 carbon peak target. First, an input-output model is used to explore the equitable allocation scenario, and total provincial emissions are determined by calculating provincial carbon emission coefficients and using them to set the allowance amounts. Second, a ZSG-DEA model is used to examine the efficiency allocation scheme, in which emission reduction efficiency is improved by increasing or decreasing different carbon emissions in each province, and iterations are performed to achieve optimal allocation efficiency. The entropy value method is used for both the equity and efficiency principles to calculate the allocation results under the comprehensive allocation scheme. Finally, the ZSG-SBM super-efficiency model is used to calculate and compare each province's marginal abatement and total costs under different scenarios.

This study explores different allocation schemes under ideal conditions, based on which uncertainties in achieving the carbon peak target in China, (i.e., the uncertainties of allocation principles and multi-scheme allocation under different paths) are discussed. This study's main innovations are as follows. First, Using input-output method to estimate implied carbon emissions in each province. Second, the uncertainties of the inter-provincial carbon emission rights allocation results in China under the carbon peak target and their causes are investigated, including the uncertainties of allocation principles and carbon emission paths leading to the uncertainty of the allocation results. Our study provides a theoretical reference and policy suggestions for the inter-provincial carbon emission rights allocation scheme and related uncertainty in China.

2 Equitable Distribution Scheme Based on the Input-Output Model

2.1 Carbon Emission Coefficient Measurement

This study constructs a basic input-output model for each province in China (Table 1), which is used to estimate the implied and total carbon emissions of different regions. From the perspective of supply and demand responsibility for emissions, a province's total carbon emissions are equal to its direct carbon emissions (actual carbon emissions) plus its implicit carbon emissions, which, without considering foreign trade, are in turn equal to the carbon emissions transferred to the province from other provinces minus the carbon emissions transferred from the province to other provinces. Implied carbon emissions are closely related to the intermediate inputs each province requires; therefore, the input-output method is used to estimate relevant emission factors for each province and set appropriate allowance amounts.

The total carbon emissions of i province are as follows:

$$\mathbf{C_i = C_i^z + \sum_{j=1}^{n} C_{ji} - \sum_{j=1}^{n} C_{ij}} \qquad (1)$$

Where C_i^z means direct carbon emissions for i province, $\sum_{j=1}^{n} C_{ji}$ is the carbon emissions for j province to meet i's provincial production, $\sum_{j=1}^{n} C_{ij}$ is the carbon emissions for j province to meet provincial production, and $\sum_{j=1}^{n} C_{ji}$ and $\sum_{j=1}^{n} C_{ij}$ are collectively the implicit carbon emissions. Because this portion of $\sum_{j=1}^{n} C_{ji}$ carbon emissions is generated outside the province and due to i's provincial demand, the responsibility for this portion of emissions should be assigned to i province based on an equity perspective. Similarly, this part of $\sum_{j=1}^{n} C_{ij}$ carbon emissions is generated by i province to meet the demand of other provinces; therefore, this part should be recorded as the emission responsibility of other province.

Table 1

Input-Output Table.

Input Output	Intermediate			Final demand			Exports	Total output	Carbon allowances
Intermediate	Z_{11}	$\cdots$	Z_{1n}	F_{11}	$\cdots$	F_{1n}	E_1	X_1	K_1
	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
	Z_{n1}	$\cdots$	Z_{nn}	F_{n1}	$\cdots$	F_{nn}	E_n	X_n	K_n
Imports	M_1	$\cdots$	M_n						
Value added	V_1	$\cdots$	V_n						
Total output	X_1	$\cdots$	X_n						
Total carbon emissions	C_1	$\cdots$	C_n						

Dividing X_i by both sides of Eq. (1) simultaneously yields:

$$\frac{C_i}{X_i} = \frac{C_i^z}{X_i} + \frac{\sum_{j=1}^{n} C_{ji} - \sum_{j=1}^{n} C_{ij}}{X_i} \tag{2}$$

Where $\gamma_i = \frac{C_i}{X_i}$, γ_i *is* the integrated carbon emission factor of i province (Zhihong Fu 2018), and the composed matrix is C. $\alpha_i = \frac{C_i^z}{X_i}$ is the direct carbon emission factor of i province, and the composed matrix is A. $\beta_{ij} = \frac{X_{ij}}{X_i}$ *and* $\beta_{ji} = \frac{X_{ji}}{X_i}$ are the provincial consumption coefficient and other provincial consumption coefficients, respectively, and the composed matrices are B_{ij} *and* B_{ji}. Then, Eq. (3) can be obtained as follows:

$$\mathbf{C} = \mathbf{A} + (\mathbf{CB_{ji}} - \mathbf{CB_{ij}}) \tag{3}$$

The rectification can be obtained by:

$$\mathbf{C} = \mathbf{A}[\mathbf{I} - (\mathbf{B_{ji}} - \mathbf{B_{ij}})]^{-1} \tag{4}$$

Let $B = B_{ji} - B_{ij}$, and B be the matrix of the net inter-provincial trade outflow coefficients. Written in the general form, the Lyontief matrix is:

$$\mathbf{C} = \mathbf{A}(\mathbf{I} - \mathbf{B})^{-1} \tag{5}$$

Compared with the generalized Leontief matrix, Eq. (4) has more consumption coefficient matrices B_{ij} for other provinces. Eq. (4) is the complete integrated carbon emission factor matrix.

2.2 Carbon Allowance Factor Setting

The carbon allowance coefficient refers to the government setting a suitable allowance ratio according to the total or direct emissions of each province, that is, the ratio of controlled emissions to total emissions (direct emissions), such that it can ensure normal production and emission reduction in each province. However, setting the allowance ratio based on a region's direct carbon emissions is prone toward overestimating the carbon emissions of less-developed regions and underestimating the carbon emissions of developed regions. Thus, to set a reasonable allowance ratio, the implied carbon emissions of each region must be considered and set based on the province's total carbon emissions.

If the allowance factor is k, the carbon allowance is as follows:

$$\mathbf{K} = \boldsymbol{\theta}\mathbf{C} = \boldsymbol{\theta}\mathbf{A}[\mathbf{I} - (\mathbf{B_{ji}} - \mathbf{B_{ij}})]^{-1} = \boldsymbol{\theta}\mathbf{A}(\mathbf{I} - \mathbf{B})^{-1} \quad (6)$$

Where $\theta = (k_1, k_2, \ldots, k_n)$ is the vector of allowance coefficients for each province. The size of the quota coefficient reflects the control strength of carbon emissions in the province, and is related to the province's total carbon emissions and total emission reduction target. Although the quota coefficient cannot accurately allocate a province's needs, it does reflect the fairness of carbon emission allocation to a certain extent.

2.3 Data and Empirical Analysis

This study uses panel data from 30 provinces (excluding Tibet) from the China Carbon Emissions Database from 2005 to 2019, and data on national and provincial carbon emission targets from selected sectors from the 2017 China Multi-Regional Input-Output Table and China Carbon Peaking and Carbon Neutral Strategies and Pathways (2022), released by the Chinese Academy of Engineering. For data processing, data from 42 sectors across 30 provinces in China are uniformly used. To avoid double counting, data from inter-provincial input-output tables are diagonalized, emission data from major industries in recent years are compared and screened (mainly high-emission industries, such as electricity, petrochemicals, and smelting), trade coefficient matrices are estimated for each province, and intermediate consumption matrices for each province are collated to obtain a uniform numerical matrix.

The petrochemical, chemical, building materials, iron and steel, non-ferrous metals, paper, electric power, and aviation industries are the main research objects in the input-output table. The inter-provincial flow of trade refers to the flow of products between provinces, while the net inter-provincial trade outflow refers to the difference between the trade outflow and inflow in a province, and the coefficient matrix is the net inter-provincial trade outflow coefficient matrix. Table 2 shows the direct and total emission coefficients for each province. The total emissions coefficient includes implied carbon emissions; therefore, the results differ from the direct emission coefficient. In terms of numerical size, although Beijing, Tianjin, and Shanghai have more carbon emissions, their large GDP bases result in smaller carbon emission coefficients. Inner Mongolia, Xinjiang, and Ningxia have less carbon emissions, however, their small GDP bases lead to larger emission coefficients. In terms of the responsibility of emission supply and demand, as the demand side of intermediate inputs, economically developed regions such as Beijing, Shanghai, Jiangsu, and Guangdong have higher total emission coefficients than actual emission coefficients, and therefore must bear more responsibility and obtain fewer allowances. Less economically developed regions such as Shanxi, Shandong, and Guangxi have higher total carbon emission coefficients than actual emission coefficients because they have taken over the industrial transfer from north China, Shanghai, and Guangzhou, and as the supply side of intermediate goods. The total carbon emission factor is lower than the actual emission factor; therefore, the responsibility should be reduced and the allowance amounts increased. China's carbon peak target is approximately 12.2 billion tons, and taking 2017 as the base year, the overall emission growth rate should be controlled at less than 1.41% annually to ensure that the target can be achieved by 2030. Therefore, setting a reasonable allowance factor is key to achieving the carbon peak target.

Table 2

arbon Emission Factors by Province. (million tons/billion yuan)

Order	Province	Direct emission factor	Total carbon emission	Order	Province	Direct emission factor	Total carbon emission

1	Beijing	0.3054	0.4408	16	Henan	1.1264	0.407
2	Tianjin	0.7763	0.6748	17	Hubei	0.9347	1.259
3	Hebei	2.3292	2.4059	18	Hunan	0.9547	0.9948
4	Shanxi	3.2752	2.876	19	Guangdong	0.6208	0.6816
5	Inner Mongolia	4.0808	4.007	20	Guangxi	1.2303	1.0292
6	Liaoning	2.1224	2.2058	21	Hainan	0.9447	0.4899
7	Jilin	1.3673	1.1990	22	Chongqing	0.8266	1.1439
8	Heilongjiang	1.7413	1.6768	23	Sichuan	0.8622	0.9275
9	Shanghai	0.6403	0.7161	24	Guizhou	1.9029	1.8553
10	Jiangsu	0.8826	0.9310	25	Yunnan	1.2152	1.3983
11	Zhejiang	0.7429	1.0911	26	Shaanxi	1.2513	1.2861
12	Anhui	1.4147	1.3927	27	Gansu	2.037	1.9886
13	Fujian	0.7302	0.6607	28	Qinghai	2.0377	2.113
14	Jiangxi	1.1445	1.2026	29	Ningxia	5.1872	5.3447
15	Shandong	1.1507	1.0828	30	Xinjiang	3.7471	3.5926

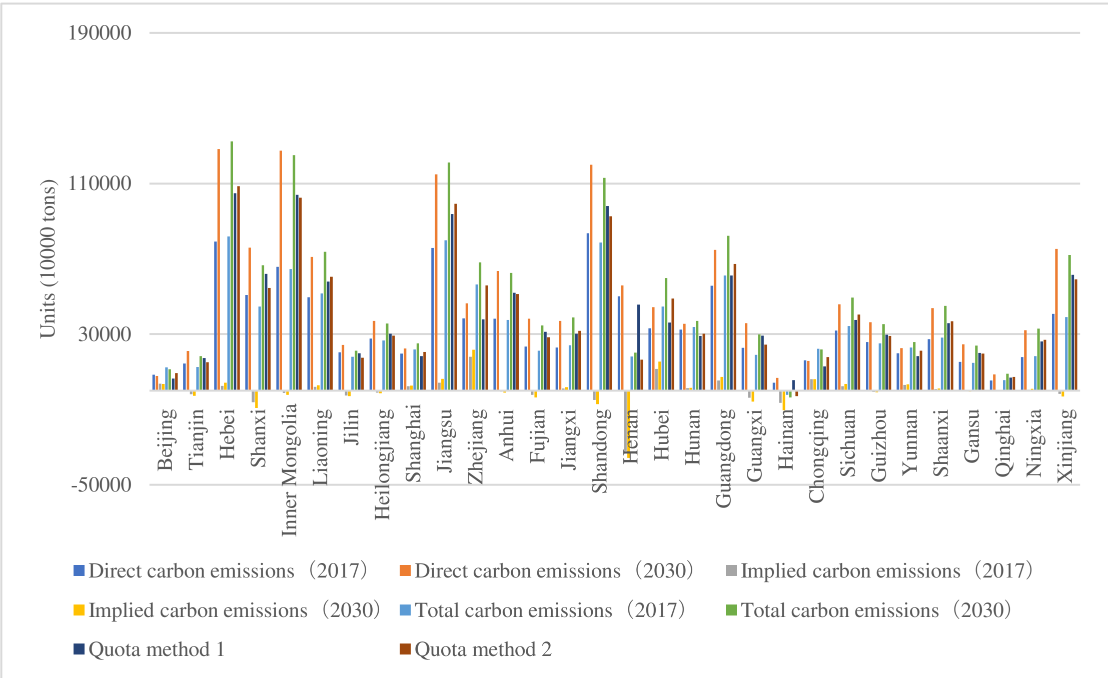


Fig. 1. Carbon Emissions and Control Emissions by Province in 2017 and 2030.

The quota factor is the ratio of allowance amounts to total carbon emissions. Based on the carbon emission factor and carbon transfer ratio in 2017, this study estimates carbon emissions and carbon emission control in 2030, and calculates two quota methods for 2030 (Fig. 1). In terms of implied carbon emissions, the implied carbon emissions of Beijing, Hebei, Liaoning, Shanghai, Zhejiang, Jiangxi, and Hubei are positive, indicating that these regions have transferred some of their carbon emissions to other provinces, while the implied carbon emissions of other regions, such as Tianjin, Shanxi, Jilin, Heilongjiang, Fujian, Shandong, and Henan, are negative, indicating that Henan has the most implied carbon emissions because of the transfer of carbon emissions from other regions. This is because Henan is densely populated and has a low economic development level which, coupled with the transfer of industries from other provinces, results in a large amount of implied carbon emissions. Compared with 2017, the total carbon emissions of Beijing and Chongqing are less than 2030, indicating that they will reach the carbon peak by 2030 and can achieve negative carbon emissions growth, while other regions such as Shanghai and Zhejiang, excluding transferred implied carbon emissions, have the same total and direct carbon emissions, indicating that these regions can reasonably control local carbon emissions.

Quota Methods 1 and 2 are carbon allowances obtained from direct and total carbon emissions in 2030, respectively. The results of the two allowance methods show that, although both methods in Beijing, Shanghai, Jiangsu, Zhejiang, Guangdong, and Hainan are less than the total carbon emissions in the region, the allowance amount under Allowance Method 1 is comparatively smaller, and its emission control is more stringent than that of Allowance Method 2. Some geographical areas rely on the emission standards of Allowance Method 1 to maintain normal province-level socioeconomic development. Other regions, such as Tianjin, Shanxi, Henan, Fujian, and Guangxi, have higher carbon quotas under Quota Law 1 than Quota Law 2, whereas in some provinces, such as Henan, the allocated carbon quotas even appear to be more in supply than demand, indicating that Quota Law 1 is insufficiently strong to punish some high-emission provinces. This is highly likely to cause confusion in the carbon trading market and make it difficult to control carbon emissions in these regions; thus, compared with Quota Law 1, Quota Law 2 is fairer and more reasonable than Allowance Law 1. Therefore, carbon emission reduction policies should consider not only each region's actual carbon emissions but also other comprehensive factors, such as implied carbon emissions and economic development, to promote more equitable carbon allocation.

3 Efficiency Allocation Scheme Based on the ZSG-SBM Model

3.1 ZSG-DEA Model with Non-desired Outputs

The SBM model with non-expected outputs can be used to address the input-output efficiency measurement problem of multiple comparable decision units. In this study, the set of decision units is used to represent the 30 provinces of China (excluding Tibet), $j = 1,2,\dots,30$ to represent j province, $i = 1,2,\dots,q$ to represent the existence of the q type of input factors, $r_1 = 1,2,\dots,m$ to represent m type of desired outputs, and $r_2 = 1,2,\dots,n$ to represent n type of non-desired outputs. Let the actual input set $X = \{x_{ij}\}$, where $c_{r_2 j} \in \mathbb{R}^{n\times 30}$, the desired output set $Y = \{y_{r_1 j}\}$, where $y_{r_1 j} \in \mathbb{R}^{m\times 30}$, the non-desired output set $Z = \{c_{r_2 j}\}$, where $c_{r_2 j} \in \mathbb{R}^{n\times 30}$, the non-desired output set Z is known to be the set of carbon dioxide, nitrogen, and other emissions.

Lins et al. (2003) and Wang et al. (2022) added the concept of a Zero-Sum Game when studying the efficiency evaluation method, and the basic research idea is that, under the condition that the total amount of carbon emissions is determined, each decision unit continuously reduces carbon emissions and thus increases the efficiency value through the game, before finally reaching the optimal state. This is reflected in the model through continuous adjustment of the non-desired output $c_{r_2 j}$ slack variable S_2^-.

The DMU indicators with zero-sum games are constructed as follows:

$$\min \boldsymbol{\rho}^* = \boldsymbol{h} = \frac{\boldsymbol{c_{r_2 j} - S_2^-}}{\boldsymbol{c_{r_2 j}}}$$

$$\mathbf{s.t.}\begin{cases} \sum_{j=1}^{30}\lambda_j x_{ij} + S^{+} = x_{ij}^{*} \\ \sum_{j=1}^{30}\lambda_j\, y_{r_1 j} - S_1^{-} = y_{r_1 j}^{*} \\ \sum_{j=1}^{30}\lambda_j\, c_{r_2 j} = hc_{r_2 j}^{*} \\ \sum_{j=1}^{30}\lambda_j = 1 \\ S^{+}, S_1^{-}, S_2^{-}, \lambda_j \geq 0 \end{cases} \tag{7}$$

Where S^{+}, S_1^{-}, S_2^{-} are slack variables, and λ_j is a non-negative vector, in which $(\rho^{*}, S_{+}^{*}, S_1^{*}, S_2^{*})$ can be solved optimally by linear programming.

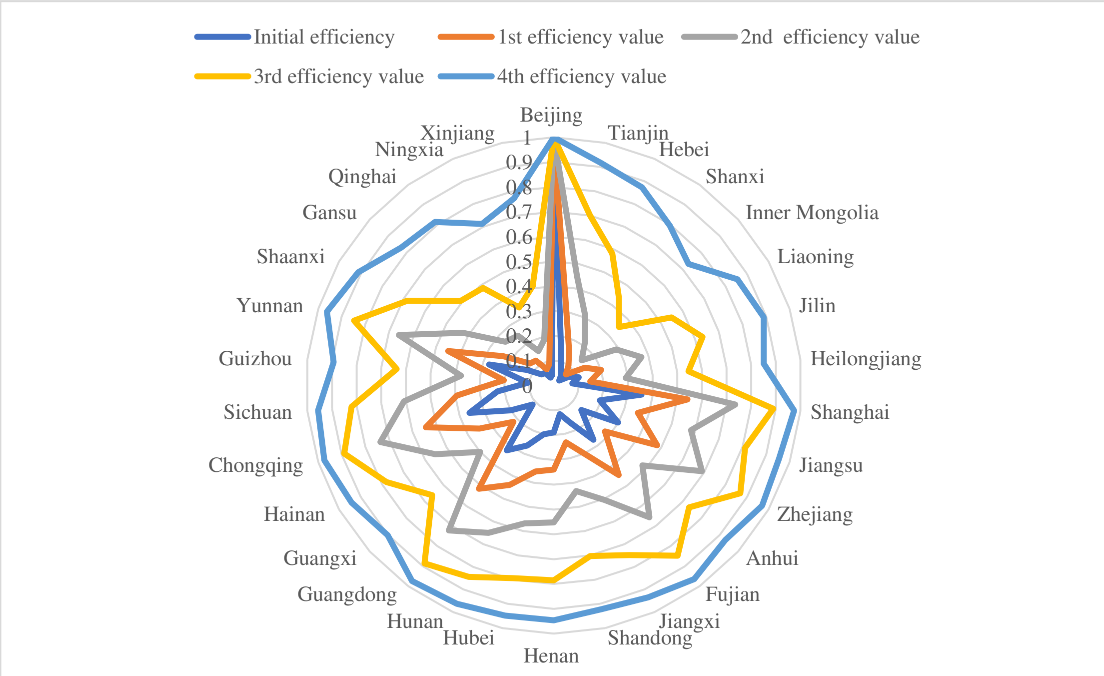
Provinces achieve efficiency improvement by continuously reducing emissions, and according to the idea of zero-sum game DEA, when the energy use rights and carbon emission rights of one province increase, other provinces must reduce the same amount of energy use rights and carbon emission rights to keep the total amount constant. The carbon emission rights were reallocated according to Lins(2008) et al. The allocation formula is as follows:

$$\mu_m' = \mu_m - \mu_m\left(1 - \varphi_\mu^m\right) + \sum_{i\neq n}\frac{\mu_m\left(1-\varphi_\mu^i\right)\mu_i}{\sum_{n=1,n\neq i}^{N}\mu_n} = \mu_m\varphi_\mu^m + \sum_{i\neq n}\frac{\mu_m\left(1-\varphi_\mu^i\right)\mu_i}{\sum_{n=1,n\neq i}^{N}\mu_n} \tag{8}$$

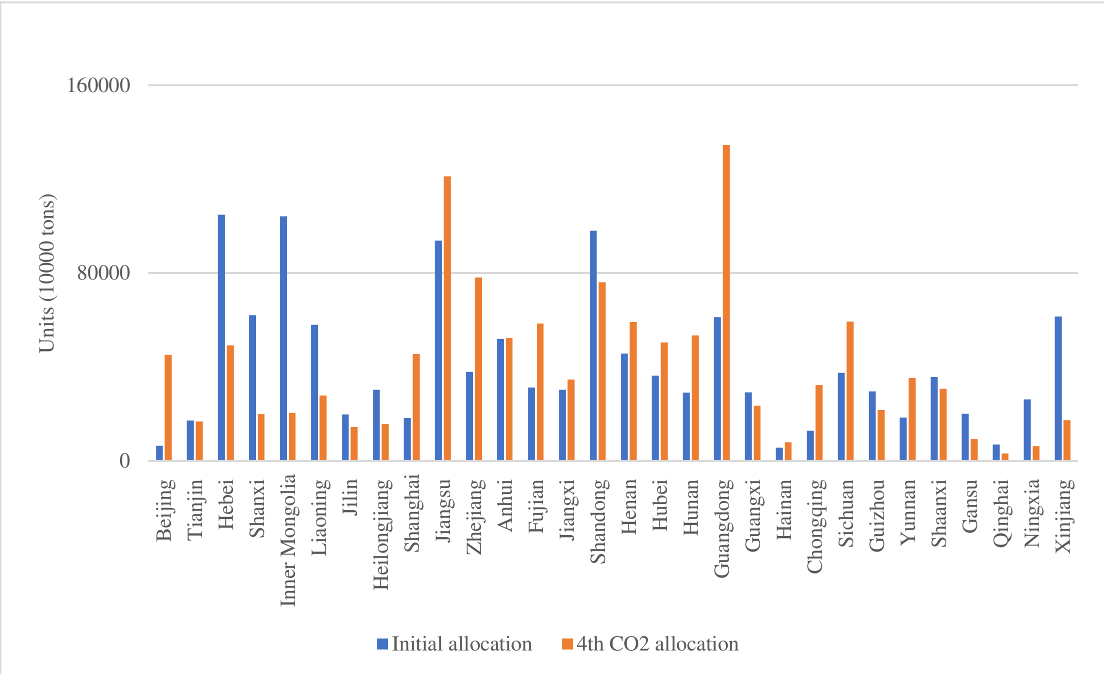
μ_m' that is, the carbon emission allowances allocated to *m* province. In this model, one adjustment generally cannot reach zero, and the DEA is effective and must be solved iteratively until all provinces reach the maximum efficiency value.

(ii) Data and empirical analysis

In this study, 30 Chinese provinces (excluding Tibet) are used as DMU indicators. To obtain a clearer value of carbon allocation efficiency, the coefficient of the efficiency variable (i.e., carbon emissions) is set to 1 in this paper to avoid confusion with other variables. Panel data on each provinces' GDP from 2000 to 2020 are used to calculate each province's average growth rate, from which the expected output data for 2030 are obtained. The input variables are labor *L* and capital *K*. The labor indicator is selected from the employed population of each province from 2005 to 2020, and its average growth rate is calculated to obtain the labor input data. The calculation results based on the ZSG-DEA method are shown in Fig. 2 and Fig. 3.



264 **Fig. 2.** Comparison of efficiency values.



265 **Fig. 3.** Initial allocation and redistribution under efficiency schemes.

266 Beijing has the highest efficiency value under the initial efficiency results, which is mainly
267 influenced by the demonstration role of the capital, industrial transfer and construction of
268 Xiong'an New Area. The efficiency values of regions such as Shanghai, Guangdong, and
269 Chongqing are slightly higher than those of other provinces because of the relatively higher
270 economic and technological development, energy utilization efficiency, and pollutant treatment
271 efficiency compared with other provinces. Some provinces in the northeast, mid-west, and west
272 have more room for efficiency improvement and can continuously improve carbon quota
273 utilization efficiency by introducing technologies from developed and other places and

reducing carbon quotas. Compared with Wang & Chen(2019), the initial efficiency values obtained from this study's calculations are generally lower, likely because of two reasons. First, this study is based on the 12.2 billion tons of emissions under the target peak of 12.2 billion tons in China's Carbon Reaching Carbon Neutral Strategy and Pathway (2022) released by the Chinese Academy of Engineering, which is lower than the peak in other literature; thus, more room exists for improving carbon emission efficiency nationwide. However, some problems remain with policy implementation, industrial transfer, and upgrading.

To obtain more realistic calculation results, four iterations of the efficiency values for each province are conducted instead of finding the maximum efficiency value for each province because the carbon peak target is near, and maximizing all provinces' emission efficiency in the short term is impossible. The results of the iterations show that efficiency values have significantly improved in 30 provincial regions. Other regions, such as Tianjin, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, and Guangdong, have been able to approach the frontier of efficiency values by virtue of their economic and technological advantages, while the central and western regions have some room for efficiency improvement because of their low economic and technological development levels. In terms of final carbon allocation, Guangdong has the highest quota because of its large economic volume and labor-capital intensive factors. Economically developed regions, such as the eastern and southeastern regions, have high economic demand and must increase their allocated quotas to improve efficiency, whereas less economically developed regions, such as Hebei, Shanxi, Inner Mongolia, Heilongjiang, and the western regions, need to improve efficiency, and therefore must reduce their allocated amounts.

4 Integrated Allocation Scheme Based on the Entropy Value Method

Both the equity and efficiency schemes are carbon allocation methods under a single principle, whereas inter-provincial carbon allocation under the carbon peak target requires both equity and efficiency; therefore, the allocation scheme must consider multiple principles. The comprehensive allocation scheme uses the entropy value method to assign weights to different allocation principles separately and integrates multiple indicators. Entropy value is a measure used to judge the degree of dispersion of indicators; the smaller the entropy value of indicators, the greater the degree of dispersion. The entropy value method is used to judge the degree of dispersion of indicators according to the size of the information in the indicator observation value. Calculate the weight of indicators j as $W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$; the larger the weight, the greater the influence of the indicator on the comprehensive evaluation.

Combining the allocation results of the first two schemes, the entropy value method is used to calculate the weights of the two indicators of equity and efficiency as 0.504 and 0.496, respectively; thus, carbon allocation under the comprehensive method is $CO_{2Comp} = 0.504CO_{2Fair} + 0.496CO_{2Eff}$. Fig. 4 shows the results of the three allocation schemes. Under the integrated allocation scheme, Jiangsu and Guangdong are allocated more than 1 billion tons; however, emissions are reduced by 100–400 million tons compared with the efficiency scheme. Other provinces, such as Shandong, Inner Mongolia, and Hebei, are allocated between 600–900 million tons, which is a 100–400 million ton reduction compared with allocation under the equity scheme. The quota results under the integrated scheme fall between those of the equity and efficiency schemes, indicating that the former considers both equity and efficiency.

Under the three allocation schemes, the most carbon is allocated to the eastern regions, such as Jiangsu and Guangdong, because these provinces have strong economies, large populations, and high development potential, which results in high carbon emissions and, therefore, more emission rights. Less economically developed regions, such as the central and western and some southern regions, have low population density and economic development levels; thus, they receive less carbon allocation. The most economically developed and least developed provinces have different results under the equity and efficiency scenarios. The rationale is that, if improving emission reduction efficiency is considered, economically developed regions need to increase carbon emissions while less developed regions need to reduce carbon emissions, and considering the principle of equity requires controlling emissions in some developed regions while increasing emissions in less developed regions, and the two different principles lead to obvious differences in allocation results. Other regions, such as Jilin, Guangxi, and Hainan, have smaller changes in carbon allocation because these regions have lower economic development levels and lower population densities than the eastern regions. Therefore, they are less influenced by the allocation scheme, and the allocation results are more stable.

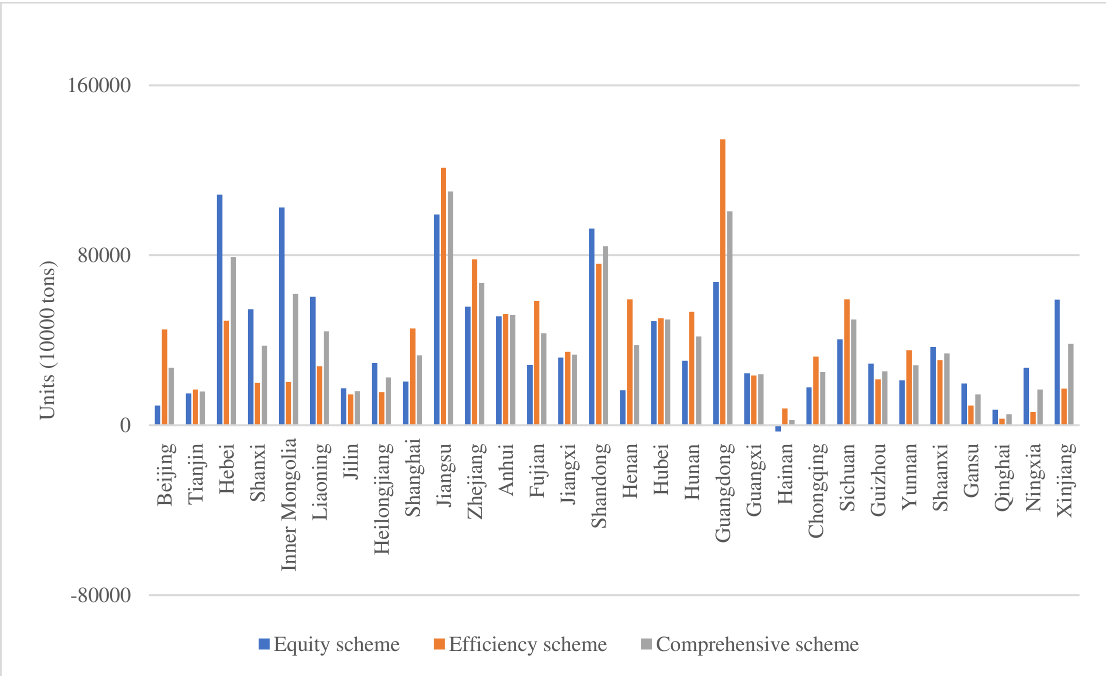


Fig. 4. Carbon Quotas under the Three Allocation Schemes.

5 Comparison of Abatement Costs for Three Options

5.1 Calculation of Abatement Costs

An important way to measure carbon emission allocation options is to compare future abatement costs (Pan et al., 2014). Carbon abatement costs are the cost of reducing carbon emissions, marginal carbon emission costs are the costs consumed to reduce one unit of carbon emissions, and total carbon emission cost is the total cost required to reach the emission reduction target. The design of China's allocation scheme under the peak carbon target must minimize abatement costs as much as possible to achieve the abatement target. Carbon emission reduction costs can be accounted for in various ways, of which the most common is calculating the shadow price of carbon emissions. We use the SBM-DEA method to measure the shadow price under profit maximization. The basic model framework is shown in Eq. (9):

$$\max.\pi = \sum_{j=1}^{m} p_{r_{1j}} y_{r_{1j}} - \sum_{j=1}^{q} p_{r_2 j} x_{ij} - \sum_{j=1}^{n} p_{3j} c_{r_3 j}$$

$$s.t.\begin{cases} \pi \le 0 \\ p_{r_{1j}} \ge \frac{1+\pi}{m+n}\left(\frac{1}{y_{r_1 j}}\right) \\ p_{r_2 j} \ge \frac{1}{q}\left(\frac{1}{x_{ij}}\right) \\ p_{r_3 j} \ge \frac{1+\pi}{m+n}\left(\frac{1}{c_{r_3 j}}\right) \end{cases} \qquad (9)$$

Where π is the expected profit; $p_{r_{1j}}$、$p_{r_2 j}$、$p_{r_3 j}$ are the shadow prices of expected output, input factors, and non-expected output, respectively; the marginal abatement cost is calculated using Roy's constant equation as follows:

$$MC_j = -r_{yj}\frac{p_{r_{1j}}}{p_{r_3 j}} \qquad (10)$$

r_{yj} is the market price of output, referring to the studies of Wang et al. (2019) and Yan et al. (2020), which r_{yj} will be set to 1:

$$MC_j = -\frac{p_{r_{1j}}}{p_{r_3 j}} \qquad (11)$$

Therefore, the total cost in *j* region is obtained as follows:

$$TC_j = \sum(C_1 - C_2)MC_j \qquad (12)$$

Where C_1 is the actual carbon emissions, C_2 is the allowance amount, and the total carbon emission reduction of j region is the difference between the actual carbon emissions and the allowance amount. Thus, a region's total emission reduction cost can be calculated.

5.2 Cost Comparison of the Three Allocation Schemes

Fig. 5 and Fig. 6 shows the results of comparing the marginal and total costs of each province under the three allocation methods.

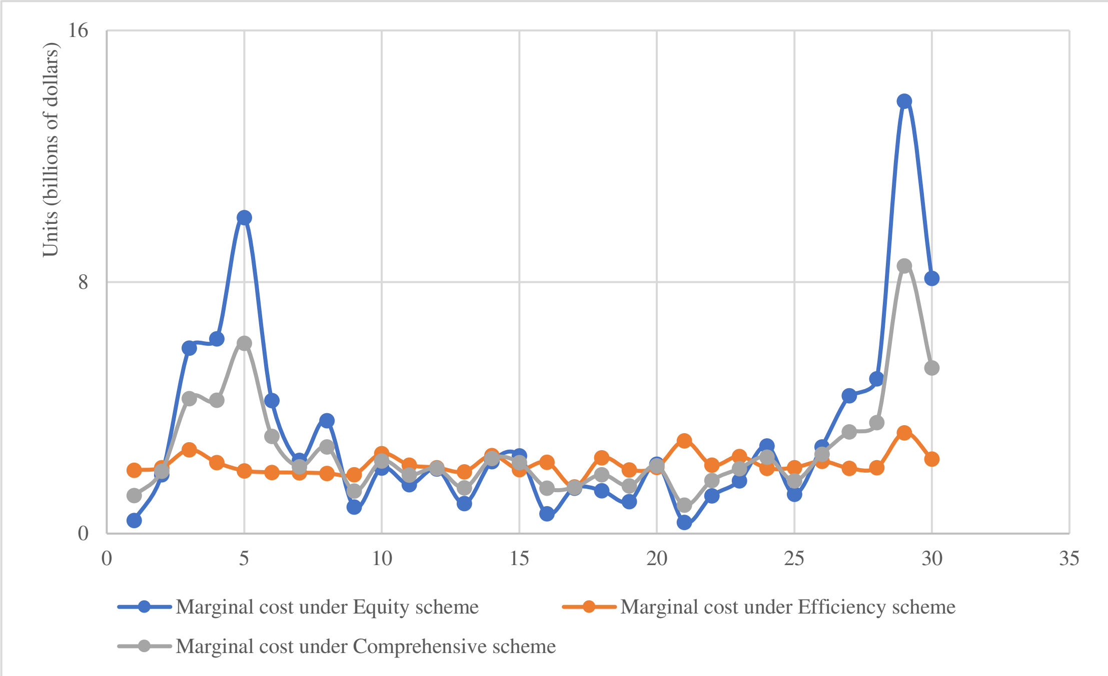


Fig. 5. marginal costs of each province under the three allocation methods.

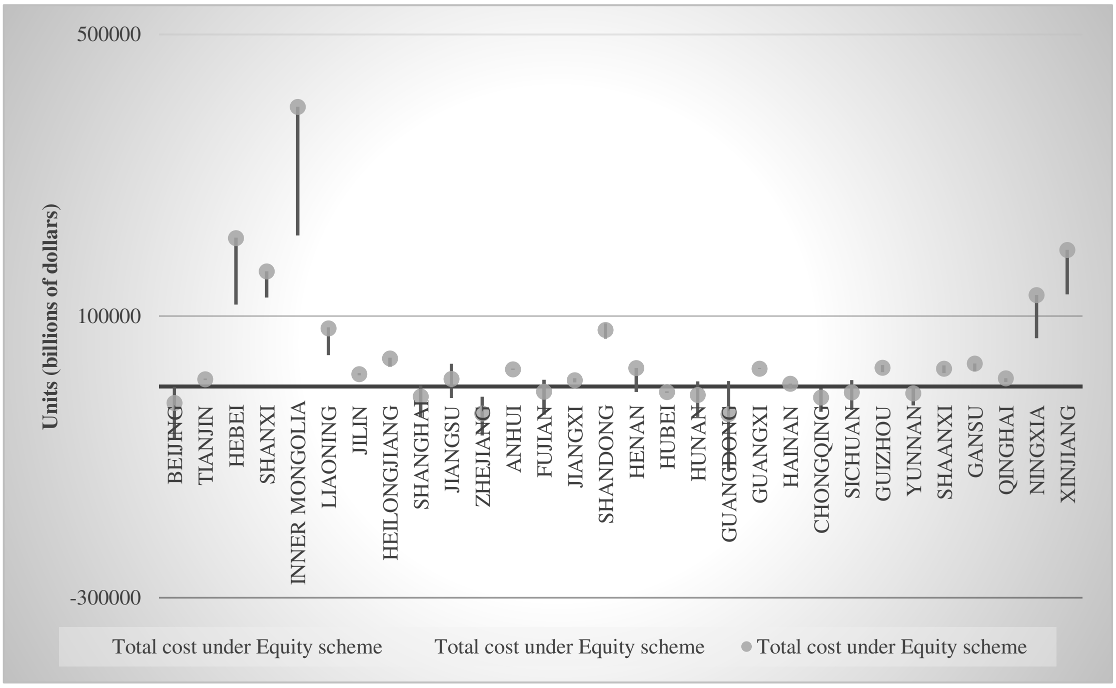


Fig. 6. Total costs of each province under the three allocation methods.

The marginal abatement and total costs are smaller in some eastern provinces under the equity scheme because of these regions' high economic development and technology levels. Thus, the pressure to reduce emissions is lower, while the marginal abatement costs are lower and the total costs are higher in other regions, such as Henan and Shandong, because of the high total amount of carbon emissions in the province and the government's encouragement to reduce emissions. The efficiency scheme promotes carbon price market integration among provinces, and the marginal abatement cost is more balanced than the fairness scheme.

Therefore, most of the more economically developed provinces gain abatement benefits, whereas some of the less-developed regions with higher carbon emissions have to pay a high price to reach the abatement efficiency value, leading to higher the total abatement costs. Comparing the three scenarios, the equity scenario can reduce total emission reduction costs in most provinces, but is difficult to accept because the marginal cost difference between provinces is too large, and the marginal emission reduction cost under the efficiency scenario is more balanced. However, achieving efficiency worthy of improvement requires increased investment in emission reduction, which is difficult to achieve for less economically developed regions. The comprehensive scheme not only reduces regional differences in marginal costs to a certain extent but also enables most provinces to reduce their abatement costs.

6 Uncertainty of Allocation Results

China has set the overall goal of peak carbon emissions by 2030, and while all provinces are working toward this goal, the allocation results of inter-provincial carbon emission rights in China are uncertain because of the diversity of carbon emission allocation principles and different long-term trends and paths of carbon emission drivers, resulting in variable carbon emission development paths. Therefore, this study focuses on two aspects of carbon emission allocation principles and development paths. First, the uncertainty of carbon allocation results due to different allocation principles under ideal conditions is explored. Second, by decomposing carbon emission drivers and setting different development scenarios to predict peak paths and peaks, and finally, by comparing and analyzing the uncertainty results of different allocation principles, different paths, and multiple scenarios under different paths, certain suggestions are provided for carbon allocation in different regions of China.

6.1 Uncertainty of Inter-Provincial Carbon Emission Rights Allocation in China under Different Allocation Principles

This study examines the uncertainty under different allocation principles (Fig. 7), and the results show that the standard deviation is larger in Beijing, Shanghai, Guangdong, and Fujian because the economic volume and emission demand in these regions are large, and the consideration of improving emission reduction efficiency requires increasing carbon emissions. However, under the principle of equity, these provinces and regions transfer a large portion of their carbon emissions to less economically developed regions, the main methods of which include industrial transfer and inter-provincial trade. The opposite is true for the large standard deviations in Hebei, Henan, Shanxi, Inner Mongolia, Yunnan, and Xinjiang. In terms of equity, considering the regional transfer of carbon emissions, these provinces should relax their emission standards because they include carbon transfer from economically developed regions; however, the standard deviation caused by different scenarios is also large because they need to reduce carbon emissions to improve emission reduction efficiency. Further, Tianjin, Jilin, Anhui, and Guangxi have smaller standard deviations, indicating that they are less affected by the uncertainty of the allocation principle and the allocation results are more stable. This indicates that the uncertainty of allocation principles affects regions differently, and provinces with larger standard deviations should be the focus when implementing different carbon emission allocation schemes.

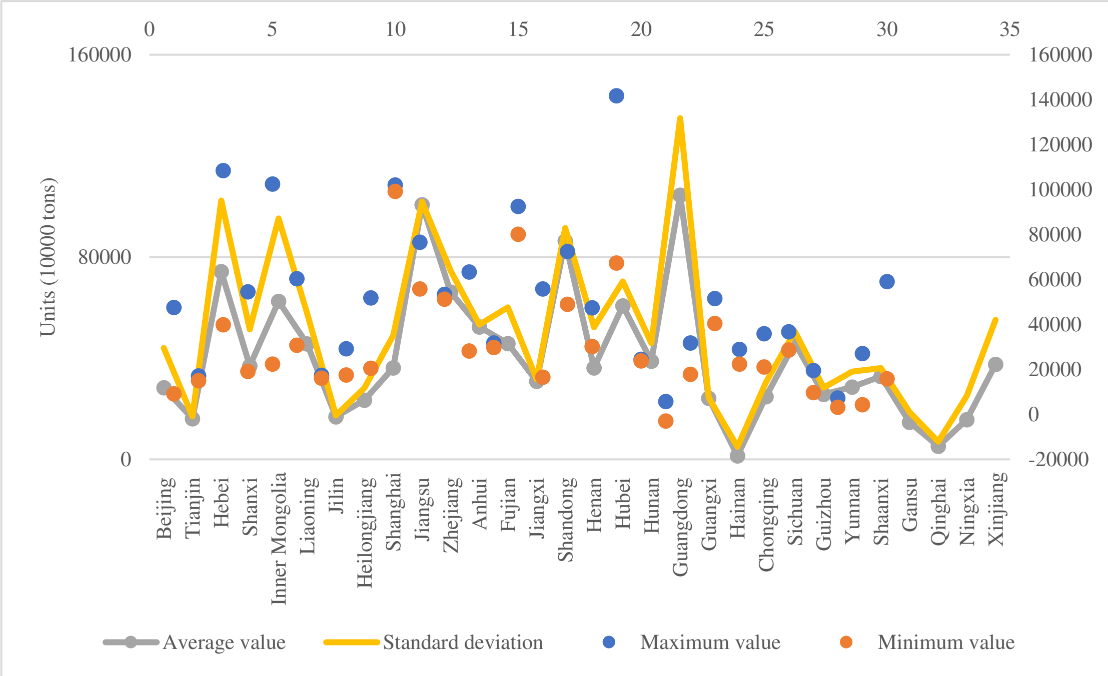


Fig. 7. Uncertainty of Different Allocation Principles.

6.2 Uncertainty of the Results of Inter-Provincial Carbon Emission Rights Allocation in China under Different Carbon Peaking Paths

In addition to the uncertainty of the allocation principle, uncertainty exists in the path to peak carbon achievement in China. China's carbon emissions are unevenly distributed in time and space with a variable growth rate; therefore, forecasting carbon emissions in different provinces is difficult. The factors affecting carbon emissions are complex and variable.

6.2.1 *Decomposition of Factors Influencing Carbon Emissions in China*

Referring to Shao et al. (2016), the factor decomposition method is adopted to decompose the important influencing factors of carbon emissions. Among the various driving factors of carbon emissions, the main influencing factors are fixed asset investment, investment efficiency, energy intensity, and energy carbon intensity. The factor decomposition of carbon emissions is as follows:

$$\mathbf{CE = I \times \frac{CE}{I} = I \times \frac{GV}{I} \times \frac{E}{GV} \times \frac{CE}{E}} \qquad (13)$$

Where GV is value added and E is energy consumption; CE, I, $\frac{GV}{I}$, $\frac{E}{GV}$, $\frac{CE}{E}$ are carbon emissions, fixed asset investment, investment efficiency, energy intensity and energy carbon intensity, respectively; and their annual rates of change are ω, α, β, δ, φ. Then, the rate of change of carbon emissions can be expressed as follows:

$$\boldsymbol{\omega = (1+\alpha)(1+\beta)(1+\delta)(1+\varphi)} \qquad (14)$$

In the past, the main source of China's economic growth was large-scale infrastructure construction; however, that rough and high-energy-consuming development model also produced a large amount of carbon emissions. Therefore, fixed asset investment growth is an important reason for generating a large amount of carbon emissions. Investment efficiency measures the return of fixed asset investment, and a decrease in investment efficiency causes an increase in fixed asset investment and a decrease in resource utilization efficiency. Energy intensity and carbon intensity measure the energy utilization effects and carbon emission share, respectively. Eq. (14) explains the main drivers of carbon emissions in China, and the influencing factors of carbon emissions in China can be decomposed into the above four.

6.2.2 Different Peaking Paths of Carbon Emissions in China

The baseline scenario is set according to the inertia of the development of each factor, the green development scenario is set according to the policy requirements of ecological sustainable development in China, and the technological progress scenario is not only set according to the requirements of emission reduction policy and environmental sustainable development but also contains the technological upgrading factor, which requires certain breakthroughs in technological innovation for emission reduction and new energy utilization. The following three scenarios set in this study are generally in line with the possible carbon emission development in China.

In the baseline scenario, fixed asset investment is influenced by external uncertainties, such as major emergencies. Affected by the COVID-19 epidemic, fixed asset investment growth in China's secondary industry has changed more, with negative growth in 2020, while growth reached approximately 12% in 2022; therefore, investment efficiency will change more. China consumes large amounts of energy. Although energy consumption has recently shown stable growth, because the growth contribution of the tertiary industry is increasing while the value-added contribution of the secondary industry is decreasing, the energy intensity changed from -4% to -3.03%. Influenced by domestic and foreign policies, China has been controlling the growth rate of carbon emissions, and the energy intensity has shown changes between -2.18% and 0.39%, the scenario model is setas Table 3.

Table 3

Analysis of Carbon Emission Drivers in the Baseline Scenario. (%)

Influencing factors	2022–2035		
	Low	Medium	High
Fixed assets	3.48	5.29	11.24
Investment efficiency	-2.67	3.15	12.48
Energy intensity	-4	-3.68	-3.03
Carbon intensity	-2.18	-0.56	-0.39

The green development scenario is based on the requirements of environmental sustainability, especially *Origin and Connotation of Green Development*, released by the Development Research Center of the State Council, and the requirements for sustainable development, and considering China's the five-year economic development plan, and is therefore divided into three time periods of 2022–2025, 2026–2030, and 2031–2035 and designed growth rates in different time periods. The green development scenario requires a more stable investment and stable energy intensity and energy carbon intensity growth rates; therefore, the scenario model is set as Table 4:

Table 4

Analysis of Carbon Emission Drivers in the Green Scenario. (%)

Influencing factors	2022–2025 Low	2022–2025 Medium	2022–2025 High	2026–2030 Low	2026–2030 Medium	2026–2030 High	2031–2032 Low	2031–2032 Medium	2031–2032 High
Fixed assets	7	8	9	5	6	7	4	5	6
Investment efficiency	-3	-2	-1	-2.47	-1.47	-0.47	-2.47	-1.47	-0.47
Energy intensity	-3.9	-3.7	-3.1	-3.81	-3.61	-3.21	-3.81	-3.61	-3.21
Carbon intensity	-1.1	-1	-0.85	-0.89	-0.69	-0.49	-0.89	-0.69	-0.49

The technological progress scenario is set for China's "double carbon" target, which aims to achieve carbon peak by 2030 and carbon neutrality by 2060. Therefore, the technological progress scenario proposes higher requirements for energy and carbon intensity, and seeks to achieve further technological breakthroughs based on the green development scenario model is set as Table 5

Table 5

Analysis of Carbon Emission Drivers under the Technological Progress Scenario. (%)

Influencing factors	2022–2025 Low	2022–2025 Medium	2022–2025 High	2026–2030 Low	2026–2030 Medium	2026–2030 High	2031–2032 Low	2031–2032 Medium	2031–2032 High
Fixed assets	7	8	9	5	6	7	4	5	6
Investment efficiency	-3	-2	-1	-2.47	-1.47	-0.47	-2.47	-1.47	-0.47
Energy intensity	-4.29	-3.89	-3.49	-3.99	-3.59	-3.19	-3.99	-3.59	-3.19
Carbon intensity	-1.26	-1.06	-0.86	-1.26	-1.06	-0.86	-1.85	-1.65	-1.45

In this study, the evolution of carbon emission distribution trends for the three scenarios from 2022 to 2030 are presented separately as Figs. 8-1.

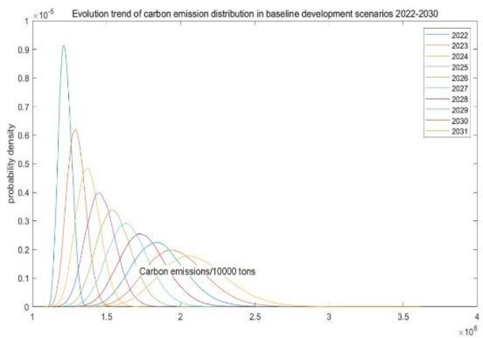


Fig. 8. Evolution trend of carbon emission distribution in baseline development scenarios 2022-2030.

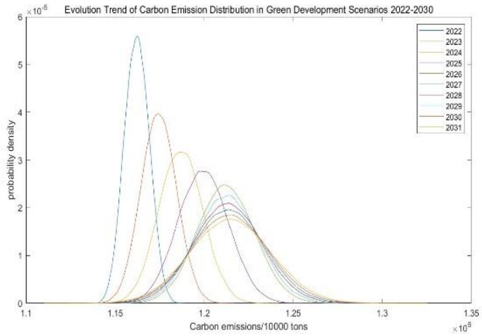


Fig. 9. Evolution trend of carbon emission distribution in green development scenarios 2022-2030.

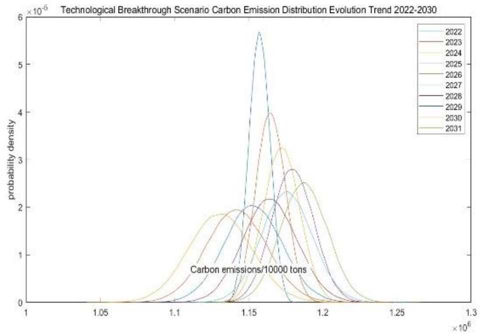


Fig. 10. Technological Breakthrough Scenario Carbon Emission Distribution Evolution Trend 2022-2030.

A Monte Carlo simulation shows that the possible carbon emission peak under the baseline scenario far exceeds the target value. The green development and technological progress scenarios can achieve the carbon emission peak target; however, the possible emission peak under the technological progress scenario is comparatively lower. Intuitively, the technological progress target is more in line with the reality of China's current development and urgent need to seek technological breakthroughs in carbon emission reduction and sustainable development. Carbon emissions under the baseline scenario are in a state of continuous growth, which does not meet China's development requirements. In the green scenario, although it makes certain requirements for energy intensity and carbon intensity, the carbon reduction target is difficulty to achieve at a specific time, and the maximum emissions may slightly exceed the peak target of 12.2 billion tons. Thus, the technological progress scenario is the most consistent with future development scenarios for China. Under the three development scenarios, the upper, median, and lower bounds of China's carbon emission peaks are estimated (Table 6), in which the peaks are 21,528.6, 19,624.2, and 17,913.8 million tons, respectively, under the baseline scenario; 12,341.6, 12,149.3, and 11,959.7 million tons, respectively, under the green development scenario; and 12,066.3, 11,874, and 11,685.3 million tons, respectively, under the technological progress scenario. The latter two scenarios can potentially achieve the peak target of 12.2 billion tons in "China's Carbon Neutral Strategy and Pathway" (2022), published by the Chinese Academy of Engineering; however, the technological progress scenario is more likely to achieve carbon neutrality by further improving energy use efficiency and stimulating reduction incentives on the basis for achieving carbon peaking.

Table 6

Carbon Emission Peaks under Different Scenarios. Units (billion tons)

	Baseline scenario	Green development scenario	Technological progress scenario

	Upper bound	Median bound	Lower bound	Upper bound	Median bound	Lower bound	Upper bound	Median bound	Lower bound
Peak	215.286	196.242	179.138	123.416	121.493	119.567	120.663	118.74	116.853

6.2.3 Effects of Different Carbon Attainment Paths on Inter-Provincial Allocation Results

The uncertainty of the allocation results is calculated for different development paths and different paths with multiple scenarios (Fig. 11 and Fig. 12). The uncertainty results under the different paths in Fig. 12 are calculated based on the integrated scenarios. The results show that the standard deviations of Jiangsu, Guangdong, Shandong, Zhejiang, and Inner Mongolia are larger than other provinces, indicating that these regions' allocation results under different development paths are the most unstable, and therefore must be focused on under different peak attainment paths. Economically developed provinces such as Jiangsu and Guangdong need to strengthen green technology innovation, improve energy-use efficiency, adopt modern technology to control carbon emissions, and reduce carbon emission intensity. For less economically developed regions, such as Inner Mongolia and Hebei, although the results vary widely under different paths, the requirements for their science and technology innovation have slowed down considering their economic and technological development levels; however, they must adjust their industrial structures and accelerate the transformation of their economic development method. The standard deviations of Tianjin, Hainan, Qinghai, and Ningxia are smaller than other provinces, indicating that the allocation results of these regions are less influenced by the emission paths. However, their carbon emissions should not be neglected, and they need to further strengthen the concept of sustainable development and take the green development path.

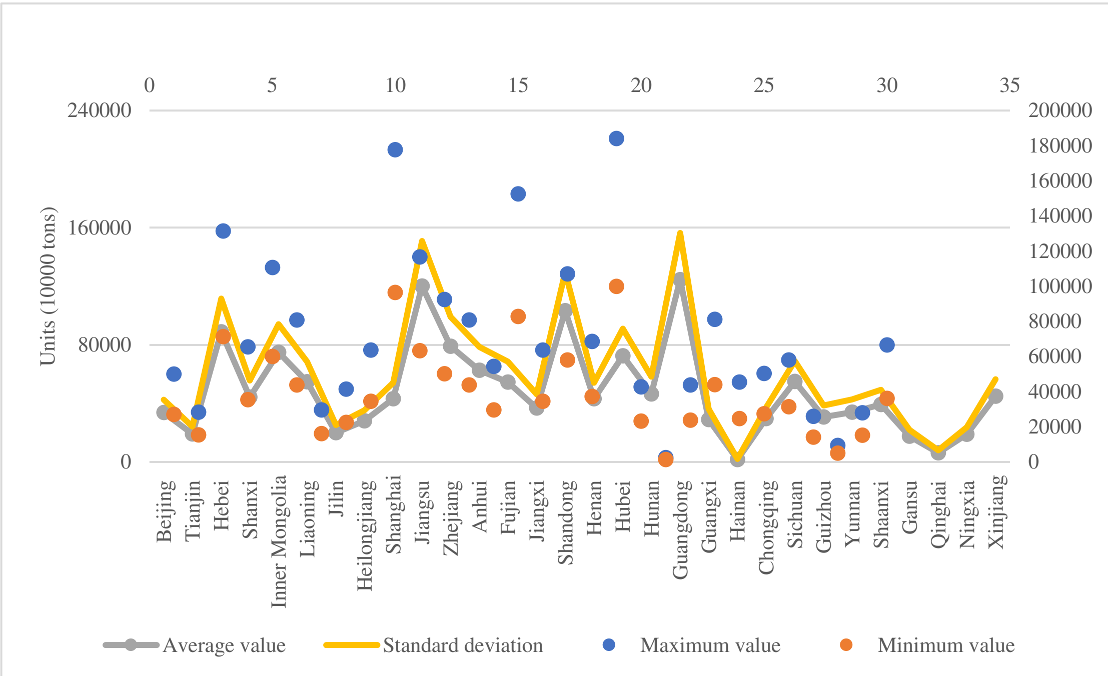


Fig. 11. Uncertainty of Allocation under Different Paths.

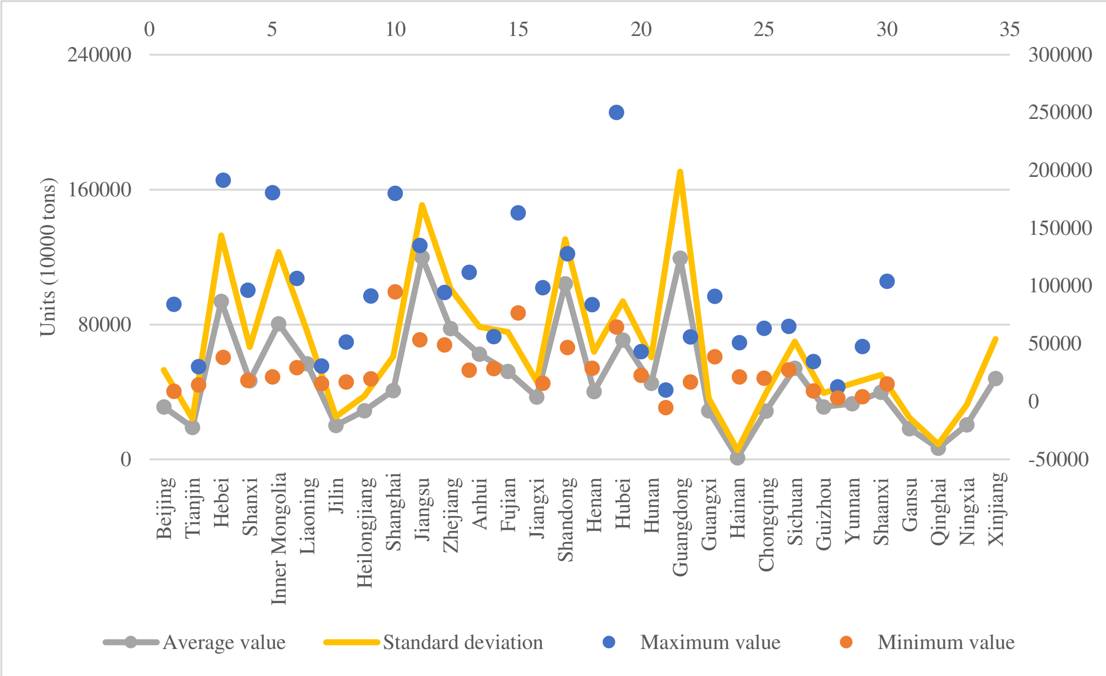


Fig. 12. Uncertainty in the Results of the Allocation of Multiple Scenarios for Different Development Paths.

Under the influence of allocation uncertainty in multiple scenarios under different development paths, the standard deviations are small in Hainan, Gansu, Jilin, and Guangxi, indicating that carbon emissions in these regions are more stable. However, the emission reduction space needs to be further improved. Liaoning, Shanxi, Hebei, Henan, Inner Mongolia, Yunnan, and Xinjiang have large standard deviations, all above 200 million tons, indicating unstable results under different development scenarios. As traditional carbon emission provinces, Henan, Hebei, and Shanxi have previously displayed rough development patterns and weak emission reduction policies. Excessive concentration of high-energy-consuming and high-polluting industries has caused large amounts of carbon emissions, and if not restricted, their pollution and emissions will intensify. According to the baseline development model, most of the above regions have emissions of more than 1 billion tons, whereas Hebei and Inner Mongolia have emissions of approximately 2 billion tons. If policy controls are adopted for these traditional regions to take the path of green development, energy conservation, and emission reduction to improve their emissions reduction efficiency, carbon emissions will be substantially reduced. Beijing, Shanghai, Guangdong, Jiangsu, and Zhejiang have large standard deviations because of their large economic volumes and high demand for carbon emissions, and the implied carbon emissions of some provinces far exceed the actual carbon emissions.

Thus, following the traditional development model will not only cause a large amount of carbon emissions in the region but also affect the emissions of other regions. Beijing, as an economic and science-intensive central city, has reached 800 million tons of emissions under the benchmark model, while the emission reduction under the science and technology model is approximately 80 million tons, which contributes greatly to China's carbon emission reduction and can play a certain demonstration role. Therefore, under the current carbon peak target, comprehensive equity and efficiency not only require a green path but also higher emission reduction requirements for these regions, making it imperative to strengthen innovation in environmental technology, control demand for energy products, improve energy use efficiency, and continuously reduce energy and carbon intensity.

Compared with the uncertainty of different allocation schemes and paths, multiple scheme allocation under different development paths comes with greater uncertainty, and the differences in the most valuable results, mean, and standard deviation are greater; Thus, the extreme results are more obvious than under ideal conditions, and the emission reality facing China is more severe. China must abandon the traditional rough development model because high energy consumption and pollution make the carbon peak target difficult to achieve; however, China must adopt green and sustainable development to further increase environmental technology innovation, improve energy use efficiency, and reduce carbon emission intensity. Because of the comprehensive influence of the allocation scheme and development path, the inter-provincial carbon allocation process should not only consider regional equity and emission reduction efficiency but also economic and technological development and energy demand, focusing on the dynamic changes in investment, energy, and carbon emissions, and formulating a reasonable carbon allocation scheme to achieve the carbon peak target.

7 Conclusions and Policy Recommendations

This study analyzes three inter-provincial carbon emission allocation schemes under the principles of equity, efficiency, and comprehensiveness for China's carbon peak target and compares the schemes' abatement costs. Further, it explores how uncertainty affects the inter-provincial carbon emission allocation results in China and concludes the following. First, the carbon allocation results under the comprehensive scheme lie between the equity and efficiency schemes, which consider both equity and efficiency. Second, the marginal costs under the efficiency scheme are more balanced but the total costs are larger for each province, which some Economically underdeveloped provinces may have difficulties to achieve. Most provinces can achieve abatement cost reductions under the equity scheme but large inter-provincial marginal cost differences make some provinces unwilling to accept. Thus, most provinces will more easily accept the abatement costs under the comprehensive scheme. Third, Compared to the uncertainty of different allocation principles and paths, the results of multi scheme allocation under different development paths are more extreme. Fourth, the carbon peak target is difficult to achieve under the baseline development model, while green development and technological progress can easy to achieve.

The allocation scheme of China's inter-provincial carbon emission rights is not rigid but rather must be dynamically adjusted according to the uncertainty of each province's socioeconomic development and various driving factors affecting carbon emissions to achieve the most beneficial effects on socioeconomic development, energy conservation, and environmental protection. The allocation of inter-provincial carbon emission rights in China should not only consider equity and efficiency but also the uncertainty impact of carbon emission peaking paths on the allocation results. Allocation plan implementation should consider various allocation principles to improve emission reduction efficiency and consider inter-provincial equity, such that the allocation considers the economic and social development needs of multiple provincial units. In addition, carbon allocation should consider emission reduction costs in different provinces and regions and aim to promote carbon price parity within the scope of regional affordability to achieve a national carbon emission market, which can provide both emission reduction and a cost-saving effect. Considering the actual situation of China's economic development and energy environment, the carbon emission reduction target will be difficult to achieve by simply relying on the traditional development model. The green and innovation-driven path is the inevitable choice for the future sustainable development of

China’s provinces and key to achieving the carbon peak target.

In contrast, the results of green development and technological progress differ. Although the green development scenario can achieve the carbon peak target, a certain lag exists in the time needed to achieve do so, and the emission reduction effect has room for improvement. Therefore, the technological progress scenario can more easily achieve the carbon peak target, which is also in line with China’s future economic and social development goals. Considering the economic and technological development levels in different regions, achieving the carbon peak target puts forward different requirements for across regions. For traditional emission provinces such as Shandong, Henan, Hebei, and Shanxi, it is necessary to accelerate changes in development mode, implement the concept of green development, adjust the industrial structure, and conduct industrial upgrades, while economically intensive regions such as the north, Shanghai, Guangzhou, and Jiangsu should utilize economic and technological advantages to accelerate the drive for green innovation. The development and use of new energy sources improves energy efficiency, energy conservation, and emission reduction.

Presently, reaching the carbon peak is only the beginning of achieving the emission reduction target, and China continues to face great environmental pressure. Only by further optimizing industrial structures, implementing emission reduction policies, continuously intensifying investment in science and technology, seeking breakthroughs in energy science and technology innovation, and promoting new energy research, development, and utilization can China ensure achievement of the carbon peak by 2030.

7 Statements and Declarations

7.1 Ethics approval

No ethical approval was necessary for this study.

7.2 Consent to participate

All participants in this study consent to participation.

7.3 Consent for publication

All authors consent to this publication.

7.4 Data availability

The datasets used in this study are available from the corresponding author on reasonable request.

8 Funding information

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9 Competing Interests and Authors’ Contributions

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Credit authorship contribution statement as follows: The first draft of the manuscript was written by Qian Zeng and Peng Guo, ZiJian Liang undertakes the work of translation.

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