



Effectiveness and risk of initial carbon quota allocation principle under the uncertainty of the Chinese electricity market

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ABSTRACT

The carbon market's effectiveness in deep decarbonization and energy transition has been widely proven. However, as other industries join the carbon market in China, the uncertainty and impact of it on the power industry are still under explored. Here, we define the industry-wide scenarios which power industry might confront in the carbon market. Then, we compare its economic output, market activity and environmental impact under initial carbon quota allocation principles based on efficiency and grandfather methods by the comprehensive evaluation model of energy and carbon markets combined with inverse DEA method. Our results show that when the power industry is in an advantageous position, the efficiency method is fairer and more efficient than the grandfather method. The potential economic output rate has more than doubled compared to that of the grandfather method. Market activity and emission reduction potential are 7% and 25% more than that in the grandfather principle, respectively. Nevertheless, when the power industry is in a disadvantageous position, the efficiency method leads to an imbalance between power supply and demand in the market and power shortages in 19 regions. Then the trading activity of the power market drops by 12%, resulting in serious economic loss, especially in China's eastern region (-7.29%). The economic risk caused by the grandfather method has been significantly reduced than that of the efficiency method. And there may be greater potential risks under the efficiency method. This study identifies the potential challenges and obstacles of future carbon market and addresses the urgency of policy to tackle this issue to facilitate a carbon market that operates robustly under uncertainty.

1. Introduction

In 2020, General Secretary Xi solemnly announced at the general debate of the 75th United Nations General Assembly that China will increase its nationally determined contributions (NDC) and adopt stronger policies and measures to achieve carbon peaking by 2030 and carbon neutrality by 2060 (Zhao, Ma, Chen, Shang, & Song, 2022). These two goals are both challenges and opportunities, which require the policy drive and guidance of the market to realize the country's energy transition and green and low-carbon development. As a market-based method, carbon trading realizes the mandatory and binding policy goals, reduces the emission

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reduction cost of enterprises, and achieves optimal cost-effectiveness (Yi, Bai, Yang, Li, & Wang, 2020). CO₂ trading increases the cost for companies, thereby forcing them to reduce emissions. The establishment of the carbon trading system is considerably significant for achieving carbon neutrality. This can help China achieve emission reductions of tens of billions of tons of carbon emissions. CO₂, in the power industry, accounts for a large proportion of total carbon emissions in China (Li, Zhang, Tian, Cheng, et al., 2020). Achieving the “dual carbon” goal is an uphill battle and an unprecedented challenge in major carbon reduction technologies and management. It is necessary to promote the optimal allocation and efficient utilization of green and low-carbon electricity resources and comprehensively promote the exchange and sharing of new green and low-carbon experiences, technologies, methods, and business forms in the power industry.

Similar to the EU emission trading system (ETS), China's ETS is also divided into two types: primary and secondary markets. The primary market is mainly for the “creation of allowances,” which is managed by the relevant national authorities and entrusting agencies to create and distribute CO₂ quota. Participants in the secondary market are mainly enterprises and financial institutions. Quota allocation is distributed from top to bottom, central to local governments, local governments to enterprises, and finally decided by local governments (Wu, Wang, Liu, Chen, & Song, 2020; Zhang & Hao, 2017). The allocation basis employed in the pilot phase is historical emissions; while entering the national carbon market phase, the “benchmark method” will first be used as the allocation basis.

Currently, the different allocation methods have been discussed (Cucchiella, Adamo, Gastaldi, & Miliacca, 2018; Kong, Zhao, Yuan, & Chen, 2019; Li, Wei, Zhang, & Tao, 2020; Liu & Lin, 2017), in which the comparison between the efficiency method and grandfather method is widely investigated (Miao, Geng, & Sheng, 2016; Yu, Lin, Zhang, Jiang, & Peng, 2019; Feng, Chu, Ding, Bi, & Liang, 2015). However, their conclusions obtained are basically based on the discussion of results without considering uncertainty risks. Subjects have different positions in the market, the advantage of bidding and the disadvantage of bidding, which will bring different results, thus causing risks. Uncertainty analysis is extremely important in assessing risk (Li & Budh, 2008; Maler & Li, 2010), and different principles of CO₂ quota allocation will have varied consequences in uncertain markets. According to the previous studies (Chen, 2010; Chen, Pan, & Wu, 2016; Jiang & Zhang, 2018; Wang & Gao, 2018; Wei, 2014; Zhao & Yan, 2019), the CO₂ marginal abatement cost of the power industry is low, and the electricity price is low (set by the government). Therefore, we cannot take the advantage position of power market for granted. When the power industry is at a disadvantage position in the carbon market, some plant may not be able to buy enough carbon quotas to supply the demand of power, resulting in an overall loss of social welfare. Under uncertainties, potential risks of different allocation principles on economic development and the environmental impact on each region have not been sufficiently studied. It is necessary to consider the potential risks brought by different allocation principles under different uncertainty scenarios for future policy reference.

Meanwhile, the existing literature mainly discusses the impact of different distribution principles on fairness and efficiency. We take fairness and efficiency as the criteria to evaluate the advantages and disadvantages of CO₂ quota distribution. (Chen, Zhao, Xia, Cui, & Li, 2021; Cheng, Gu, Tan, Yan, & Sheng, 2022; Feng, Tang, Niu, & Wu, 2018; He & Zhang, 2021; Kong et al., 2019). The criteria may not fully cover the impact of carbon quota allocation on economy, market activity and environment. Which are vital in the transition towards carbon neutrality. Under uncertainty, will there be any deviation in the evaluation indicators of fairness and efficiency? Further investigation is in urgent need. This paper focuses on the uncertainty of the future electricity market in the carbon market, and we define this uncertainty from the perspective of its competitiveness. We define advantages and disadvantages position of the future electricity market in the carbon market, and investigate the potential economic, electricity market and environmental risks of different allocation principles under uncertainty scenarios.

Here, we first define the advantage and disadvantage of the power industry in the carbon market. To determine the position of the power industry in the carbon market transaction, that is, the power with bidding and the power without bidding, this paper employs the carbon shadow price in economics to measure the bidding ability. Meanwhile, we also infer the advantage position and the disadvantaged position in the carbon market. Subsequently, to evaluate different distribution principles, we compare the differences between the grandfather and efficiency methods in quota allocation, equity, and efficiency. Further, to explore the impact of different distribution principles on regional trading behavior in the carbon market and electricity market, considering the uncertainty scenario analysis of the energy and carbon markets, we compare the differences in potential economic growth, electricity market activity, and emission reduction space of different allocation principles.

The contributions of this study are as follows. First, theoretically, we define the advantage and disadvantage of the power industry based on the marginal abatement cost and employ it as the basis for future national carbon market uncertainty projection. Second, methodically, we put forward a comprehensive evaluation model of energy and carbon markets combined with inverse DEA method to analyze the power industry in the future carbon market. Moreover, the impact of the grandfather and efficiency methods on equity, efficiency, potential economic growth, market activity, and emission reduction potential have been measured under the advantage position. Meanwhile, the gap between power supply and demand and carbon reduction potential are compared and the economic losses caused by power shortage are analyzed through the inverse DEA model under the disadvantaged position. Third, empirically, we measure the impact of initial carbon quota allocation principles over 30 provinces in China under the uncertainty of the electricity market and projections regarding transaction risks and economic losses have been made; then, the policy implications have been put forward.

The remainder of this paper is organized as follows. Literature review is the [Section 2](#). [Section 3](#) provides the methodology and data, and [Section 4](#) presents and discusses the results. Finally, [Section 5](#) concludes this study.

2. Literature review

Previous literature on carbon allocation is based on the perspectives of countries, regions, sectors, and companies. At the national level, it is mainly concentrated in 30 provinces in China ([Cai & Ye, 2019](#); [Fang et al., 2019](#); [Xie, Hu, Jiang, & Li, 2019](#)). Further, at the regional level, the research includes the eastern coastal regions of China, the Beijing-Tianjin-Hebei region, Yangtze River Delta region, and Pearl River Delta region ([Li, Li, Ye, & Zhang, 2018](#); [Liu et al., 2018](#)). [Du and Xu \(2018\)](#) proposed an interactive and iterative algorithm based on a directional distance function and assigned China's carbon emission reduction targets at the provincial level. Moreover, at the industry level, the existing literature mainly studies industry and transportation ([Lin, Zhang, Zou, & Peng, 2020](#); [Zhao, Min, Geng, & He, 2017](#)). [Cui and Kong \(2016\)](#) proposed a nonlinear social cost optimization model to allocate the carbon emission reduction targets of industry in China.

The efficiency and grandfather methods have been widely studied by many scholars as the main research methods in carbon allowance allocation ([Zhou and Wang, 2016](#); [Zhou, Sun, & Zhou, 2014](#); [Feng, Wang and Bi, 2017](#); [Schmidt & Heitzig, 2014](#)). The grandfather method allocates a fixed initial emission allowance to the ETS participants based on their historical emission levels. As the most basic allocation scheme, grandfathering is usually used as a convenient base case in ETS literature. It is commonly applied at the early stages of ETS, such as in China's ETS pilots. An important critique of grandfathering is "unfair punishment"—producers historically invested more in emission control would consequently obtain less allowance. The grandfather method takes the historical emissions as the allocation principle. It does not consider the optimal allocation of resources and is prone to adverse selection of "beating the fast cow" ([Zhou & Wang, 2016](#)). However, this conclusion is often based on a perfectly competitive market. The price of electricity is controlled by the government; subsequently, the carbon price cannot be reflected through the price mechanism. Therefore, is there really no advantage to it in this case?

The efficiency method is an allocation method derived from the benchmark method and is a benchmark method for composite indicators ([Liu & Wang, 2020](#)). This single-sector ETS scheme is a tradable performance standard without a clear emission cap. Previous studies have shown that the efficiency method better considers sectoral development and competitiveness, as well as macroeconomic dynamics ([Demailly & Quirion, 2008](#); [Meunier, Ponsard, & Quirion, 2014](#); [Zhu, Zhang, Li, Wang, & Guo, 2017](#)). As the efficiency method, zero-sum gains DEA has been widely mentioned and applied in recent years. [Gomes and Lins \(2008\)](#) applied the method to the study of the initial allocation of carbon emission rights for the first time. [Ma, Ren, Zhang, and Sharp \(2018\)](#) simultaneously applied the two-layer programming model and zero-sum gains DEA model to reallocate the quota of China's five largest power companies. Most scholars believe that the initial allocation method based on the zero-sum gains DEA model can achieve optimal allocation so that all decision-making units reach DEA effectiveness, and Pareto improvement is achieved ([Cucchiella et al., 2018](#); [Miao et al., 2016](#); [Pang, Deng, & Chiu, 2015](#); [Wu, Fan, Xia, & Liu, 2015](#)). [Cai and Ye \(2019\)](#) employed the zero-sum gains DEA model to allocate China's carbon quota. The result shows that the carbon quota in the western region is generally less than that in the eastern region. [Cheng et al. \(2022\)](#) also used the same model to decompose China's carbon allocation, and evaluated the effectiveness and fairness of the allocation. The carbon quota is mainly concentrated in the eastern region with high efficiency in conclusions. [Cui, Tao, and Wang \(2021\)](#) utilized the zero-sum gains DEA model and entropy method to allocate the carbon quota of China's power industry, and found that Guangxi, Hainan and Shandong had the largest carbon quota. [Yu et al. \(2019\)](#) used the zero-sum gains DEA model to adjust the carbon quota, and the eastern region had the most carbon quota compensation. [Fang et al. \(2019\)](#) also used the same model to allocate China's carbon quota, and found that southern and eastern provinces of China often account for a large proportion of the overall carbon quota. Meanwhile, [Li, Zhao, Wang, and Cui \(2021\)](#) also found that the eastern region has the largest carbon quota, followed by the central and western regions, through the same DEA model. [Ma et al. \(2018\)](#) and [Cui et al. \(2021\)](#) allocated carbon emissions to the power sector based on the model, however, they did not consider the consequences of different quota allocations based on uncertainty analysis.

Some studies believe that China is in the early stage of establishment of the ETS, and a free distribution method based on historical emissions should be adopted ([Liu & Wang, 2020](#)). Some findings suggest that industry heterogeneity can lead to differences in the applicability of different allocation methods. [Wu et al. \(2015\)](#) established a CGE model, including carbon trading. The results show that in the early stage of Chinese ETS, the energy industry should adopt a free distribution method. [Lu and Fang \(2015\)](#) compared and analyzed two free distribution methods based on the dynamic game model—the grandfather and efficiency methods. The grandfather method is more favorable for high-emitting companies, whereas low-emitting companies have higher returns and fewer emissions when the benchmark method is used for allocation. Additionally, some scholars have turned their research perspectives to the distribution of carbon emission reduction targets.

Most studies basically employ fairness and efficiency as the criteria to judge the quality of distribution, but this often leads to the flow of resources to more efficient eastern regions. What happens after the allocation of resources urgently needs to be studied under the presence of cooperation and transaction between regions. It is necessary to further study the trading behavior

of different carbon quotas in the carbon market. Meanwhile, the results in the existing literature are basically based on the absence of uncertainty risk, and their conclusions often deviate from reality. Combining the carbon market and electricity market with Chinese characteristics, copying foreign research will ignore the huge risks hidden behind. And under such uncertain conditions, how much losses of the economic development and the environmental impact have not been effectively studied in each region.

3. Methodology and data

In this section, we first introduce the uncertain position of the electricity industry in the carbon market. Subsequently, we introduce the zero-sum DEA model, which allocates carbon quota based on the principle of efficiency. Finally, we introduce the comprehensive evaluation model of the energy and carbon markets; it is employed to explore potential economic growth, market activity, and emissions reduction space under different principles.

3.1. The uncertain position of the electricity industry in the carbon market

To determine the position of the electric power industry in the carbon market transaction, the carbon shadow price needs to be determined from economics. This paper defines the advantages and disadvantages through the price, to judge the bidding ability of the electric power industry in the transaction process. Here, we explore the advantageous and disadvantageous positions of the power sector in the carbon market. Assume that there are three enterprises in the market: A , B , and C . Enterprise A is an electricity enterprise lacking a carbon emission quota, enterprise B is a non-electricity enterprise lacking a carbon emission quota, and enterprise C is an enterprise with a carbon emission quota surplus. The marginal abatement cost of CO_2 has been explored by many scholars as an important indicator (Du, Hanley, & Wei, 2015a, 2015b). According to previous studies (Chen, 2010; Chen et al., 2016; Jiang & Zhang, 2018; Wang & Gao, 2018; Wei, 2014; Zhao & Yan, 2019), the shadow price of the power industry is considerably low. Therefore, this study assumes that firm A 's shadow price is lower than that of firm B . Subsequently, given the same scarcity of carbon quota in companies A and B , B has the possibility to accept a higher carbon price. In other words, in the choice of carbon quota and purchase of emission reduction equipment, enterprise B is more willing to purchase carbon quota at a higher price than enterprise A . Assume that the shadow price of carbon emission of firm A is Z_A and the shadow price of firm B is Z_B , where $Z_A \leq Z_B$. Subsequently, the carbon and shadow prices have the following relationship.

$$\begin{aligned} P_c^B &\leq P_c^A \leq Z_A \leq Z_B \\ P_c^A &\leq P_c^B \leq Z_A \leq Z_B \\ P_c^A &\leq Z_A \leq P_c^B \leq Z_B \end{aligned} \quad (1)$$

P_c^A and P_c^B are the carbon prices of enterprises A and B , respectively. The level of carbon price of enterprises A and B depends on the value of their respective marginal products. From the above relationship, in the latter two cases, power enterprise A is at a disadvantage in the carbon market. As a resource, carbon quota will flow to companies with higher prices. Therefore, in the latter two cases, it is difficult for company A to buy enough quota.

3.2. Zero-sum gains DEA

CO_2 quota is a resource and has the characteristics of competitiveness and exclusiveness. The quota game in each region is applicable to the zero-sum game. Different from the distribution method of grandfather method, CO_2 quota is adjusted based on actual data by zero-sum gains DEA method, so that all decision-making units can reach the effective level. Zero-sum gains DEA is an allocation method similar to the benchmark method. The traditional benchmark method allocates quota based on output and employs carbon intensity as the allocation benchmark, while zero-sum gains DEA allocates quota based on both input and output. It is a benchmark method for composite indicators (Liu & Wang, 2020).

This study aims to explore the issue of CO_2 quotas in the power industry. Electricity is different from other energy sources. The transfer of power does not produce carbon emissions, but its production leads to carbon emissions. If CO_2 emissions caused by electricity is employed as an input, then it is not conducive to the study of the electricity transfer problem, which causes unfair distribution. Meanwhile, part of the electricity produced in this region will be transferred to other provinces, and the transferred electricity is to ensure the economic development and people's lives of other regions. Therefore, this study takes electricity as the only input variable; the output variables are population and GDP. Subsequently, the CO_2 quotas are allocated according to the allocated electricity. The formula of the zero-sum gains DEA model is as follows:

$$\begin{aligned}
 & \text{Min} \delta_0 \\
 & \sum_{i=1}^n \lambda_i x_{ik} \left[1 + \frac{x_{i0}(1 - \delta_0)}{\sum_{i \neq 0} x_{ik}} \right] \leq \delta_0 x_{0k}, k = 1, \dots, l \\
 & \sum_{i=1}^n \lambda_i y_{ij} \leq y_{0j}, j = 1, \dots, h \\
 & \lambda_i \geq 0, i = 1, \dots, n
 \end{aligned} \tag{2}$$

Here, x is electricity, y is GDP and population, n is the number of *DMUs*, l is the number of input elements, and h is the number of output elements.

3.3. Inverse DEA model

Potential economic loss is a very important basis for evaluating the losses. For this reason, this paper employs the inverse DEA model to measure the potential loss caused by power shortage. The inverse DEA model is proposed by [Wei, Zhang, & Zhang \(2000\)](#) and [Hong, Wei, & Gang \(2002\)](#). The potential loss model is to explore the impact of power shortage in a certain region on the economy and population. The principle is that the DEA value is invalid for the decision-making unit, and when the electricity is lost, the output of the minimum proportion to be reduced while maintaining the original efficiency value.

$$\begin{aligned}
 & \text{Min} \sum_{i=1}^n a_i \sigma_i \\
 & \lambda_k (x^k + (-\Delta x^k)) + \sum_{j=1, j \neq k} \lambda_j x^j + s^- = (x^k + (-\Delta x^k)) \theta^k \\
 & \lambda_k (1 - \sigma) y^k + \sum_{j=1, j \neq k} \lambda_j y^j - s^+ = (1 - \sigma) y^k \\
 & \lambda_j \geq 0, k = 1, \dots, k - 1, k + 1, \dots, n \\
 & 0 \leq \lambda_k < \theta^k, s^+ \geq 0, s^- \geq 0
 \end{aligned} \tag{3}$$

where $\sigma = \frac{\Delta y^k}{y^k}$, x is the electricity, Δx is the transferred electricity, and σ is the minimum loss when the electricity is lacking. Both a_1 and a_2 are 1/2.

Since the loss here includes GDP and population, it must be converted into value. The loss of the population can be understood as the migration of the population. On the one hand, the electricity affects the economic development of the region, resulting in a decline in employment opportunities, and the labor force cannot find a suitable job. On the other hand, the lack of electricity leads to a decline in people's quality of life. In pursuit of a higher quality of life, they chose to relocate. This paper uses the C—D production function to convert the population into value. Since the element in the C—D production function is labor, when calculating the value of the population, this paper transforms the population of each region according to the proportion of labor in each region, so as to obtain the labor force lost in each region. The C—D production function is: $GDP = A(t)K^\alpha L^\beta$. $A(t)$ represents technological progress. K represents capital. L represents labor. α and β respectively represents the coefficients of capital and labor. Due to the heterogeneity of the production situation in each region, this paper uses the data of each region from 2000 to 2019 to calculate the production function of 30 regions. Therefore, the final economic loss calculation formula is as follows.

$$gl = \sigma_1^* y + A(t)K^\alpha (\sigma_2 L)^\beta \tag{4}$$

σ_1, σ_2 are the ratio of economic loss and population loss in the above model.

3.4. Energy market and carbon market trading model

The comparison of fairness and efficiency belongs to the static discussion of the differences between different initial allocation methods, and does not test the impact of different initial allocation methods on the trading behavior of each region in the dynamic market trading model. Therefore, we introduce the energy market and carbon market trading model to further study the differences between the grandfather method and the efficiency method. The market trading model in this study assumes that both energy use and carbon emission rights can be freely traded. However, the two markets are interconnected, mainly because the burning of fossil energy causes changes in the demand for carbon quota. Based on the carbon emission trading model of [Fare, Grosskopf, and Pasurka \(2013\)](#) and [Liu and Wang \(2020\)](#), we establish the energy and carbon market trading model in this study. Different from them, in the comprehensive trading model of this paper, carbon emission trading and energy trading constraints are more consistent with the real scene, including price (carbon emission price, electricity price and non-electric energy price), some restrictions of trading behavior, characteristics of electricity that are not conducive to storage (market clearing), characteristics of other energy that can be stored (market clearing is not necessarily) and so on. The model formula is shown below.

$$\begin{aligned}
 PG &= \max \sum_{j=1}^n g_j \\
 \sum_{i=1}^n \lambda_i^* x_i &= x_i + k_j \\
 \sum_{i=1}^n \lambda_i^* e_i &= e_i + d_j \\
 \sum_{i=1}^n \lambda_i^* a_i &\leq a_i \\
 \sum_{i=1}^n \lambda_i^* y_i &\geq y_i + g_j \\
 \sum_{i=1}^n \lambda_i^* p_i &\geq p_i \\
 \sum_{i=1}^n \lambda_i^* c_i &= c_i + z_j \\
 g_j - p_j^c z_j - p_j^k k_j - p_j^e d_j &\geq 0 \\
 d_j^* f^1 &\leq z_j \\
 (g_j - g_j^*) z_j &\geq 0 \\
 (g_j - g_j^*) / (k_j^* f^2 + d_j + \epsilon) &\geq 0 \\
 \sum_j k_j &= 0 \\
 \sum_j d_j &\leq 0 \\
 \sum_j z_j &\leq 0 \\
 \lambda_i^j &\geq 0, j = 1, \dots, n
 \end{aligned} \tag{5}$$

Here, g_j represents the economic potential increment of the j_{th} region, and x represents electricity. Further, e represents non-electric energy, a is capital and labor input, and y is economic output. p represents population. Moreover, c is carbon emissions, and p^c, p^k , and p^e , respectively, represent the carbon emission price (RMB/10,000 tons), electricity price (RMB/kWh), and non-electric energy price (RMB/10,000 tons of standard coal). Additionally, f^1 is the smallest emission factor among fossil energy, and natural gas is selected here; f^2 represents the conversion factor for converting electricity into standard coal; it refers to the electricity conversion factor in the Energy Statistical Yearbook. Furthermore, g^* represents the potential growth that can be achieved only by resource allocation under the premise of no energy and carbon emissions trading. In the model, k_j, d_j , and z_j represent the increments of power input, non-power energy input, and carbon emissions, respectively, in the j_{th} region (positive value means buying electricity, non-power energy, and carbon emissions, and negative value means selling). The economic potential increment g must be greater than or equal to zero. If it is less than zero, the decision-making unit will not take its measures based on the principle of maximizing its own interests.

$g - p^c z - p^k k - p^e d \geq 0$ indicates that the region will only implement buying if the economic potential is greater than the cost of buying CO₂ quota and energy. $d^* f^1 \leq z$ means that after the purchase of non-electric energy, the region will generate more carbon emissions due to the purchased non-electric energy. Therefore, the region will also purchase the corresponding CO₂ quota. Further, $(g - g^*) z \geq 0, (g - g^*) / (k^* f^2 + d + \epsilon) \geq 0$ indicates that the increase in economic potential is accompanied by an increase in carbon emissions and energy. Here, ϵ is a positive Archimedes infinitesimal constant, which is taken as 0.001 to prevent the denominator from being zero. $\sum_i k_i = 0, \sum_i d_i \leq 0, \sum_i z_i \leq 0$ represents the constraints of electricity, non-electric energy, and carbon quotas, respectively. Electricity trading needs to achieve market clearing, considering that electric energy is not conducive to long-term storage as much as is used, and other non-electric energy can be transferred for storage. Carbon quota is not necessarily market clearing. Therefore, allowing the supply of non-electric energy and carbon emission rights to be greater than or equal to the demand is to measure the potential emission reduction level.

For the convenience of comparison, this study assumes that if enterprises do not participate in the transaction, there is still economic potential achieved by relying on resource optimization. Thus, to avoid the situation of economic potential differences caused by reasons other than market transactions, this study compares the economic potential differences before and after market transactions. Assuming that the potential economic output generated by not participating in the carbon and energy markets is PE , the model of not participating in market transactions can remove all transaction constraints from eq. (5).

The growth rate of potential economy (CP) is calculated as follows:

$$CP = \frac{(PG + y) - (PE + y)}{PE + y} * 100\% = \frac{PG - PE}{PE + y} * 100\% \quad (6)$$

3.5. Data

This study takes the data of 30 provinces in China (excluding Tibet, Hong Kong, Macao, and Taiwan) in 2019, including electricity, non-electric energy, capital, labor force, GDP, and total population. The above data are from the China Statistical Yearbook, China Labor Statistics Yearbook, China Energy Statistical Yearbook, China Electric Power Industry Annual Development Report, and Statistical Yearbook of various regions. The provincial capital stock calculation method is the perpetual inventory method (Shan, 2008). The specific data descriptions are shown in Table 1.

The formula for calculating carbon emissions is as follows:

$$C = \sum_j E_j \times \alpha_j \times \beta_j \times \frac{44}{12} \quad (7)$$

Here, E_j refers to the consumption of the j -th energy (unit: 10,000 tons, 100 million cubic meters), and α_j is the standard coal coefficient converted to the j -th energy. Further, β_j represents the carbon emission coefficient of the j -th energy, and $44/12$ is the mass conversion coefficient of CO₂ molecules oxidized by carbon atoms. Moreover, C represents the CO₂ emissions of the industry, and the relevant parameter refers to the IPCC (2006).

As shown in Fig. 4, from the perspective of power transfer, the western region is the main force of power transfer, with Inner Mongolia, Shanxi, Yunnan and Sichuan being the largest. Inner Mongolia and Shanxi are dominated by thermal power, while Yunnan and Sichuan are dominated by hydropower. Inner Mongolia is mainly exported to Hebei, and Yunnan is mainly exported to Guangdong. In the northwest region, Ningxia, Gansu and Xinjiang are also the major provinces for power transfer. Xinjiang is mainly exported to Henan, Gansu to Ningxia and Ningxia to Zhejiang. Guangdong, Hebei, Jiangsu and Zhejiang are the main recipients of external power transfer. Guangdong is dominated by hydropower, while Hebei, Jiangsu and Zhejiang are dominated by thermal power.

4. Results and discussion

4.1. Carbon emission allocation under different principles

There is a clear difference in the allocation of CO₂ between the efficiency and grandfather methods. As shown in Fig. 1, compared with the grandfather method, Inner Mongolia, Shanxi, Ningxia, Xinjiang, Shandong and Hebei are the main force of CO₂ quota transfer. Beijing, Shanghai, Zhejiang, Hubei, Hunan, Guangdong, Sichuan, and Yunnan received excessive carbon allowances, with Sichuan having the most. Similar to the results in Cui et al. (2021), Guangxi and Hainan have received many carbon allowances. Intuitively, CO₂ quotas are mainly transferred from the economically backward western regions and central and eastern regions dominated by thermal power to the economically developed eastern regions and central and western regions dominated by clean electricity. Sichuan and Yunnan are dominated by hydropower, which accounts for more than 80% of electricity. Owing to the development of a large amount of clean electricity, these regions have received more CO₂ quotas, which they can use to trade in the carbon market to obtain additional economic support to develop more clean electricity. Shandong, Inner Mongolia, Shanxi, and Xinjiang are dominated by thermal power, with thermal power accounting for more than 77%. These areas will receive less CO₂ quotas than before. Owing to the lack of it, these areas will buy more CO₂ quotas, which will increase the cost of electricity production. Meanwhile, these areas will also be motivated to develop clean electricity actively. Guangdong's thermal power is also relatively high, at 66.4%; however, its high utilization efficiency in power has led to an increase in CO₂ quotas.

4.2. Comparison of equity and efficiency

The Gini coefficient is the most widely used measure of distributional equity. Generally, a Gini coefficient value of less than 0.2 means absolute fairness, that between 0.2 and 0.3 means fairness, that between 0.3 and 0.4 means relatively reasonable, that between

Table 1
Sample data.

	Min	25%	50%	75%	Max	Mean	Variance
Labor (10,000 persons)	330.20	1398.99	2154.70	3822.95	7150.25	2764.02	1825.09
Capital stock (100 million RMB)	16,494.22	57,517.55	88,367.88	142,001.50	267,352.96	105,298.32	66,542.32
GDP (100 million RMB)	2941.10	14,733.95	24,761.30	41,718.48	107,986.90	32,687.42	25,673.82
Population (10,000 persons)	608.00	2566.75	3924.50	6256.25	11,521.00	4667.80	2855.28
Electricity (100 million kWh)	354.58	1196.81	1885.75	2809.62	6695.85	2405.93	1679.16
Non-electric energy (10,000 tons of standard coal)	1827.16	7541.75	10,903.99	17,790.29	32,994.32	13,280.17	7653.72
CO ₂ of electricity (10,000 tons)	820.66	6312.12	11,250.61	20,709.24	48,203.50	14,587.68	11,763.22
CO ₂ of non-electric energy (10,000 tons)	2596.70	13,034.40	17,079.89	26,398.74	313,514.60	30,124.45	54,944.52

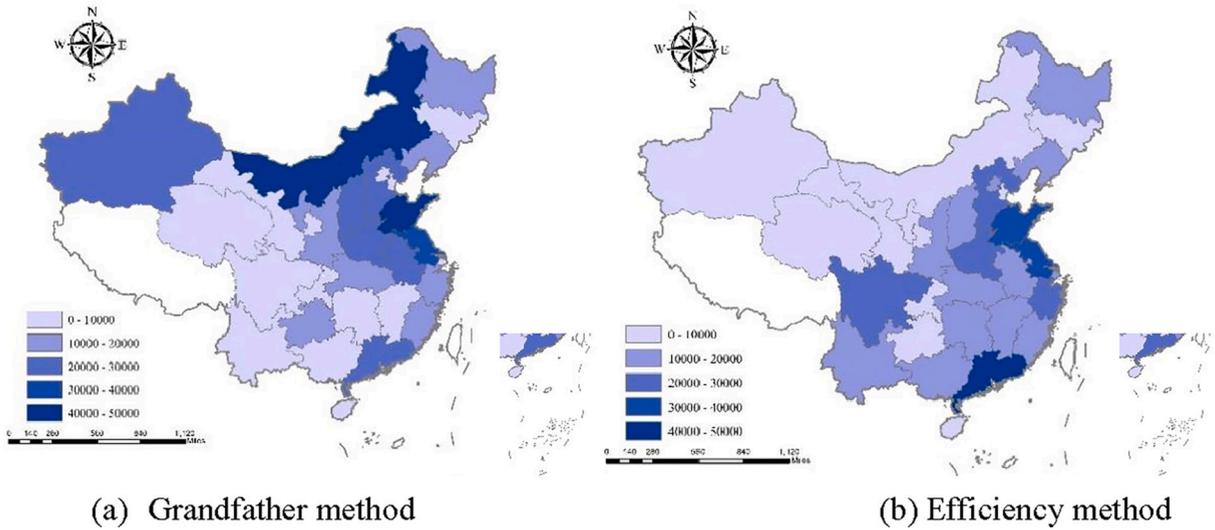


Fig. 1. Carbon emission quota in each region based on different principles.

0.4 and 0.5 means a large gap, and that above 0.6 means a huge gap. As shown in Fig. 2, under the principle of efficiency, various Gink coefficients lie between 0.1 and 0.4—between absolutely fair and relatively reasonable. Under the grandfather method, various Gink coefficients are higher than those of the efficiency method and even exceed the warning line of serious unfairness. Notably, the efficiency method can improve the fairness of the distribution. Under the allocation of efficiency method, the efficiencies of all decision-making units are effective. Under the grandfather method, the efficiency values are much smaller than that of the efficiency method. In many studies, the efficiency method can allocate carbon quota more effectively (Cai & Ye, 2019; Cui et al., 2021; Fang et al., 2019; Yu et al., 2019). Overall, the efficiency method is fair and efficient compared to the grandfather method.

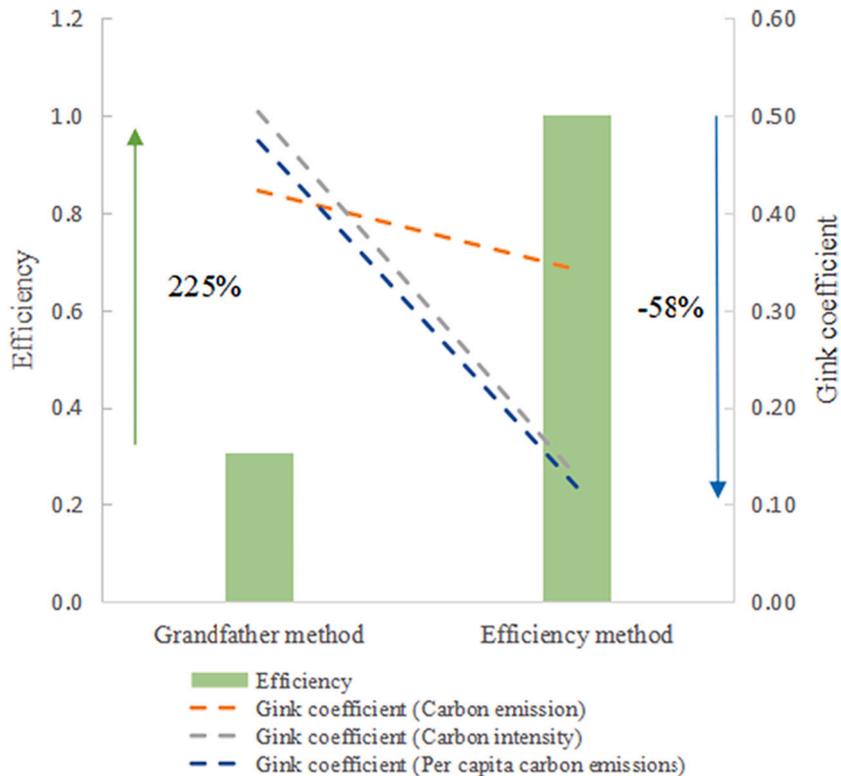
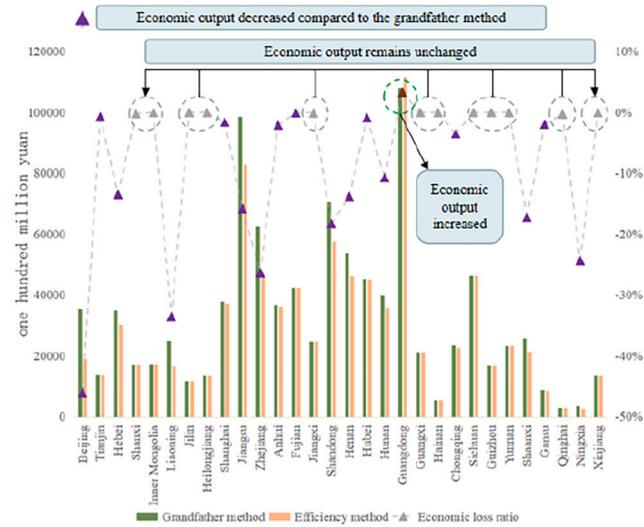
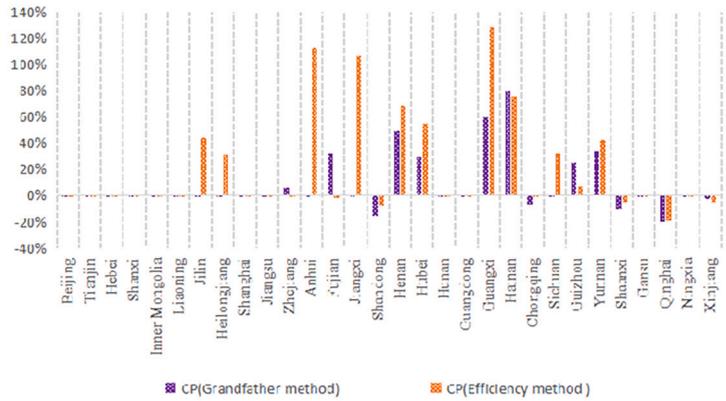


Fig. 2. Comparison of equity and efficiency.



(a) Potential economic output at advantage

(b) Economic loss at disadvantage

Fig. 3. Output caused by different positions of the power industry.

4.3. Comparison of principles under uncertainty

The cost of emission reduction in the power industry is also low. Under the carbon market in future, it is difficult for the power industry in the western region to purchase sufficient CO₂ quotas at a reasonable price; this will lead to fewer CO₂ quotas in the power industry in the western region. It will be at the disadvantage of carbon trading and price competitiveness, which will affect the power transmission from west to east. This study subsequently discusses the situation where the power industry is in advantageous and disadvantageous positions in the carbon market.

4.3.1. Comparison of potential economic output under uncertainty

This section explores the trading behavior arising from the two allocation principles in the electricity, non-electric energy, and carbon markets. Fig. 3 shows that the economic potential of Fujian, Jiangxi, Henan, Hubei, Guangxi, and Hainan has increased more. Different from the results in Wu et al. (2020), the regions with large economic potential are concentrated in Tianjin, Beijing, Shanghai and other regions. However, in study of Liu and Wang (2020), economic potential is zero in Beijing, Tianjin, Shanghai, Jiangsu, Guangdong and Inner Mongolia. They conclude that the market transaction mechanism cannot change their production behavior, that is, the production in these regions has reached the optimal and saturated level. In our study, those with great economic potential are concentrated in the central region. We believe that carbon trading has changed the production behavior of these regions and improved the efficiency of resource utilization. Compared with the grandfather method, the efficiency method has stimulated the economic potential of more regions, such as Jilin, Heilongjiang, and Anhui. Overall, the efficiency method sacrifices the economic potential of some regions in exchange for greater economic potential in other regions. Further, the allocation of resources is optimized to avoid excessive concentration of resources and unnecessary waste.

When the power industry is in a disadvantageous position, under the efficiency method, provinces that transfer electricity are seriously affected by their own carbon quota restrictions, cost constraints, and disadvantageous positions in the carbon market, which affect the power transfer. Electricity is the basic energy for economic development, and the lack of it will cause serious damage to the economy. The qualitative result is similar to Zhang, Zhang, Liu, and Bi (2013). They investigated the underperforming emission trading markets in China, and they found there are obvious differences between the complete competitive market and other markets with policy interference. The cost saved in other markets is far less than that in complete competitive markets. Many research results

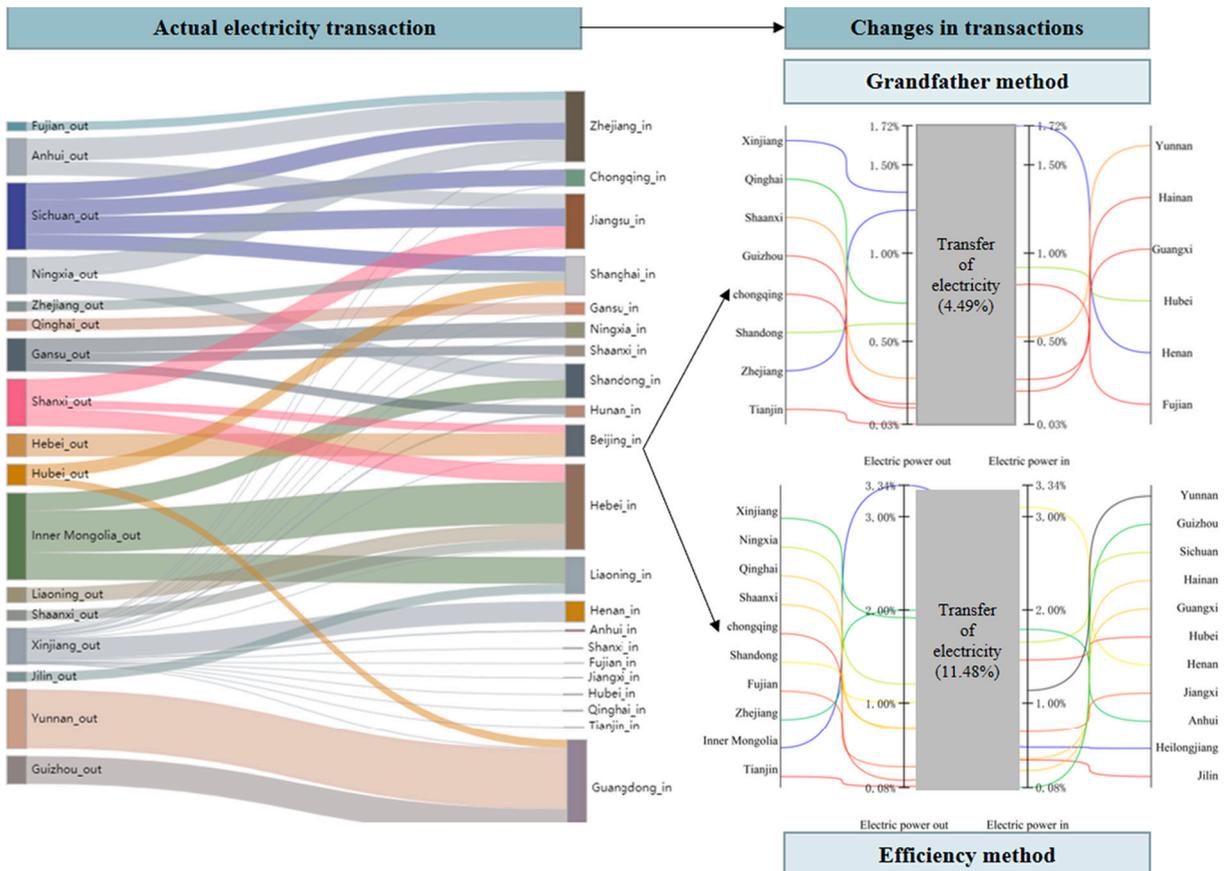


Fig. 4. Electricity market transactions at an advantage.

assume that the trading subject is in a complete competitive carbon market (Fare et al., 2013; Liu & Wang, 2020; Wu et al., 2020) and ignores various risks, thus overestimating the benefits of the economy, market and environment. Meanwhile, they also did not assess potential losses and potential risks. In this paper, when the power industry is in the market of CO₂ without government intervention, as low electricity prices cannot compete with high carbon prices, carbon trading cannot flow to areas with demand and low efficiency, but to areas with high efficiency, which results in power shortage. As shown in Fig. 3, the economies of Beijing, Jiangsu, Zhejiang, and Shandong have been affected the most. Conversely, most areas in the western region have been less affected, which also shows the importance of the West-East Power Transmission to the economic development of the eastern region. Owing to excess carbon quotas in Yunnan and other regions, more electricity may be sent to Guangdong, which can only increase 358.2 billion RMB by using excess external power and account for only 3.32% in economic output. This is far from compensating the losses suffered by the entire economic system. From the perspective of the proportion of economic losses, Beijing was the most affected, followed by Liaoning. In the western region, Ningxia and Shaanxi were severely affected. The losses in the eastern region, the central region and the western region were - 7.29%, -1.32% and - 0.65%, respectively. Hainan, Jilin, Heilongjiang, Inner Mongolia, Guangxi, Sichuan, Guizhou, Yunnan and Xinjiang did not suffer any losses. Overall, when the power industry is at a disadvantage, under the efficiency method, the economic interests of most regions are damaged, and it is only beneficial to the economic development of Guangdong.

4.3.2. Comparison of the electricity market activity under uncertainty

Under the premise of satisfying the original power transaction, when the power industry is in an advantageous position, as shown in Fig. 4, under the grandfather method, Zhejiang and Xinjiang transferred the most electricity, accounting for 0.18% and 0.20% of the total electricity, respectively. The western region is the main force of electricity transfer, accounting for 0.39% of the total electricity and 58.34% of the total electricity transfer. The central region is the main receiving area of electricity, and the received electricity accounts for 0.39% of the total electricity. Further, under the efficiency method, Zhejiang and Inner Mongolia transferred the most electricity, accounting for 0.29% and 0.49% of the total electricity, respectively. The western region is the main force of power transfer, accounting for 8.08% of the total electricity and 70.36% of the total electricity transfer. Moreover, under the optimization of resource allocation, parts of the central, western, and eastern regions have received more electricity for economic development, among which Henan and Anhui have received the most electricity. The efficiency method causes more electricity transactions than the grandfather method. Xinjiang, Qinghai and Shaanxi have transferred a large amount of electric energy, which is consistent with Liu and Wang (2020). The difference is that the central region is the main inflow area of electric energy in the electricity trading market in this paper. It shows that the carbon trading market and energy trading market have changed the production activities in the central region and stimulated the economic potential.

When the power industry is in a disadvantageous position, based on the efficiency method, the total amount of electricity that each region is willing to generate and transfer according to carbon quotas is 502.355 billion kWh. However, the total amount of main transfer electricity selected in this study based on the statistical yearbook is 1073.928 billion kWh. Of the transfer electricity, 53.22% is

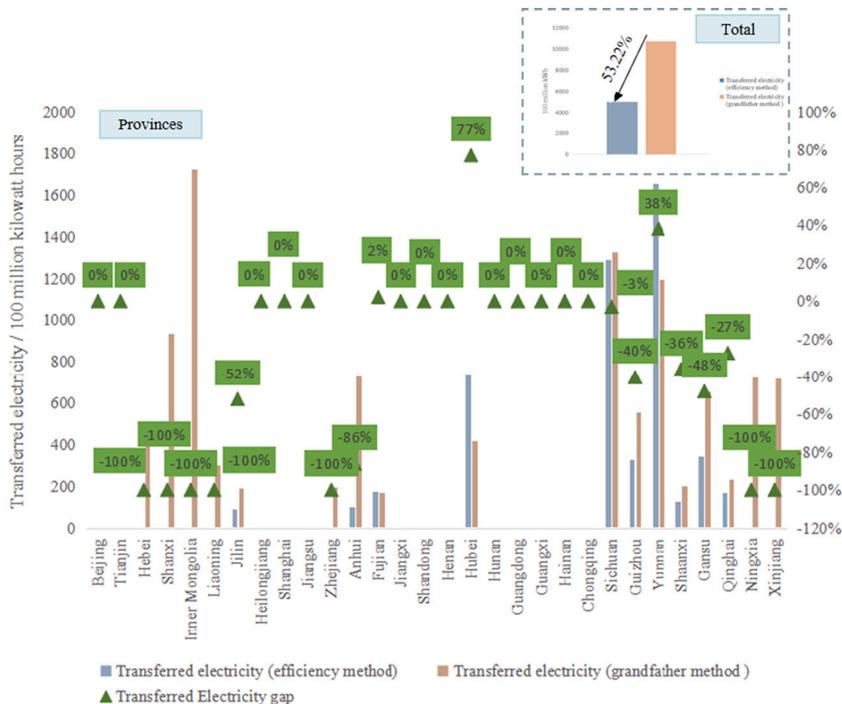


Fig. 5. Electricity transfer at a disadvantage.

not met, which will significantly damage the economic development of the electricity receiving area. The problem of power shortage caused by carbon quota allocation has not been answered in some literatures. The results in Liu and Wang (2020) conclude that energy and carbon emission rights have reached the market clearing state. We believe that they ignored the disadvantageous position of the power industry in the carbon market. As shown in Fig. 5, if the electricity price is controlled by the government and is considerably low, Inner Mongolia, Shanxi, Ningxia, Xinjiang, and Hebei will not have the motivation to transfer electricity for the development of other regions. Hubei, Yunnan, and Sichuan are willing to produce electricity and transfer it to other provinces due to the high allocation efficiency of electricity resources and excess carbon quotas. Other large power generation provinces such as Inner Mongolia, Shanxi, Xinjiang, and other places have low power allocation efficiency and less carbon quotas allocated. The power generation companies do not use sufficient carbon quotas for the current economic development; thus, they purchase excess carbon quotas in the carbon market to generate electricity. On the one hand, the profits of power companies are not high, and a small amount of carbon quotas increases the cost of electricity production. Subsequently, profits are further reduced, leading power companies with small quotas to a disadvantage in the carbon market. On the other hand, under the action of a complete carbon market, the allocation of carbon quotas will be optimized and actively flow to high-profit industries. These industries have greater advantages in price competition. Therefore, these regions with a small amount of carbon quotas would generate sufficient electricity for their own province rather than have an incentive to generate excess electricity. Under the efficiency method, it is difficult for the eastern region to receive the power transferred from the western region. Although some developed eastern regions have been rewarded with carbon quotas due to the high efficiency of power resource allocation and gained additional income, they have also lost external power, resulting in huge losses to the local economy. If they want to continue to transfer electricity from the west, they must give sufficient carbon quota compensations, such as lower prices. However, these measures will affect the operation and development of the carbon market.

4.3.3. Comparison of emission reduction space under uncertainty

As shown in Fig. 6, the abscissa and ordinate represent the emission reduction ratios of the power industry and CP value, respectively. The two indicators of CP value and emission reduction space are opposite. To obtain higher emission reduction space, a certain CP value must be sacrificed, which is in line with the assumption that economic and carbon emissions increase and decrease simultaneously. The qualitative results are consistent with He, Zhang, Li, and Chen (2021), and there is this difference in numerical value. In their study, the emission reduction space under the disadvantageous position is ignored. Assuming a carbon emission reduction behavior in the industry, when the economic potential increment is zero, the industry will not implement emission reduction measures. When the industry is in an advantageous position in the carbon market, the emission reduction potential of the efficiency method is higher than that of the grandfather method, which is 6.40% compared with 5.13% for the grandfather method. The CP of the efficiency method is higher than that of the grandfather method, but it is more sensitive to carbon emission reduction than the latter. When the carbon emission reduction rate reaches 6%, the CP decreases rapidly. When the industry is in a disadvantageous position, the efficiency method cannot meet the electricity demand of west-east electricity transmission, and the overall economy is seriously damaged. As the government’s first priority is to develop the economy, cutting emissions in this case is meaningless. Therefore, the government will not force each region to take initiatives to reduce emissions—there is zero potential for emission reduction.

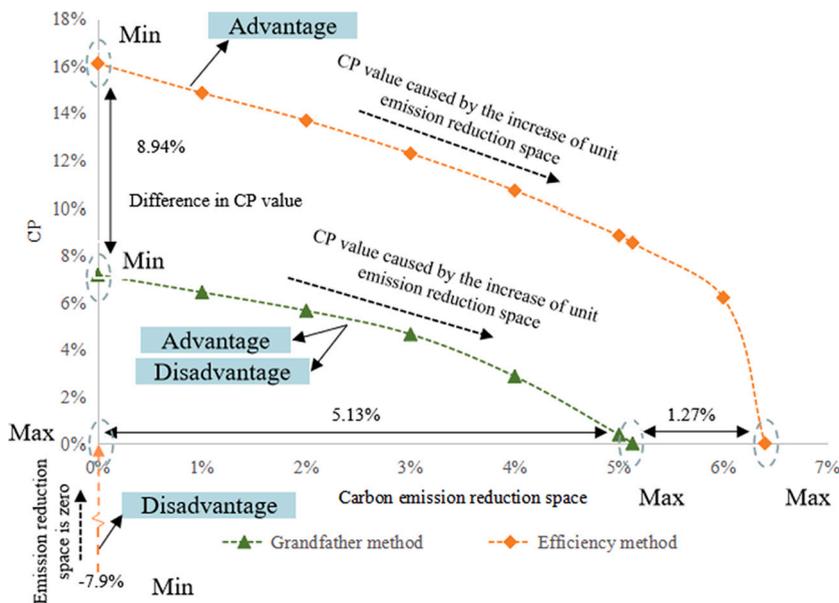


Fig. 6. Emission reduction space under different allocation principles.

5. Conclusions and policy recommendations

This study discusses the impact allocation of carbon quota under different principles under electricity and carbon market uncertainty scenario. Based on the potential status of China's power industry in the future carbon market, we investigate the potential economic output, electricity market activity, and emission reduction space under different principles of carbon quota allocation. These evaluations are made based on model of energy and carbon markets transaction combined with inverse DEA method.

The results show the following. From the perspective of potential economic output, when the power industry is in an advantageous position in the carbon market, CP under the efficiency method is the largest, and the regions with large CP are mainly concentrated in the central region. However, when it is in a disadvantageous position, it will seriously damage economic development. The grandfather method can avoid this loss under this scenario, with much lower CP than that of the efficiency method at an advantage position. From the perspective of electricity market activity, when power market is in an advantageous position in carbon market, the electricity transaction under the efficiency method is more active than the grandfather method. While in a disadvantageous position, the electricity transaction drop by 12%, which lead to the insufficient supply of power. From the perspective of emission reduction, when power market is in an advantageous position, the emission reduction space of the efficiency method (6.40%) is higher than that of the grandfather method (5.13%).

Considering the impact on regions, when the power industry is in an advantageous position, the economic output of the central region is greater under the efficiency and grandfather methods. Under the premise of satisfying the original transaction, Xinjiang electricity traded the highest amount of electricity under the efficiency method, and Inner Mongolia traded the most electricity under the grandfather method. When in a disadvantageous position, under the efficiency method, 53.22% of the power gap is formed caused by the lack of the motivation to produce electricity in Inner Mongolia, Shanxi, Ningxia, Xinjiang, Hebei and other areas. The economic losses in the western region are smaller; the largest is in the eastern region, among which Beijing is the most serious. The losses in the eastern region, the central region and the western region were -7.29% , -1.32% and -0.65% , respectively. Moreover, Inner Mongolia, Shanxi, Ningxia, Xinjiang, and Hebei will not transfer electricity to other areas. Meanwhile, due to the possibility of economic loss, the emission reduction space is zero. Unlike the efficiency method, the grandfather method avoids economic losses by guaranteeing electricity transactions. In terms of equity and efficiency, the efficiency method is far superior to the grandfather method from carbon quota, carbon intensity and per capita carbon quota. But the losses caused by the efficiency method allow us not to ignore its potential huge risk losses under the disadvantageous position. Efficiency method seems to be both fair and efficient, but under the uncertain market mechanism, the comparison between fairness and efficiency may not be able to play its due potential. On the contrary, there may be greater potential risks.

Our results have important implications for the decarbonization process, not only for China but also for any country or region that similar power market with potentially increasing uncertainties under future carbon market. Choosing the efficiency allocation principle might seem the best choice. However, with the restructuring process of China power industry, the chance of our power sector in disadvantageous position in the carbon market and the potential damage of it on economics and decarbonization will gradually emerge. Different quota allocation principles will generate different impacts. The efficiency method, which has been regarded as the ideal method of CO₂ allocation, might cause a series of problems and lead to reduced economic output in this case. Our results highlight this uncertainty in the accelerating process of the construction of national electricity market and address the urgency of policy to tackle this issue to facilitate a carbon market that operates robustly under uncertainty.

Several measures and policy approaches can be adopted to address this challenge. First, the government should track and analyze the participation of power sector in the online trading of the national carbon market and reasonably evaluate the advantages and disadvantages of the existing allowance allocation method under different uncertainty scenarios. Second, it is recommended that government establish normal quota and emergency adjustment mechanisms to predict and avoid potential risks that the carbon market may bring to the power industry. Meanwhile, the allocation of carbon quota should be comprehensively considered considering countries' economic development stage, energy and power transition, international carbon emission reduction responsibilities, and the degree of electricity marketization.

Author contributions statement

Z.H.W. and B.W. designed the study; J.Y.L., Z.H.W. and K.N.S. completed data processing and visualization; J.Y.L., B.L. B.W. and M. F. completed model related work; Z.H.W., J.Y.L. and B.W. wrote the first draft; Z.H.W., B.W., Z.B. and B.L. contributed to the interpretation of the results.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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