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Initial Provincial Allocation and Equity Evaluation of China's Carbon Emission Rights—Based on the Improved TOPSIS Method

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Abstract: As the world's largest carbon emitter, China considers carbon emissions trading to be an important measure in its national strategy for energy conservation and emissions reduction. The initial allocation of China's carbon emissions rights at the provincial level is a core issue of carbon emissions trading. A scientific and reasonable distinction between the carbon emission rights of provinces is crucial for China to achieve emissions reduction targets. Based on the idea of multi-objective decision-making, this paper uses the improved Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method to allocate China's initial carbon emission rights to the provinces and uses the Gini coefficient sub-group decomposition method to evaluate the fairness of the allocation results. First, the results of a theoretical distribution show that in the initial allocation of carbon emission rights, a large proportion of China's provinces have large populations and high energy use, such as Shandong Province, Jiangsu Province, Hebei Province and Henan Province; the provinces with a small proportion of the initial allocation of carbon emissions consist of two municipalities, Beijing and Shanghai, as well as Hainan Province, which is dominated by tourism. Overall, the initial allocation of carbon emission rights in the northern and eastern regions constituted the largest proportion, with the south-central region and the northwest region being the second largest and the southwest region being the smallest. Second, the difference between the theoretical allocation and the actual allocation of carbon emission rights in China was clear. The energy consumption of large provinces and provinces dominated by industry generally had a negative difference (the theoretical allocation of carbon emissions was less than the actual value), while Qinghai, dominated by agriculture and animal husbandry, showed a positive balance (the theoretical allocation of carbon emissions was greater than the actual value). Third, the results based on the Gini coefficient showed that the carbon emission right allocation scheme proposed by the Topsis model in this paper has good fairness. Fourth, the economic development structure, technological innovation level, carbon emissions and other indicators have certain impacts on the fairness of the initial allocation of carbon emission rights. Finally, this paper offers some suggestions on energy conservation and emissions reduction in China, taking four aspects into account: regional disparities, technological innovation, industrial structure and the initial allocation of carbon emission rights. This paper could be helpful to provide a reference for the rational allocation of China's carbon emission right.

Keywords: carbon emission rights; initial provincial distribution; equity evaluation; TOPSIS; Gini coefficient

1. Introduction

Global warming has become an important international political issue according to the Intergovernmental Panel on Climate Change's (IPCC) third climate change assessment report released in 2001. Establishing a green, low-carbon, sustainable economic system to address global climate change is an important task facing all countries in the world. With the sustained and rapid growth of the population and the economy, China has consumed substantial energy in recent decades, resulting in a high amount of carbon dioxide emissions and a series of environmental problems that have attracted worldwide attention. According to data released by the International Energy Agency (IEA), China emitted 6.2 billion tons of carbon dioxide in 2007 [1], surpassing the United States as the world's most carbon-emitting country. In 2011, China's total primary energy consumption exceeded that of the United States, and in 2013, China's carbon dioxide emissions accounted for 28.0% of the world's emissions [2,3]. In addition, China's carbon emissions continue to rapidly increase; under the benchmark scenario, China's carbon emissions will reach one-third of the world's total emissions by 2020 [4]. Faced with this grim reality, the Chinese government is reducing carbon emissions and developing a low-carbon economy as a national strategy. The Chinese government has made a solemn commitment to the world that, on the basis of the values of 2005, the carbon intensity of 2020 and 2030 will be reduced by 40–45% and 60–65%, respectively. [5]. It will not be easy for China to achieve its ambitious emissions reduction targets is not easy. On the one hand, considering China's economic transformation and the upgrading of its industrial structure for this key period, energy resources in particular, as the main driving force of economic development patterns in the short term, are difficult to fundamentally change. On the other hand, the problem of uneven development between regions remains outstanding; the levels of economic and social development and natural environmental conditions are different in different provinces, and the responsibilities, abilities and needs of provinces are also highly varied, not only leading to regional decreases in carbon intensity that are inconsistent with the national carbon emissions intensity decrease but also indicating that provinces differ in their target times for carbon emissions reductions. The use of market mechanisms can effectively reduce the cost of emissions reduction. The Chinese government has already determined that a nationwide carbon trading system will be established during the 13th Five-Year Plan to reduce the intensity of energy consumption and carbon dioxide emissions.

The core issue of the carbon emissions trading system (ETS) is the initial allocation of emission rights. The initial allocation of different emission rights will impact the operating efficiency of the ETS. During the building of a carbon trading system, the initial emission rights must be fully understood. The initial allocation of carbon emissions rights refers to the emission permits or emission quotas allocated by the government to the carbon emission enterprises in the form of emission permits under the cap-and-trade mechanism. The Clean Air Act Amendment, passed by the U.S. Congress in 1990, formally proposed an initial allocation of carbon emissions. The program proposed three types of distribution: free distribution, public auction and pricing. Among these three, the first two modes of distribution are the most common [6]. Based on different principles, free distribution can also be divided into two types: grandfathering and benchmarking. The grandfathering system refers to the method of determining the initial allocation of carbon emissions based on the historical average emissions of the discharging entity during the base period. Benchmarking means that regulators will establish a benchmark emissions rate for each industry and then multiply the output of the emissions entities by the baseline emissions rate as a quota for the emissions entity [7]. On 18 June 2013, China's first carbon trading platform launched in Shenzhen, marking the fact that the construction of China's carbon market had taken a crucial step. Since then, Beijing, Tianjin, Shanghai, Guangdong, Hubei, Chongqing and other provinces have launched the carbon emissions trading pilot. After more than a year of development, the rules of the carbon trading market in all the pilot provinces gradually improved. Similar to foreign carbon trading markets, China's current carbon trading market is also divided into two parts, namely mandatory quota trading and voluntary Chinese Certified Emission Reduction (CCER) transactions, of which quota trading is the mainstay; all seven pilots allowed companies to use a certain percentage of CCER when performing their duties. Most of the seven pilot provinces have allocated quotas to enterprises free of charge. Among them, Guangdong, Shenzhen and Hubei also paid part of their quotas to enterprises in the form of auction bids. On 19 December 2017, the national carbon emissions trading system officially started. A reasonable, fair and efficient initial allocation can maximize the realization of the rational allocation of resources, as well as maximizing the complementary advantages between different provinces; at the same time, it can mobilize enthusiasm for economic development, help avoid unnecessary conflicts of interest and the wasting of resources, and it can promote low carbon industry innovation and the optimization of reform. As China is the largest carbon emitter in the world, the carbon emissions in the various provinces in China vary greatly: China's carbon dioxide emissions have obvious differences between the east and the west. Overall, the developed provinces in the east have the characteristics of large total emissions, low emission intensity, high per capita emissions and high emission density; meanwhile, the central and western regions (especially the western regions) show opposite characteristics [8]. Carbon emissions in Shandong Province account for more than 10% of the national total, while carbon emissions in Beijing, Hainan, Qinghai and other provinces account for less than 2% of the entire country's emissions. Under the premise of ensuring economic growth, an effective initial allocation of carbon emissions will help motivate the provinces in China to implement the strategy of sustainable development, in order to meet the energy saving and emissions reduction goal as soon as possible. Thus, both the intensification of the research on China's carbon emissions trading and the building of reasonable carbon ETSs have important theoretical and practical significance.

2. Literature Review

2.1. Study of the Initial Allocation Schemes of Carbon Emission Rights among Countries or Regions

The methods for distributing international carbon emission rights are mainly divided into two categories: one is developed according to the current status of carbon emissions and the long-term goals of global emissions reduction, based on an emissions per capita allocation; and the other is advocated for by developing countries, emphasizing the cumulative per capita emissions allocated based on historical responsibility [9].

Currently, the EU Emissions Trading Scheme (EUETS) is the largest ETS in the world. The first stage (2005–2007) was conducted by auctioning 5% of carbon quotas and freely distributing the remainder. The second stage (2008–2012) increased the auction quota to 10%, after which large-scale public auctions were used to allocate quotas until the 2013 auction quota reached 50%; a 100% auction is expected in 2027 [10]. In 2009, the Korean cabinet approved a 30% reduction in carbon dioxide emissions by 2020, compared to the general practice of a 5% decrease compared to 2005. Korea also devised a phased carbon trading market plan in 2013 that allocates the initial carbon emissions for free during the first five years and gradually increases the percentage of auctions over time, auctioning 100% of the quotas in the final stage in 2021 [11]. Research by Goulder et al. [12] showed that a considerable auction revenue would be produced only when sufficient free allocation of quotas compensated for the most vulnerable industries (but not excessive compensation), under the conditions of integrating U.S. industry and the overall economic form, and that some vulnerable industries would suffer enormous losses. In 2001, the Netherlands Energy Research Center and the Oslo International Center for Climate and Environmental Studies in Norway developed a more complex global multi-sectoral emissions reduction and sharing program based on the "three sector approach". The program divides the world economy into seven sectors, namely, power generation, industrial, civil, transportation, services, agriculture and waste, and it determines each sectors' carbon emission quotas according to the per capita emissions of countries [13]. New South Wales' initial allocation of carbon emissions to the state's total population and its carbon emissions per capita were set in advance as the basis for calculating the total carbon emissions from the power industry. Second, electricity demand could be used to calculate the proportion of electricity demand and determine the available carbon emission rights [14].

Given the enormous carbon emissions in China and the differences in carbon emissions between regions, the initial allocation of China's regional carbon emission rights has long been a focus of both the government and academia [15–17]. Currently, China has begun its carbon ETS. During the initial stage of carbon emissions trading in China, the implementation of the initial allocation has been coordinated by the relevant departments, and the mixed allocation method is mainly free distribution, with auctions as a supplement [18]. Based on a large amount of foreign experience and many lessons, Lu Chunju and Zhang Ruixue [19] noted that the method currently used, based on a grandfather system that allocates on the basis of historic emissions in China, can easily cause enterprises to exaggerate their declarations of carbon emissions, leading to excessive payments. Qiang et al. [7] considered that China has currently only opened its carbon trading market in seven cities and proposed adopting the benchmarking method, which Beijing decided to implement in 2013. Based on the effectiveness of the market mechanism for the allocation of carbon rights, an increasing number of scholars believe that China should choose to gradually increase the proportion of auction quotas until the auction is completed [20].

2.2. The Distribution Method for the Initial Distribution of Carbon Emissions Rights

The research on the initial distribution of carbon emission rights at home and abroad has mainly used the Zero-Sum Game Data Envelopment Analysis (ZSG-DEA) model, the Shapley model, the multi-region Computable General Equilibrium (CGE) model and the multi-factor comprehensive analysis. Based on a particle swarm optimization (PSO) algorithm, the fuzzy c-means (FCM) clustering algorithm and the Shapley decomposition method of total carbon emissions from 13 factors divided into four categories, Yu et al. [21], divided the 30 provinces of China into four categories, studied the key factors of provincial carbon emissions growth, and identified the initial allocation of carbon emissions quotas. Feng et al. [22] used the improved DEA-based centralized allocation model under the assumption of constant returns-to-scale (CRS) and variable returns-to-scale (VRS) returns to develop a plan for central allocation, citing the empirical applications of the OECD countries. Pang et al. [23] allocated carbon emissions across countries based on the ZSG-DEA model and maximized allocation efficiency. Based on emissions and output allocation rules, Böhringer et al. [24], provided an optimal scheme for carbon allowance under dynamic conditions and found that the grandfather distribution plan worked best in a closed system. However, among trading systems, the grandfather distribution plan is not the best. The drawback of the grandfather system is that it rewards companies that have done the least to reduce emissions in the past, which is not conducive to the goal of the carbon trading scheme. It would be unfair for companies with smaller space and higher energy efficiency to get fewer allocations than inefficient ones because of the early cuts. Additionally, the grandfather system applies only to facilities or capacities that were already operating at the start of a carbon trading transaction. Among open trading systems, this method cannot be corrected automatically for new entrants or additional capacity. In order to avoid carbon emission rights falling into the hands of rivals, some companies may not be willing to sell excess carbon emission rights, which will weaken the carbon emission rights market liquidity. The cost of obtaining carbon rights for new companies will increase, making it difficult for new companies to enter the market.

Tan and Junfei [25] used the ZSG-DEA model to evaluate the efficiency of the quotas for the initial allocation of carbon emissions rights in EU countries in 2009. Based on the total amount of control, Jiekun et al. [26] used the income NDV-DEA optimization model to improve allocation efficiency, considering the grandfather system, the principle of equality and the principle of the ability to pay for the initial carbon emissions allocation in China's provinces. Pan et al. [27] found that the allocation of the original DEA model was less efficient and used the ZSG-DEA model to calculate the carbon emission rights allocation results of six major industries in China. Yong and Shushu [28] considered 14 factors of fairness, efficiency and sustainable development, using the Criteria Importance Though Intercreria Correlation (CRITIC) method and fuzzy optimization to calculate the initial distribution of carbon emission rights in East China. Both Ning [29] and Sufeng [30] adopted the information entropy multi-attribute decision-making model to construct evaluation systems and to estimate the initial allocation quota of carbon emissions rights in the industry and the Chinese provinces. Kai et al. [9] used China's 2030 emission reduction target as the breakthrough point and built an allocation model for carbon emissions rights in China's 31 provinces and municipalities over 15 years a comprehensive use of factor analysis, regression analysis, correlation analysis, cluster analysis and other quantitative methods. Based on the Gini coefficient optimization model, Huihui et al. [31] devised a fair distribution of carbon emission rights in 132 countries worldwide and discussed the remaining carbon emissions in each country. Xiao [32] conducted a carbon emission quota analysis based on forward looking, population, GDP, per capita GDP, and disbursement capacity, finding that forward-looking principles are more suitable for the coordinated development of all provinces in China. Jingjing and Xiangsheng [33] considered the problem of interest games in the construction of carbon emissions trading markets and used the Analytic Network Process (ANP) method and the Shapley model based on weight improvement to allocate carbon emission rights in China.

In summary, scholars at home and abroad have conducted research into the initial allocation of carbon emission rights, laying the foundation for follow-up development in this field. Table 1 provides a summary of the research into the allocation of carbon emission rights. On the whole, there are still some shortcomings in the current research.

(1) The indicators of the influencing factors in the initial allocation of carbon emission rights must be improved. Currently, scholars have mainly considered factors such as population, carbon intensity, GDP, and energy consumption when studying the initial allocation of carbon rights [31,32,34] without considering other factors that reflect sustainable development. The lack of sustainable development factors will result in the unequal distribution of carbon emissions rights, which will lead to an excess of carbon emissions in provinces that have a better environmental infrastructure and a higher technology capacity; this is not conducive to the coordinated development of all the country's regions. In the selection of indicators, some studies have adopted a combination of subjective and objective factors [35–37]. Subjective factors are the individual subjective evaluation scores, which incur the bias of human intention and affect the allocation of carbon rights.

(2) The fairness of the allocation of carbon emission rights must be improved. Most studies only allocated the carbon emission rights regionally and did not further evaluate the fairness of the distribution results [5,25,38]. At the same time, some research used the Gini coefficient to evaluate the overall fairness but did not further explore the reasons for the unfair distribution results.

Considering the existing research, this paper applies the improved TOPSIS method (technique for order preference by similarity to an ideal solution) to China's initial carbon emissions allocation to provinces and the theoretical distribution of carbon emission rights and actual carbon emissions comparative analysis. On this basis, this paper fairly evaluates the initial provincial allocation scheme for carbon emissions. Compared with existing research, the main innovative points of this paper are as follows:

(1) It uses the improved TOPSIS method to conduct the initial provincial allocation of carbon emission rights in China. TOPSIS is a commonly used and effective method for multi-objective decision-making analysis that is also known as the superior-inferior solution distance method. This paper is the first to apply the TOPSIS method to the study of the regional decomposition of carbon emission rights. At the same time, the traditional TOPSIS method mainly relies on subjective judgment when determining the weights of various influencing factors. To eliminate the influence of subjectivity, this paper uses the TOPSIS model improved by the entropy method, with a matrix of evaluation indicators to determine the indicator weight. This method allows it to more objectively reflect the order of information, rendering the evaluation results more practical.

Table 1. Research summary of carbon emission allocation.

Author	Research Methods	Research Purposes	Research Process	Limitations of Research Methods
Yu et al. [21]	Shapley factorization method	Regional allocation of carbon dioxide intensity reduction targets in China in 2020	This paper is based on a particle swarm optimization (PSO) algorithm, the fuzzy c-means (FCM) clustering algorithm and the Shapley decomposition method; after confirming 13 macroeconomic factors and classifying the 30 provinces in China into four categories, the Shapley decomposition method is applied to calculate the emissions reductions in each region.	The Shapley decomposition method belongs to a cooperative game problem, the calculation is more cumbersome, and under normal circumstances, there cannot be meticulous analysis of every province's distribution program, so the provinces are divided into several major areas for a rough analysis.
Feng et al. [22]	Improved DEA under the assumption of CRS and VRS	Allocation of national carbon emissions reduction (CEA) in OECD countries	This paper uses the DEA model to allocate carbon emissions reductions to participating countries to maximize potential GDP and then offers two options to compensate participants for optimal efficiency calculated through the performance evaluation model.	The results of carbon emissions allocation by the DEA model are only a relative efficiency assessment rather than an absolute efficiency assessment. The DEA model is strongly influenced by the selection of input and output indicators. If the indicators are not well selected, the results will be inaccurate. At the same time, the number of targets to be evaluated should be double or more than the sum of the input indicators and the output indicators; otherwise, it will lead to the failure of most of the indicators; Although the DEA can evaluate efficiency, the cause of efficiency or inefficiency still requires further investigation.
Pang et al. [23]	ZSG-DEA model	Redistribution of the global carbon quota	This article uses the ZSG-DEA model to ensure that all countries have 100% efficiency. The results show that the most developed countries should increase their carbon emissions, and the most developing countries are required to reduce their emissions, including China and India, the two most populous countries.	
Pan et al. [27]	ZSG-DEA model	An analysis of the initial allocation of carbon emissions in China's six major industries	In this paper, the initial carbon emissions quotas are iteratively optimized many times to calculate the reasonable allocation results of carbon emissions and the adjustment plan; suggestions for improvement are offered.	
Christoph Böhringer et al. [24]	Based on emissions and output allocation rules	An optimal allocation plan for emissions allowances is derived	This paper provided an optimal scheme for carbon allowances under dynamic conditions and found that the grandfather distribution plan was the best in a closed system. However, as a trading system, the grandfather distribution plan is not the best plan.	Allocation rules are based on emissions, and outputs only consider historical factors such as emissions and do not consider other cases of inter-regional sustainable development, regional economic capabilities and other factors, resulting in allocation results related only to historical emissions.
Chen Yong and Huang Shushu [28]	CRITIC method and fuzzy optimization	Initial allocation of carbon emissions rights in East China	This paper constructs an initial allocation model of carbon emission rights and compares the model results with other distribution schemes.	The CRITIC method allows strong subjectivity in determining the weight vector of the indicator. In the case of too many indicators, the super-fuzzy phenomenon can appear and even result in a failure of judgment.
Min Ning [29]	The information entropy multi-attribute decision-making model	Predicts the initial distribution of China's carbon emissions rights by 2030 in various industries	This paper divides all industries in China into 4 levels, namely, mandatory emissions reduction industries, key emissions reduction industries, encouraging emissions reduction industries, and voluntary emissions reduction industries and allocates carbon emission rights to industries in different sectors.	Entropy is only related to the statistical characteristics of the overall information, but it cannot describe the subjective meaning of the event itself, and the calculation results are not sufficiently accurate.

Table 1. *Cont.*

Author	Research Methods	Research Purposes	Research Process	Limitations of Research Methods
Xie Jingjing and Dou Xiangsheng [33]	ANP	Formulates China's initial carbon emissions rights allocation scheme	After considering the three major principles of the allocation of carbon rights, this paper proposes a carbon rights allocation scheme based on ANP for a game in the initial allocation of carbon rights.	The ANP method requires the support of the expert system. If the indicator is unreasonable, the result is not accurate; quantitative data are small, the qualitative data are many, and the results cannot be convincing; a consistency check is required for multi-layer comparisons, and if inconsistent, the ANP method will be ineffective.
Fang Kai et al. [9]	Regression analysis	Builds a model for carbon emissions rights for China's 31 provinces and municipalities for 15 years	This paper proposes four principles: fairness, efficiency, feasibility and sustainability. It selects distribution indicators from three dimensions, social, economic and environmental, and builds a "common but differentiated" provincial carbon emission rights allocation model, based on which is calculated the allowances for the carbon emissions of 31 provinces in China from 2016 to 2030.	Which factor is used in the regression analysis and which is used is only a guess, but it affects the diversity of the factors and the unpredictability of some factors, which renders regression analysis limited in some cases; it can produce multiple collinearity, and the effectiveness of the results has an impact.
Wang Huihui et al. [31]	The Gini coefficient optimization model	Optimization of carbon emissions distributions in 132 countries worldwide	From the perspective of historical, intergenerational and intragenerational equity, this paper uses the population, GDP and carbon emissions data from 132 countries worldwide to optimize the historical carbon emissions quotas of 132 countries using the Gini coefficient optimization model. At the same time, the future of carbon emissions is fairly allocated.	The Gini coefficient optimization model considers only two indicators, population and GDP, which cannot explain internal differences, and it ignores the impact of some indicators, resulting in the results not being sufficiently accurate.

(2) It enriches the carbon emissions impact of the indicator system. In light of the shortcomings of past studies on carbon rights allocation that used a small number of factors, such as population, carbon emission intensity, GDP, and energy consumption, this paper adds forest cover, the proportion of secondary industries and the market turnover of technology as emissions factors; these three indicators respectively symbolize the accommodation environment, industrial structure and technology innovation ability. The indicator system of the factors influencing carbon emissions, constructed in this paper, better reflects the sustainability of the future development of carbon emissions in all provinces, resulting in research results with more practical significance.

(3) In the context of this research, we evaluate the initial allocation of carbon emission rights fairly and explore the deep-seated reasons for the unfair carbon emissions between regions. After the initial provincial allocation of carbon emissions rights, this paper also uses the Gini coefficient to fairly evaluate the distribution results in a fair manner. At the same time, because the Gini coefficient does not explore unfair factors, this paper further uses the subgroup decomposition of the Gini coefficient to analyze the contributions of carbon emissions to the five major economic regions within and between regions, exploring the underlying causes of the unfair distribution of carbon emissions.

The remainder of this paper is arranged as follows: the third part is the model construction, the fourth part is the calculation of the carbon emissions of China's provinces, the fifth part is the results of the analysis, the sixth part is a comparison and discussion, and the seventh part is the conclusion and suggestions.

3. Methodology

3.1. The Indicator System for the Allocation of Carbon Emissions Rights

Combined with factors such as the policies and targets of China's carbon emissions market, considering the historical conditions for the scale and level of economic development, natural environment and geographical conditions of China's provinces and autonomous regions, this paper considers the principles of fairness, efficiency and sustainable development in terms of carbon emission rights in China to establish a system for the distribution of indicators. Among these, the principle of fairness refers to the reasonable and unbiased allocation of carbon emissions rights to all provinces and autonomous regions, reflecting the right of everyone to enjoy carbon emissions. The principle of efficiency refers to carbon emissions as a scarce resource requiring optimal allocation, limiting investment as much as possible to obtain the maximum output. The principle of sustainable development refers to carbon emission reduction being long-term work; the structural sustainability of social, economic and environmental subsystems must be considered holistically. When carbon emission rights are allocated, the actual emissions of each region should be considered [25,29]. Therefore, a carbon emission indicator should be selected. The population [31] is a positive indicator, and the more people are in a region, the more carbon emissions should be allocated to the region. GDP [25,27] represents the acceptability of local governments. All regions will attach great importance to economic development, so this paper selects the GDP indicator which can fully reflect regional economic capacity, as an indicator for measuring the feasibility of carbon emission right allocation. Energy consumptions [27] are generally positively correlated with carbon emissions, and huge energy consumptions are bound to result in a large amount of carbon dioxide emissions. Carbon intensity [21] refers to the amount of carbon dioxide emitted per unit of GDP, which is used to measure the efficiency of the economic development on carbon emissions, namely, the level of carbon dioxide emissions. The proportion of secondary industry [30] represents the proportion of heavy industry in a region, and heavy industry produces a lot amount of carbon dioxide emissions. Forest cover represents a region's ability to absorb carbon dioxide and is also a symbol of regional emissions potential. The technology market turnover is an area with the ability to develop green, low-carbon and efficient industries through high technology, that also ensures that economic growth and low-carbon emission reduction are carried out simultaneously. So this paper selects provincial carbon emissions, population and GDP as indicators of fairness, selects energy consumption and carbon intensity as efficiency indicators, and selects the proportion of secondary industry, forest coverage and technology market turnover as indicators of sustainable development in 2015, as shown in Table 2.

Table 2. Indicator selection.

Allocation Principles	Indicator Selection
the principle of fairness	carbon emissions GDP population
the principle of efficiency	energy consumption carbon intensity
the principle of sustainable development	the proportion of secondary industry forest coverage technology market turnover

In Table 2, carbon intensity = carbon emissions/GDP, and the proportion of secondary industry = the secondary industry added value/GDP.

The data on the population, GDP, secondary industry added value, forest cover rate and technical market turnover in each province in 2015 were derived from *the Chinese Statistical Yearbook (2016)* [39]; the energy consumption was derived from *the China Energy Statistics Yearbook* [40]. All of the data came from China's 30 provinces, municipalities and autonomous regions, except for Taiwan, the Tibet Autonomous Region, Hong Kong and Macao.

3.2. The Initial Allocation Method of Carbon Emission Rights in Provinces Based on the Improved TOPSIS Method

TOPSIS is a type of sequential optimization technique with ideal target similarity. It is a very effective multi-objective decision analysis method and is widely used in research on target allocation [41–43]. Through the data normalization matrix obtained by vector normalization methods, according to efficiency and cost attributes, it is divided into two types of indicators and determines the best and the worst two targets from multiple targets, that is, the ideal solution and the negative ideal solution. Evaluating the Euclidean distance between the objective and ideal solution and the negative ideal solution, it finds the closeness between each object and the ideal solution and calculates the weight of each target according to this closeness. After the standardization process, the initial allocation quotas of carbon emission rights for all of the provinces are obtained.

The first step is to establish a standard decision matrix.

To eliminate the dimensional relationship between the indicator data, the min–max standardized method is applied to standardize the benefit indicators that affect the initial allocation of carbon emission rights in China. The formula is shown in Equation (1). The cost indicator undergoes a standardized treatment. That formula is shown in Equation (2).

$$x_B = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{1}$$

$$x_C = \frac{x_{\max} - x}{x_{\max} - x_{\min}} \tag{2}$$

The effective indicators are indicators of positive correlations with carbon emission rights, and they include emissions, population, GDP, energy consumption, carbon intensity and secondary industry proportion. The cost indicators are the indicators of negative correlations with carbon emission rights, and they include forest coverage and technology market turnover. Equations (1) and (2), x_B and x_C, represent the standardized values of the benefit indicator and the cost indicator, respectively; x is the actual value of each indicator, and $x_{\max}$ and $x_{\min}$ are the maximum and minimum value of each indicator, respectively.

Furthermore, a standardized decision matrix is obtained:

$$R = \begin{pmatrix} x_{11} & \cdots & x_{1\mathrm{m}} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{pmatrix} \quad (3)$$

In Equation (3), n is the number of evaluation objects, that is, the number of provinces in China; and m is the number of indicators, that is, the factors that affect the allocation of carbon rights.

The second step is to build a weighted norm matrix.

To objectively measure the distribution indicators of the whole system and to avoid human preference behaviors, this paper uses information entropy to determine the weight of each indicator. The basic principle of information entropy is to determine the weight of the information according to the amount of information transmitted by the indicator. The larger the information entropy of an indicator is, the more chaotic the system is, and the more information is needed to determine it. Therefore, if indicator can present less information, the weight of this indicator is very small. In contrast, the smaller the entropy of an indicator is, the greater its weight is. In other words, the greater the information entropy of an indicator, the smaller the weight that affects the initial allocation of carbon emission rights. The normalized decision matrix R is calculated, and the weight entropy formula is shown in Equation (4):

$$e_j = \frac{\sum_{i=1}^{n} p_{ij} \times \ln p_{ij}}{\ln n} \quad (4)$$

In Equation (4), e_j is the entropy of the j indicator, p_{ij} is the proportion of the j influencing indicator in the i province, and n is the number of provinces in China.

$$w_j = \frac{1 - e_j}{m - \sum_{j=1}^{m} e_j} \quad (5)$$

In Equation (5), w_j is the weighted entropy value of each final influential indicator, that is, the weight of each indicator that affects the allocation of provinces; and m is the number of indicators that influence the allocation of carbon emissions. In this paper, $m = 8$.

The weighted normalization matrix formula of the indicator is shown in Equation (6):

$$Q = \begin{pmatrix} q_{11} & \cdots & q_{1m} \\ \vdots & \ddots & \vdots \\ q_{n1} & \cdots & q_{nm} \end{pmatrix} = \begin{pmatrix} w_1 x_{11} & \cdots & w_m x_{1m} \\ \vdots & \ddots & \vdots \\ w_1 x_{n1} & \cdots & w_m a_{nm} \end{pmatrix} \quad (6)$$

The third step is to determine the ideal solution and the negative ideal solution.

$$Q^{+} = \left\{ \max_{1 \le i \le n} q_{ij} | j = 1, 2, \ldots, m \right\} \quad (7)$$

$$Q^{-} = \left\{ \min_{1 \le i \le n} q_{ij} | j = 1, 2, \ldots, m \right\} \quad (8)$$

In Equations (7) and (8), Q^{+} is the ideal solution for each influence indicator, and Q^{-} is the negative ideal solution.

In this paper, the Euclidean distance is used to calculate the distance between the influence indicator of each province and the positive and negative ideal solutions. The formulas are shown in Equations (9) and (10):

$$D_j^+ = \sqrt{\sum_{i=1}^{m} \left(q_{ij} - Q^+\right)^2} (i = 1, 2, \ldots, n) \tag{9}$$

$$D_j^- = \sqrt{\sum_{i=1}^{m} \left(q_{ij} - Q^-\right)^2} (i = 1, 2, \ldots, n) \tag{10}$$

In Equations (9) and (10), D_j^+ and D_j^- are the distances from the influence indicator of each province to the positive ideal solution and the negative ideal solution, respectively. The larger the value of D_j^+ is, the greater is the influence indicator for the positive ideal solution, and the smaller is the initial allocation of carbon emissions rights.

The fourth step is to determine the proportion and quota of the allocation of carbon emissions in the provinces.

Equation (11) shows the calculation of the closeness of the indicators that affect the final distribution ratio in each region, that is, the relative weight of the initial allocation of carbon emission rights in each province:

$$\mathrm{d}_j = \frac{D_j^-}{D_j^- + D_j^+} \tag{11}$$

After d_j is normalized, the initial allocation ratio of carbon emission rights is as shown in Equation (12):

$$p_j = \frac{\mathrm{d}_j}{\sum\limits_{j=1}^{n} \mathrm{d}_j} \tag{12}$$

3.3. The Fairness Evaluation Method of the Provincial Allocation—Gini Coefficient

3.3.1. A Basic Overview of the Gini Coefficient

The Gini coefficient is an indicator of the fairness of income distribution and was invented by American economist Albert Hirschman in 1943. The Gini coefficient is also widely used to judge the distribution of fairness in other fields. At present, the Gini coefficient has been widely used in the field of carbon emission allocation [31,34,44].

As shown in Figure 1, line OY is an absolutely equitable distribution line, which indicates that the carbon emission rights are completely evenly distributed among the influential indicators without any gaps. Curve OY is a Lorenz curve, which curves to the lower right, and the greater degree of bending indicates that the distribution of carbon emission rights in all provinces is less fair. The broken OPY line is an absolutely unfair distribution line, indicating that all of the carbon emission rights are concentrated in one province, and that the other provinces have zero carbon emission rights. In general, the Lorenz curve is located between the absolutely fair and absolutely unfair distribution lines. The area between the actual carbon emission rights initial allocation curve and the carbon emission rights allocation absolute equality curve is A, and the area below the actual carbon emission rights initial distribution curve is B. $A/(A + B)$ can represent the degree of inequality, and this value is called the Gini coefficient or Lorenz coefficient. When the Gini coefficient is 0, it indicates that the allocation of carbon rights is completely equal. When the Gini coefficient is 1, it indicates that the allocation of carbon rights is completely inequitable.

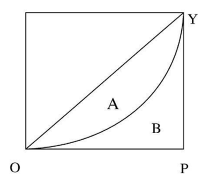


Figure 1. The Gini coefficient.

According to the relevant provisions of the Gini coefficient [31,44], the specific value and meaning of the Gini coefficient are shown in Table 3.

Table 3. The value and meaning of the Gini coefficient.

Gini Coefficient	Meaning
Less than 0.2	Distribution is absolutely fair
0.2–0.3	Distribution is fairly fair
0.3–0.4	Distribution is relatively fair
0.4–0.5	Distribution is not fair
0.5 or greater	The distribution gap is very wide

There are many ways to calculate the Gini coefficient, such as the direct calculation method, group area method, fitting curve method and decomposition method. This paper uses the group area method, the formula for which is shown in Equation (13).

$$G = 1 - \sum_{i=1}^{n} (X_i - X_{i-1})(Y_i + Y_{i-1}) \tag{13}$$

In Equation (13), G is the Gini coefficient, X_i is the cumulative proportion of the influence indicators on the horizontal axis, Y_i is the cumulative proportion of the initial allocation of carbon emission rights on the vertical axis, and n is the number of regions.

3.3.2. Subgroup Decomposition of the Gini Coefficient

Using the size of the Gini coefficient, we can determine the fairness of the initial allocation of carbon emission rights to provinces. This calculation, however, has some limitations: although an overall level of fairness is obtained, it is impossible to judge the unfair factors. Therefore, we introduce the subgroup decomposition of the Gini coefficient to explore the factors that affect the fairness of carbon emissions.

First, the 30 provinces and autonomous regions, excluding Taiwan, the Tibet Autonomous Region, the Hong Kong Special Administrative Region and the Macao Special Administrative Region, are divided into five parts according to the principle of the six administrative divisions of China (North China and Northeast China are one part, collectively referred to as the northern regions); the specific partition is shown in Table 4.

Table 4. The specific zoning of various provinces in China.

Name	Provinces
Northern region	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang
East China	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong
Central-southern	Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan
Southwest region	Chongqing, Sichuan, Guizhou, Yunnan
Northwest region	Shanxi, Gansu, Qinghai, Ningxia, Xinjiang

Currently, the subgroup decomposition of the Gini coefficient is mainly divided into three types [45]. The first type of decomposition calculates the within-group inequality on the overall contribution rate. The second finds the contribution rate of the group in the whole population. However, both of these decompositions ignore the remaining terms that indicate the overlapping of the subgroups. According to Xingjian [46], the residual generated by the overlapping of subgroups indicates the influence of the change in the initial allocation of carbon emissions on the Gini coefficient according to the five regional theories after subgroup clustering. The residuals are generated because the sorting numbers of some provinces will change from the original ones after being sorted according to the initial allocation of carbon emissions rights in the five major regions. Therefore, this paper uses the third decomposition method, which uses the overall Gini coefficient and part of the Gini coefficient to calculate the overall levels of unfairness and inequality within each group; it then calculates the contribution rates of the unfairness degree among the subgroups to the overall unfairness, and it then finds the residual.

The specific calculation model is shown in Equations (14)–(16):

$$G = G_A + G_B + G_R \tag{14}$$

$$G_A = \sum_{i=1}^{k} r_i t_i G_i \tag{15}$$

$$G_B = \frac{1}{2}\sum_{i=1}^{k}\sum_{m=1}^{k} r_i r_m \left| \frac{\overline{E_i}}{\overline{E}} - \frac{\overline{E_m}}{\overline{E}} \right| \tag{16}$$

In Equation (14), G is the total Gini coefficient, G_A is the internal Gini coefficient in each region, G_B is the Gini coefficient in each region, and G_R is the residual. In Equation (15), r_i and t_i are, respectively, the proportions of the indicators of the impact and the proportion of carbon emissions allocation in the i region, and G_i is the Gini coefficient of the i region. In Equation (16), $\overline{E}$ is the average of the ratio of the distribution of carbon emissions to the influence indicators on the x-axis, and $\overline{E}_i$ is the average of the ratio of carbon emissions distribution and the ratio of the influence indicators on the x-axis in the i region.

The complete process of model construction for the initial provincial allocation and equity evaluation of China's carbon emissions rights is represented in Figure 2.

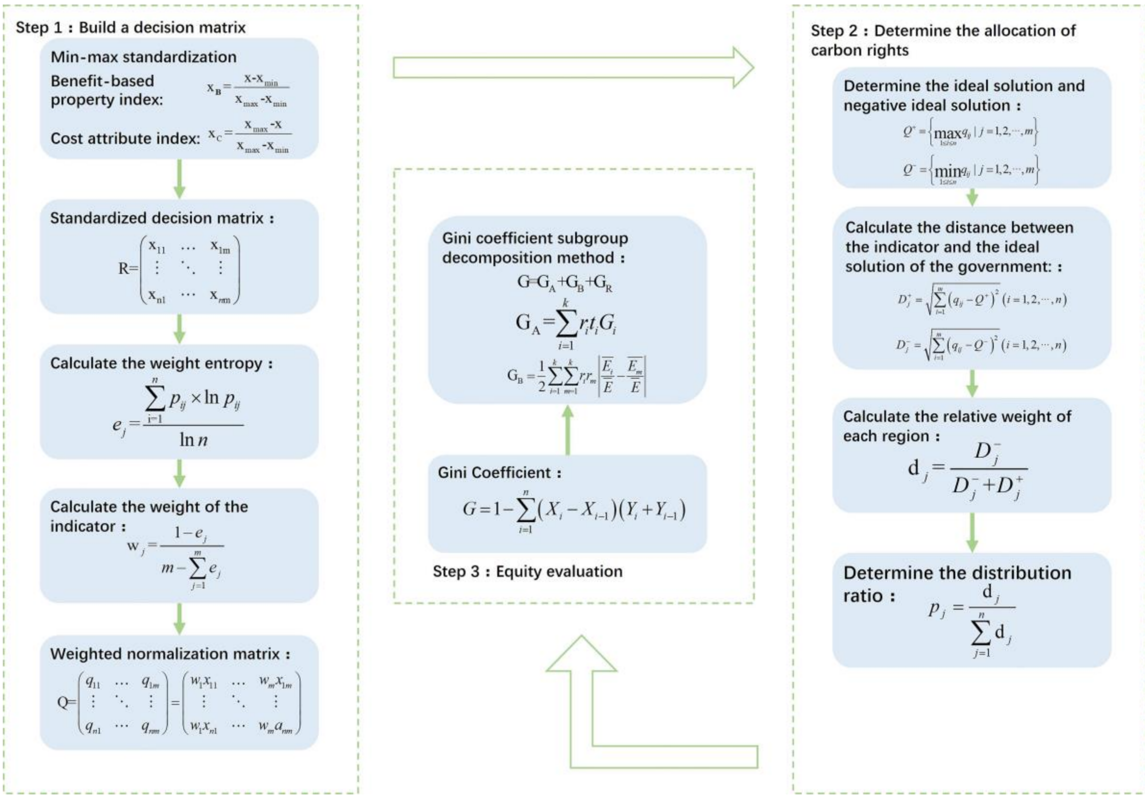


Figure 2. The model building process in this paper.

4. Calculation of Regional Carbon Emissions

Using the recommendations of *The 2006 IPCC Guidelines* [47], this paper uses the emissions of the energy fossil fuel used in each region to calculate the carbon emissions for that region. Based on *The 2006 IPCC Guidelines*, the carbon emissions are calculated as follows, in Equation (17)

$$C = \sum_{i}^{n} E_i \times NVC_i \times CC_i \times COF_i \times \frac{44}{12} \tag{17}$$

In Equation (17), C is the carbon emissions, and the unit is t. i is the i energy source. According to *The 2006 IPCC Guidelines*, energy is divided into eight common categories, namely, coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil and natural gas; E_i is the consumption of the i energy, and the unit is t or m^3; NVC_i is the average low calorific value of the i energy source, and the unit is TJ/tce; CC_i is the carbon content of the i energy source, and the unit is t/TJ. COF_i is the carbon oxide factor of the i energy source; based on *The 2006 IPCC Guidelines*, the emission factor is derived from the 100% oxidation hypothesis, and the value is usually taken as 1; 44/12 represents the ratio of CO_2 to the molecular weight of carbon, namely, the conversion coefficient of carbon into CO_2, and the above data are taken from *The 2006 IPCC Guidelines*.

5. Results Analysis

5.1. Analysis of the Results of the Initial Allocation of Carbon Emissions in the Provinces

5.1.1. The Results of the Initial Provincial Allocation of Carbon Emissions Rights

(1) Results for the weight of each indicator. Using Equations (4) and (5), the indicator weights of 30 provinces and autonomous regions in China are substituted to obtain the final weight entropy of each indicator, as shown in Table 5.

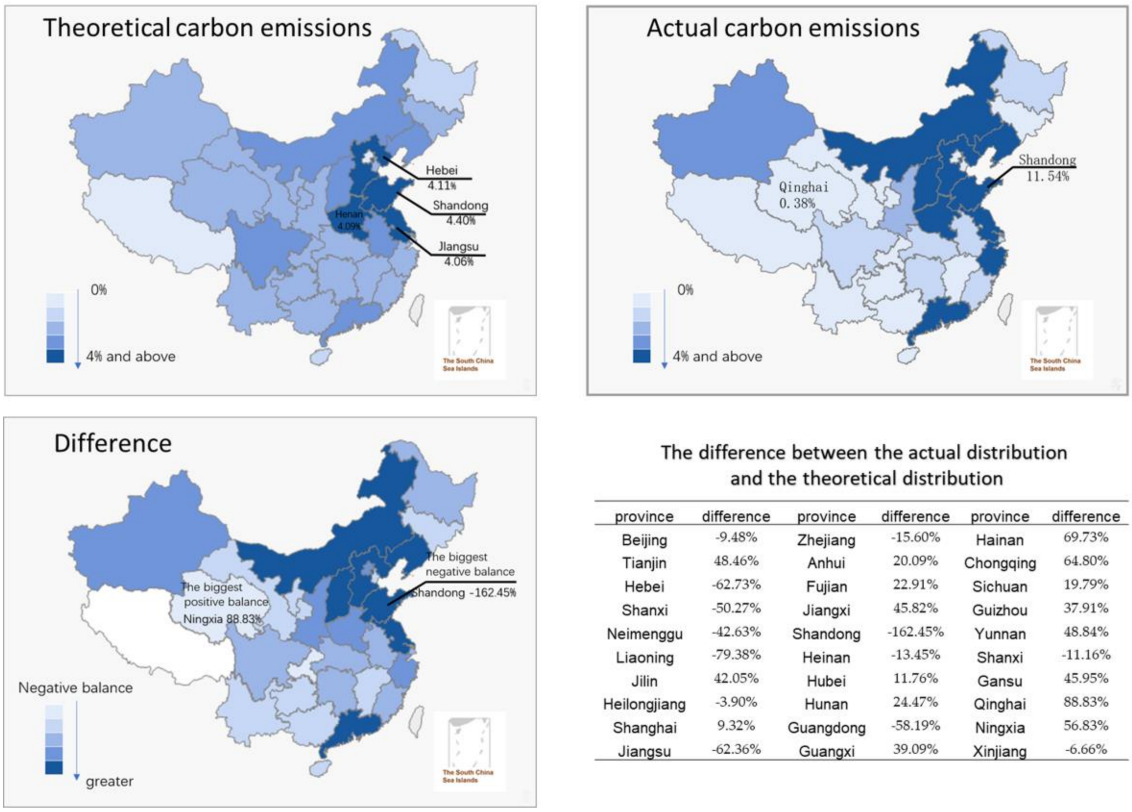
Table 5. Final weight entropy of each indicator.

Indicator	Entropy of Final Weight
actual carbon emissions	5.34%
population	10.66%
GDP	7.39%
energy consumption	10.43%
carbon intensity	5.78%
forest coverage	15.48%
the proportion of secondary industry	21.26%
technology market turnover	23.56%

The final weight entropy in Table 5 shows that the technology market turnover and the proportion of secondary industry account for a large proportion: 23.56% and 21.26%, respectively. The technology market turnover shows the potential for science and technology development in a region where high turnover in the technology market shows that it is capable of using innovative technologies in follow-up low-carbon emission reduction efforts while maintaining strong economic development and achieving low-carbon goals. The proportion of secondary industry represents the industrial structure of a region. Taking into account that the secondary industry is a traditional industry with high consumption, high pollution and high emissions, a large proportion of secondary industry shows that the economic structure of the region must be transformed and optimized. Therefore, it is also an important indicator to measure, as a means of capturing the potential of low-carbon development in a region. The weight of the actual carbon emissions and carbon emissions intensity account for small proportions (5.34% and 5.78%, respectively), indicating that these two indicators play a small role in the initial allocation of carbon emission rights in China. Changing the industry structure will change energy needs, and therefore emissions. At present, as China's economic development enters the "new normal" (with the GDP growth rate droping from double digits to a single digit), China's industrial structure is constantly optimizing and adjusting. At the same time, changes in the industrial structure have largely changed the energy mix. During the 12th five-year plan period, the share of coal consumption fell by 5.2 percentage points, to 64%, in 2015. The share of natural gas consumption rose by 1.9 percentage points [48]. The Chinese government has also taken the improvement of energy structures as an important measure of energy conservation and emission reduction.

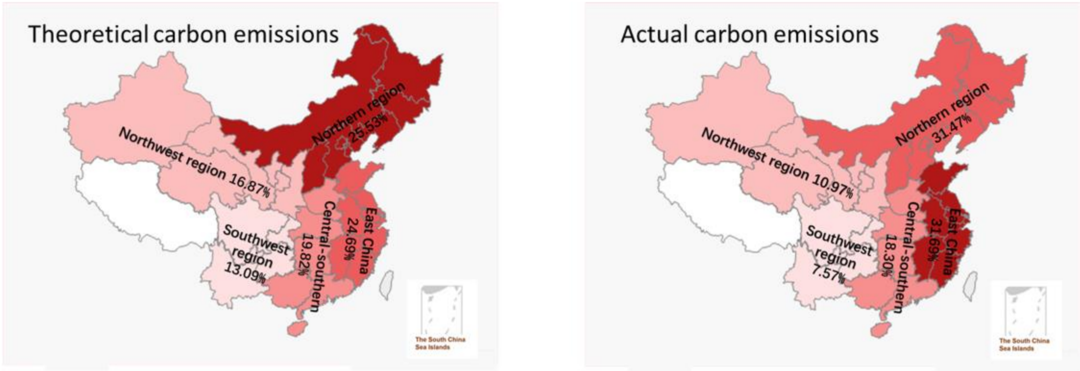
(2) Carbon emission rights allocation program results. According to the improved TOPSIS model, the initial allocation proportion of the carbon emission rights of provinces and the five regions is calculated, as shown in Figures 3 and 4, respectively. The absolute values of the carbon allocation for each province—the current allocation and theoretical ideal are shown in Appendix A.

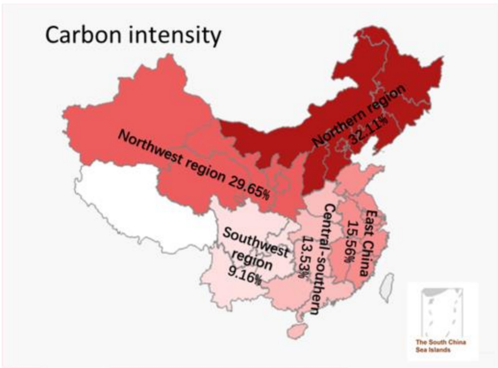
(1) The provinces with a high initial allocation of carbon emission rights are generally China's major population centers and major energy provinces. Figure 3 shows that Shandong Province (48,585, 4.40%), Henan Province (45,204, 4.09%), Hebei Province (45,383, 4.11%) and Jiangsu Province (44,913, 4.06%) are the provinces where the initial allocation of carbon rights is more than 4%. Shandong Province, Henan Province and Hebei Province have large populations. Their economic structures are dominated by industries with high input and high consumption. The cumulative emissions of carbon dioxide of Shandong Province, Henan Province and Hebei Province are also historically high in China. Jiangsu Province has great economic strength, and its GDP ranks second in the country. Moreover, traditional industries with high energy consumption in Jiangsu Province are in a dominant position, and the tension between energy supply and demand is intense. In the future, provinces with a high initial allocation of carbon emission rights will need to increase technology imports, strengthen the knowledge of traditional industries, and give full play to the energy structure in greening and acquiring innovation.



province	difference	province	difference	province	difference
Beijing	-9.48%	Zhejiang	-15.60%	Hainan	69.73%
Tianjin	48.46%	Anhui	20.09%	Chongqing	64.80%
Hebei	-62.73%	Fujian	22.91%	Sichuan	19.79%
Shanxi	-50.27%	Jiangxi	45.82%	Guizhou	37.91%
Neimenggu	-42.63%	Shandong	-162.45%	Yunnan	48.84%
Liaoning	-79.38%	Heinan	-13.45%	Shanxi	-11.16%
Jilin	42.05%	Hubei	11.76%	Gansu	45.95%
Heilongjiang	-3.90%	Hunan	24.47%	Qinghai	88.83%
Shanghai	9.32%	Guangdong	-58.19%	Ningxia	56.83%
Jiangsu	-62.36%	Guangxi	39.09%	Xinjiang	-6.66%

Figure 3. Actual distribution results and theoretical results for the carbon emission rights of all provinces in 2015.





Region	Population	GDP	Energy consumption	Forest cover rate	The proportion of the second industry	Technology market turnover
Northern region	20. 67%	21. 86%	27. 61%	23. 18%	25. 65%	47. 87%
East China	29. 49%	36. 83%	29. 14%	25. 79%	24. 71%	20. 81%
Central-southern	28. 28%	26. 16%	22. 21%	27. 32%	19. 48%	17. 20%
Southwest region	14. 25%	9. 68%	11. 29%	16. 20%	12. 97%	4. 46%
Northwest region	7. 32%	5. 47%	9. 74%	7. 50%	17. 19%	9. 66%

Figure 4. The proportion of each indicator in the five major regions in 2015.

(2) The provinces with a small proportion of the initial allocation of carbon emissions include two municipalities, Beijing and Shanghai, and also include Hainan Province, which is dominated by tourism. The initial distribution of carbon emission rights is the lowest in Beijing (10,538, 0.95%), and the initial allocation of carbon emission rights in Shanghai (32,158, 2.91%) is also significantly lower than the national average. The low initial allocation of carbon emission rights in Beijing and Shanghai is results mainly from the fact that these municipalities are far ahead of other provinces in applying science and technology as part of their innovation capability, demonstrating that they have a strong potential for reducing emissions through science and technology. In the meantime, the Chinese government has always attached great importance to the development of low-carbon industries in large cities such as Beijing and Shanghai, and it has exerted greater efforts in its policy supervision and regulation, as the result of which the industrial structures of these cities have been constantly adjusted toward the development of tertiary industry based on the financial services industry. Hainan Province (26,101, 2.36%) has a smaller initial allocation of carbon emission rights. With tourism as its main economic structure, it has a relatively small population and few industries, and its historical carbon emissions are also low.

(3) Figure 4 shows that carbon emissions in the north and east of China are high, while carbon emissions in the southwest are low. The high carbon emission intensity in northern China is related to the richness of coal resources, and energy consumption depends on coal. GDP, population and energy consumption in East China are all in relatively large proportions. The geographic environmental resources are relatively abundant, and while maintaining economic development, they also result in relatively high carbon emissions. The proportion of indicators in Southwest China is relatively small, and the ability to engage in technological innovation is lagging, showing that the southwest is at a disadvantage in terms of resources and that the improvement of scientific and technological means could give full play to the role of technology in emissions reduction. With the general increase in pressure for emissions reductions in various regions, the overall emission reduction problem would not be solved if only the industries in developed areas with high energy consumption and

serious pollution were relocated to backward areas; only by further improving the level of science and technology, will the industrial structure, and energy efficiency provide the right path for China's low-carbon development.

5.1.2. A Comparative Analysis of the Results of the Initial Provincial Allocation of Carbon Emission Rights and the Actual Situation

(1) On the whole, there are 18 provinces that present positive differences between the allocation of initial carbon emission rights and the actual situation, and there are 12 provinces that show negative differences. Specifically, a negative difference between the initial allocation of carbon emission rights and the actual allocation occurs mainly in areas where heavy industry accounts for a large proportion (such as Shandong and Liaoning) and in areas with rapid economic growth (such as Jiangsu and Guangdong). The proportion of actual carbon emissions in these provinces is more than their share of the theoretical distribution. Therefore, they must increase the pace of energy conservation and emissions reduction, follow the road of low-carbon green development, and gradually reduce the negative balance. Areas with positive differences between the proportion of initial provincial distribution and the actual proportion of carbon emission rights are those with backward technological innovation capacity (such as Qinghai and Hainan). The actual carbon emissions in these regions are lower than the share of the theoretical distribution, and the positive development potential of carbon emissions allocation provides these regions with better space for development. At the same time, they can also sell emissions rights to other regions in exchange for development funds, while vigorously developing their scientific and technological innovation abilities to expedite the development of the region.

(2) Judging from the distribution ratio and the actual ratio, the province with the largest negative difference between theoretical carbon emissions rights and the actual distribution is Shandong Province (−78,925, −162.45%). Shandong Province is the traditional major carbon emissions province; its energy consumption and carbon emissions are ranked first in the country. At the same time, the energy structure and industrial structure of Shandong Province must be improved, as well as the technological level in the upper middle class; thus, through the optimization of its economic structures, it also has great potential for emissions reduction. Shandong Province could learn from other regions' emissions reduction policies, accelerate the development of new energy sources, and build and promote new energy industries to ensure economic growth and reduce carbon emissions.

(3) The difference between the theoretical distribution and the actual distribution of carbon emission rights is larger in the provinces, such as Hebei Province (−28,471, −62.73%), Shanxi Province (−19,974, −50.27%), the Inner Mongolia Autonomous Region (−17,702, −42.63%), Liaoning Province (−17,702, −79.38%), Jiangsu Province (−28,007, −62.36%) and Guangdong Province (−22,471, −58.19%). One of the common features of these areas is the large proportion of secondary industry; more industrial industries lead to difficulties in energy transformation, which is the major difficulty that these provinces and autonomous regions face. Among them, Shanxi Province mainly uses energy output as the basis of its economy, and coal mining has provided regional economic support for a long time. With its geographical advantage and rich natural resources, such as coal and natural gas, Inner Mongolia should further strengthen its cooperation with other regions to promote the rational flow of production factors and the reallocation of resources. Liaoning Province, as an old industrial base in Northeast China, has some imbalances in its internal industrial structure, and its ability to apply technological innovation and a degree of modernization are still relatively backward. Overall, considering the carbon emissions allocation theory and actual allocation, the negative difference is large, so these provinces and autonomous regions should undertake reasonable measures to actively promote CMD clean energy projects, improve energy efficiency, tap new low-carbon industries, and develop clean energy, such as solar and wind energy, as soon as possible to promote the upgrading of industries, such as coal consumption. At the same time, they should also optimize their

industrial structure and explore suitable development paths, based on their scientific and technological innovation capabilities.

(4) In Qinghai Province, the largest positive difference between the allocation of carbon rights and the actual distribution is the remaining carbon emissions amount of 88.83%. Qinghai Province has a relatively small population, abundant resources and heavy agriculture and animal husbandry. Furthermore, the economic structure is still in its primary stage, resulting in low carbon emissions. However, due to the low level of science and technology in Qinghai Province, as well as to the underdevelopment of the tertiary industry, it has a high theoretical allocation and low actual emissions, resulting in a large positive balance. For the remaining carbon emissions, Qinghai Province could sell carbon emission rights to other provinces through carbon trading, while strengthening exchanges and cooperation related to economy, technology and energy between regions.

We summarized the differences, causes and future development strategies of the theoretical and practical values of carbon emissions in China's provinces, and as added the information as an appendix for the reasons of article length.

5.2. Equity Evaluation of the Results of the Initial Provincial Allotment of Carbon Emission Rights

According to Equation (13), the provinces are arranged; following this, the cumulative percentages are calculated, and the Lorenz curve is drawn. Through calculation, the Gini coefficient of each indicator assigned by the province with carbon emission rights is shown in Table 6.

Table 6. Gini coefficient of each indicator.

Indicator	Gini Coefficient
actual carbon emissions	0.2949
population	0.2764
GDP	0.3445
energy consumption	0.2519
carbon intensity	0.2985
forest coverage	0.3498
the proportion of secondary industry	0.0640
technology market turnover	0.7148

According to the definition of the fairness of the Gini coefficient in Table 3 and the calculation results in Table 6, the distribution of carbon emission rights based on the proportion of secondary industry shows absolute fairness, based on the four indicators of carbon emission, population, energy consumption and carbon emission intensity, and the allocation of carbon rights to the provinces is fairly fair, according to the two indicators of GDP and forest cover. The allocation of carbon rights to the provinces is relatively fair, indicating that the allocation of carbon rights to the provinces based on these indicators is reasonable. However, it is unfair to allocate carbon emission rights to provinces based on the technical market turnover indices. Technical market turnover represents the level of technological capability in the region. Through observational data, we found that the technical market turnover of Beijing is large, accounting for 36.87%, which is a singular value, while the technical market turnover in Xinjiang, Qinghai and Guizhou Provinces accounts for less than 1%. Due to the large gap between the technology markets in China's provinces, there is a large gap in the technical market turnover index, which affects the results of the allocation of carbon emission rights in the provinces. To further explore whether the initial allocation of carbon emission rights based on the technology market turnover is fair, we divided the Chinese provinces into two groups based on the index of the technology market turnover. The first part consists of 15 provinces; the technology market turnover in these provinces accounts for no more than 1% of the national total. The second part excludes the 14 provinces except for Beijing. The Gini coefficient of the two parts of the province is calculated.

The first part of the Gini coefficient is 0.3474, and the latter part is 0.3717. Therefore, we believe that the carbon distribution based on the technology market turnover is relatively fair.

The following is a specific analysis of the situation in the five major regions of China.

(1) A study on the equity allocation of carbon emission rights in different regions. According to Equation (13), the Gini coefficients of each index in the five regions are calculated, as shown in Table 7.

Table 7. Gini coefficients of each indicator in five regions.

Indicator	Northern Region	East China	Central-Southern	Southwest Region	Northwest Region
actual carbon emissions	0.1893	0.1950	0.1357	0.0539	0.1254
population	0.2442	0.0759	0.1138	0.1282	0.2472
GDP	0.2364	0.1719	0.2023	0.1029	0.1873
energy consumption	0.1938	0.1369	0.1493	0.0753	0.1690
carbon intensity	0.1960	0.0491	0.1448	0.1223	0.0913
forest coverage	0.3418	0.3553	0.1527	0.0830	0.3419
the proportion of secondary industry	0.0718	0.0877	0.0562	0.0171	0.0694
technology market turnover	0.8606	0.4107	0.6071	0.2577	0.5205

According to Equation (15), we can calculate the impacts of unfairness, inter-regional inequity and residual inequalities on overall inequity; the results are shown in Figure 4.

The results show the following. First, as seen in Table 7, the Gini coefficients of the six indices, except for technology market turnover, are all less than 0.4 in the five regions, indicating that the initial carbon emission rights in the five major regions based on the indicators selected in this paper are all relatively fair. Second, the contribution rate of the unfairness within the regions to the overall unfairness of each indicator is basically between 10% and 25%, indicating that the contribution rate of the unfairness within the five major regions to the overall unfairness is low and further illustrating that the allocation of carbon emissions within the five regions is fairly equitable. Third, the Gini coefficients of the northern regions are all high, indicating that the differences in the economic development scales and levels of economic development among the northern provinces are greater than those in other regions. The northern region includes Hebei Province, with a large, high energy-consuming population; Tianjin, the Inner Mongolia Autonomous Region and Northeast China, with large secondary industry; and Beijing, with a balanced and coordinated development in all aspects. The economic development structure and development speed between provinces in the region vary greatly, and the scale structure in the region is relatively loose, resulting in a higher Gini coefficient in the region. In contrast, among the four provinces in Southwest China, the indicators are more balanced, the scale of economic development and the structure of economic development are similar, and the small difference between provinces in the region results in a smaller Gini coefficient of the indicators in Southwest China. Fourth, through the comparison of the actual carbon emissions and the Gini coefficient based on actual carbon emissions, we found that the Gini coefficient is also higher in the areas where the actual carbon emissions are larger, indicating that the heavily polluted areas will, to a certain extent affect the carbon emission rights allocation efficiency.

(2) The equity analysis of the allocation of carbon emission rights among the five major regions. According to Equation (16), the impact of the unfairness of carbon emission rights among the five major regions on the overall carbon emissions rights is obtained, as shown in Figure 5.

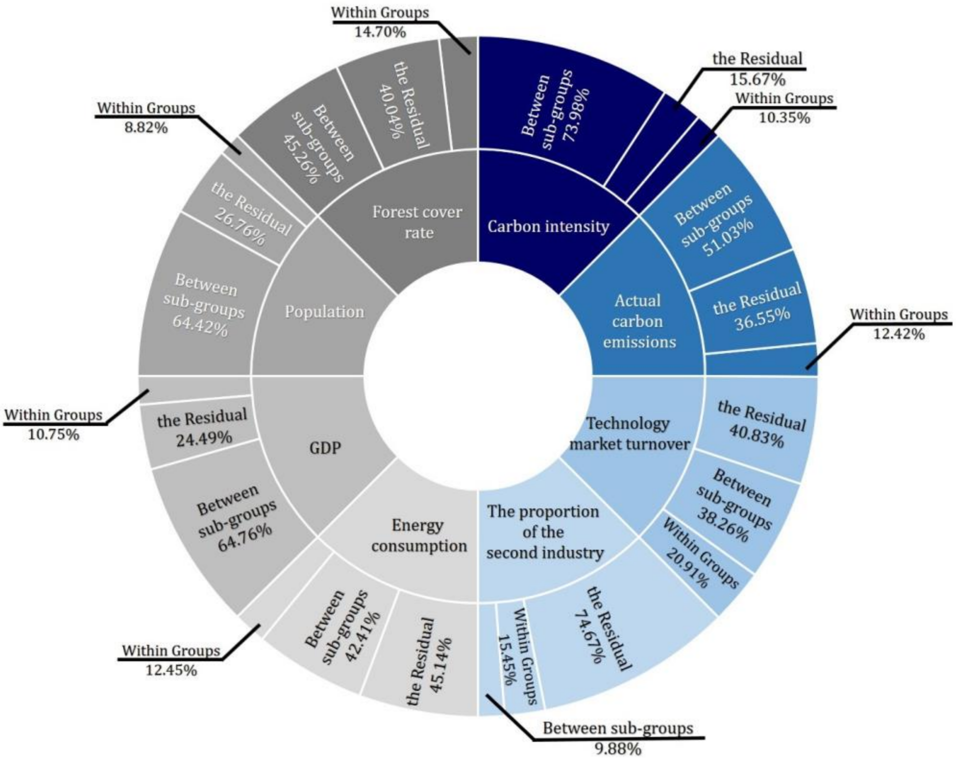


Figure 5. The contribution rate of each index to inequity in the region, between regions and in the residual.

The results show the following. First, through the comparison of inequity of carbon emission rights in the region with to the overall inequitable contribution rate, the study finds that the index of the contribution rate of unfairness among regions is larger than the unfair contribution rate in the region except for secondary industry, showing that differences among the five major regions is the main factor contributing to the unfair allocation of carbon emissions in China. Between different regions, there are not only differences in natural resources, such as the environment, but also differences in man-made factors, such as science, technology and culture. Therefore, strengthening a coordinated development between regions and promoting economic development and technological innovation in developed areas for the development of backward areas will gradually improve the overall fairness of the allocation of carbon emissions rights. Second, the unfair contribution rates of the five major regions were higher than the overall unfair contribution rate, showing that the economic development and population among the five major regions in China are not balanced. Although the country has implemented a carbon emissions convergence development policy, the situation of heavy carbon pollution in some areas is still not completely resolved. Third, the unfairness of carbon intensity among the five regions is as high as 73.98% of the total unfair contribution, which is much higher than the unfair contribution (10.35%) in the region. Judging from actual conditions in China, there are obvious geographical differences in the storage of energy and resources. There are an abundant amount of coal resources in the north and northwest regions, a large amount of water in the southwest, natural gas in the southwest and northwest regions, and oil resources in the northeast region. The economic form of coarse emissions in some regions renders the unfair contribution rate among regions higher than other factors related to the carbon intensity.

(3) Impact analysis of the overlap among the five major regions. Using Equation (14), we can calculate the degree of contribution of the direct overlap of the five regions (that is, the residual) to the fairness of the carbon emissions rights allocation results, as shown in Figure 5.

Figure 5 shows the following. First, except for when it is based on the proportion of secondary industry, the contribution of the residual of the remaining indicators to the overall inequity of the carbon emission rights is at a medium level, indicating that the division of the five major regions is relatively reasonable and further illustrating that the fairness of the distribution plan in this paper is better. Second, when compared to other factors, and considering the Gini coefficient of the indicator of the proportion of secondary industry, the distribution method developed in this article approaches absolute fairness in all aspects. Third, considering the total Gini coefficient and the Gini coefficient between regions, we can see that, although there is a certain gap among the five major regions, the carbon emissions rights allocation scheme presented in this paper does not depict a situation in which economically developed regions seriously overwhelm the carbon emission rights of economically backward regions. The distribution plan is basically in a fair state.

6. Discussion and Analysis

6.1. A Comparison and Discussion of the Results of this Paper Compared to the Existing Research Results

There have been many studies on the initial allocation of carbon emissions rights [22,49–53]. To further explore the significance of the research results in this paper, we choose two research literatures that are closely related to this study, comparing the results of the present study with the ZSG-DEA model [53] (document 1) and the Shapley decomposition [21] (document 2), which have both been widely used in research on carbon emission rights allocation. Document 1 adopts the ZSG-DEA model and initially allocates carbon emission rights in China using three aspects: energy saving potential, emission reduction potential and GDP growth potential. Document 2 is based on the particle swarm optimization (PSO) algorithm, the fuzzy c-means (FCM) clustering algorithm and the Shapley decomposition method, and 30 provinces are classified into four categories after using the Shapley decomposition of the initial allocation of carbon emissions to Chinese provinces. To facilitate a comparative analysis, the results are uniformly arranged according to the proportion of the initial allocation of carbon emissions rights in ascending order. The specific results are shown in Table 8.

Table 8. The results of this study compared with the results of current studies.

Province	The Results of This Research's Rankings	The Results of Document 1's Rankings [1]	The Results of Document 2's Rankings [2]	Province	The Results of This Research's Rankings	The Results of Document 1's Rankings	The Results of Document 2's Rankings
Beijing	30	27	26	Henan	3	3	7
Tianjin	14	23	25	Hubei	17	12	9
Hebei	2	2	2	Hunan	15	15	12
Shanxi	8	6	8	Guangdong	10	7	4
Inner Mongolia	5	8	5	Guangxi	23	26	21
Liaoning	9	5	6	Hainan	29	29	29
Jilin	16	17	16	Chongqing	20	24	24
Heilongjiang	28	10	14	Sichuan	7	13	11
Shanghai	27	19	17	Guizhou	24	18	20
Jiangsu	4	4	3	Yunnan	26	20	18
Zhejiang	18	9	10	Shanxi	19	11	15
Anhui	6	14	13	Gansu	21	22	27
Fujian	25	21	19	Qinghai	13	30	29
Jiangxi	22	25	23	Ningxia	12	28	28
Shandong	1	1	1	Xinjiang	11	16	22

[1] The results of document 1's rankings from reference [53]. [2] The results of document 1's rankings from reference [21].

Table 8 shows the following. (1) Although the allocation methods used in the three articles are different, the results still have much in common. The two provinces with the highest carbon emission allocation are Shandong Province and Hebei Province. The emissions rankings of many other provinces and autonomous regions are quite different, but the differences are small. This applies for example, to Shanxi Province, Jilin Province, Jiangsu Province, Jiangxi Province, Hunan Province and Hainan Province. (2) In the three articles, the distribution gap between Qinghai, Ningxia and Xinjiang is relatively large. The results of this study show that the rankings of the three provinces range from 11th to 13th. The other two articles show that Xinjiang ranks 16th and 22nd, respectively, while Ningxia ranks 28th, and Qinghai ranks 29th and 30th. The main reason for this difference is that compared with the other two studies, our study takes into account the indicators of technology market turnover. The technological innovation ability of these regions that show different results is poor. Based on the potential for a sustainable development perspective, these areas should have higher allocation indicators to develop their economic and technological capabilities. This difference also shows that the results of this paper are more in agreement with the actual situation.

6.2. This Paper Studies the Reference Significance of the Initial Allocation of Carbon Emissions in Various Countries

(1) In this paper, the research ideas on the initial allocation of carbon emission rights in China provide a good reference for the initial allocation of carbon emission rights among countries and regions. Currently, carbon emissions trading in various countries around the world is still in an early phase. In particular, the initial distribution of carbon emission rights, which is an important part of the carbon rights trading system, is related to national economic development and the level of social welfare, which are inevitably affected by various factors, especially the impact of political factors. Since the British established the world's first voluntary carbon ETS in 2002, it has appeared in the Australian state of New South Wales ETS (NSW GGAS), the Regional Greenhouse Gas Initiative (RGGI), the EU ETS (EU ETS), the Western Climate Initiative (WCI), New Zealand's carbon ETS (NZ ETS), India's performance, implementation and trading mechanism (IND PAT), California's carbon ETS (CAL ETS), Australia's carbon ETS (AU ETS) and so on. It is only in accordance with the development level of all of the regions that a fair and reasonable initial allocation of carbon emissions can enable countries and regions to plan carbon emissions reductions in a planned, orderly and purposeful fashion. We can pay closer attention to the responsibility and obligation of sharing emissions reductions.

(2) The Gini coefficient sub-group decomposition method used in this paper has a good applicability to the fairness evaluation of the global carbon rights allocation. Exploring the fairness of global carbon emissions and the factors that affect unfairness supports the UN mandates to discriminate in the abatement capacity of all of the countries worldwide, encourage mutual assistance and mutual supplementation of science and technology between countries, promote global new energy innovation and industrial development, achieve global resource allocation and increase energy consumption efficiency so that the global economy will become coordinated and stable.

(3) This paper also provides a reference for subsequent research on the allocation of carbon rights. The allocation of carbon rights exists not only within the distribution to internal regions but also within the distribution to different industries in a country or region, as well as different enterprises in different industries. The allocation of carbon rights should fully consider the impacts of various indicators for factors so that it is evidence based and reasonable to find.

6.3. The Shortcomings of This Article

(1) Considering the allocation of carbon rights, the selection of indicators varies from person to person, and there is a certain degree of uncertainty. Within the indicators selected in this article, there are areas worth discussing and worth further researching.

(2) Although the improved TOPSIS method based on weight entropy overcomes the subjectivity and arbitrariness of previous processes, the final distribution result cannot reach absolute fairness and can only be in a relatively fair state because the dependence of information entropy on the data is high.

(3) In view of the limitation of data accessibility and time and energy, this paper neglects the issues of unfair competition among provinces, distribution conditions and the degree of distribution in the process of building the initial allocation model for carbon emission rights.

7. Conclusions and Suggestions

Based on the principle of fairness, efficiency and sustainability, this paper constructed the initial allocation system of carbon emission rights in China, and used the improved TOPSIS method to obtain the initial carbon emission rights allocation scheme of 30 provinces in China. This paper also used the Gini coefficient to evaluate the fairness of China's carbon emission rights allocation results. The main conclusions of this study are as follows: The provinces with a high initial allocation of carbon emission rights are mainly China's major population and major energy provinces. There are small proportions of the initial distribution of carbon emission rights in Beijing and Shanghai, as well as the tourism-based Hainan Province. The negative balance between the initial provincial allocation of carbon emission rights and the actual periodicals are mainly in areas with heavy industry (such as Shandong and Liaoning) and areas with rapid economic growth (such as Jiangsu and Guangdong). The fairness of the results of the initial allocation of carbon emission rights in China in this paper is good. The main reason for the unfairness in allocating carbon emission rights is the difference between different regions. The Gini coefficient for the allocation of carbon credits within the North is higher relative to other regions. Where the actual carbon emissions account for a large proportion, the Gini coefficient of the distribution of carbon emission rights will also be relatively high, indicating that the allocation efficiency of carbon-intensive major provinces are relatively low. Based on the above research and analysis, this paper makes the following suggestions.

The first suggestion is to adjust the regional emission gap and promote the convergence of development across the country. Through the Gini coefficient sub-group decomposition method in this paper, it is found that there are still some problems with the equilibrium of carbon emissions between different regions. With the rapid economic development of China in recent years, some developed regions have shifted their highly energy-intensive industries to the central and western regions to reduce their own carbon emissions. This approach can only ease pressure on emissions reduction in some areas for a short period of time and allow the central and western regions to embark on the path of pollution re-treatment. In the future, China needs to further strengthen mutual cooperation and mutual support between regions, with developed regions providing funds to introduce advanced technology to the backward areas to develop industries with clean, green environmental protection; the country also needs to, change the fragmentary nature of each region, give full play to the advantages of all the regions, and promote a coordinated development.

Our second suggestion is to optimize the regional industrial structure and promote a compulsory emission reductions strategy. We can see from the difference between the proportions of the distribution and the actual emissions in provinces that some provinces and autonomous regions have large differences and excessive carbon emissions. To completely solve this problem, we must optimize the regional industrial structure as soon as possible and promote the development of a low-carbon green economy in the region. First, all of the provinces and autonomous regions should recognize the importance of carbon emissions reduction from a strategic and overall perspective and should rationally control the total consumption of energy and carbon emissions; adjust and optimize the industrial structure in the region; use clean energy more efficiently; reduce coal emissions to develop clean energy, such as solar and wind energy, according to local conditions; restrain the rapid development of high-emission industries: and do a better job with ecological protection. At the same time, the provinces should also transition from high energy-consuming secondary industry to low-emission tertiary industry, cultivate emerging high-yield and low-consumption industries, persist in promoting supply-side structural reforms and promote a resource-saving and environment-friendly development mode.

The third suggestion is to establish a perfect trading market for carbon emissions rights and promote a fair distribution system. Currently, the carbon emissions pilot market is gradually advancing to become a national market. Determining the carbon rights quota and initial allocation mode are at the heart of establishing and improving the carbon emissions trading market. If the initial allocation of carbon emissions is too large in some areas and unfair in others, this will have a negative impact on low carbon development, energy savings and emissions reduction. Therefore, the state should perform a unified accounting and examination of the historical amount of carbon emissions and related data in all of the provinces and autonomous regions, consider the development differences between different provinces and autonomous regions and combine the current situation and market structure of the provinces to determine an allocation plan.

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Appendix A

Table A1. Actual distribution results and theoretical results of carbon emission rights for all provinces in 2015.

Province	Theoretical Results		Actual Results		Difference	
	Value	Percentage	Value	Percentage	Value	Percentage
Beijing	10,538	0.95%	11,537	1.04%	−999	−9.48%
Tianjin	37,415	3.39%	19,282	1.75%	18,133	48.46%
Heibei	45,383	4.11%	73,853	6.68%	−28,471	−62.73%
Shanxi	39,732	3.60%	59,706	5.40%	−19,974	−50.27%
Neimenggu	41,522	3.76%	59,223	5.36%	−17,702	−42.63%
Liaoning	39,067	3.54%	70,077	6.34%	−31,010	−79.38%
Jilin	37,058	3.35%	21,476	1.94%	15,582	42.05%
Heilongjiang	31,389	2.84%	32,613	2.95%	−1224	−3.90%
Shanghai	32,158	2.91%	29,161	2.64%	2998	9.32%
Jiangsu	44,913	4.06%	72,920	6.60%	−28,007	−62.36%
Zhejiang	36,389	3.29%	42,065	3.81%	−5676	−15.60%
Anhui	40,591	3.67%	32,436	2.94%	8155	20.09%
Fujian	34,901	3.16%	26,906	2.44%	7995	22.91%
Jiangxi	35,276	3.19%	19,114	1.73%	16,162	45.82%
Shandong	48,585	4.40%	12,7510	11.54%	−78,925	−162.45%
Heinan	45,204	4.09%	51,283	4.64%	−6079	−13.45%
Hubei	36,747	3.33%	32,425	2.93%	4322	11.76%
Hunan	37,249	3.37%	28,135	2.55%	9114	24.47%
Guangdong	38,613	3.49%	61,083	5.53%	−22,471	−58.19%
Guangxi	35,088	3.18%	21,373	1.93%	13,715	39.09%
Hainan	26,101	2.36%	7900	0.72%	18,201	69.73%
Chongqing	35,933	3.25%	12,648	1.14%	23,285	64.80%
Sichuan	39,765	3.60%	31,897	2.89%	7869	19.79%
Guizhou	35,069	3.17%	21,776	1.97%	13,293	37.91%
Yunnan	33,857	3.06%	17,320	1.57%	16,537	48.84%
Shanxi	36,329	3.29%	40,382	3.65%	−4053	−11.16%
Gansu	35,465	3.21%	19,168	1.73%	16,297	45.95%
Qinghai	37,998	3.44%	4243	0.38%	33,755	88.83%
Ningxia	38,237	3.46%	16,505	1.49%	21,732	56.83%
Xinjiang	38,353	3.47%	40,906	3.70%	−2553	−6.66%

Note: Difference percentage = (theoretical values − Actual values)/theoretical values.

Appendix B

Table A2. Characteristics and effective strategies of carbon emissions for each Province in China.

Carbon Emissions	Provinces	Locations	Characteristics	Future Development Strategies
The theoretical value of carbon emissions is less than the actual value	Shandong, Jiangsu, Liaoning, Hebei	Eastern coastal provinces	High carbon emissions, large population, high secondary industry, high energy consumption, high carbon emission intensity	Control population growth, actively adjust the industrial structure and reduce energy consumption
	Guangdong, Zhejiang, Beijing	Eastern coastal provinces	Large population, high GDP	Control population growth and actively develop low-carbon technologies
	Shaanxi, Inner Mongolia	Central and Western provinces	High carbon emission intensity	Actively develop low-carbon technologies
	Henan, Xinjiang, Shaanxi	Central and Western provinces	High secondary industry, high carbon emission intensity	Improve industrial structure and reduce carbon intensity
The theoretical value of carbon emissions is greater than the actual value	Shanghai, Fujian, Hainan, Tianjin, Chongqing	Eastern coast and Central developed provinces	The secondary industry accounted for a small proportion, low-carbon service-based; advanced low-carbon technology	Continue to focus on the service to develop the economy
	Heilongjiang, Jilin, Ningxia, Qinghai	Northeast and Western provinces	The secondary industry accounts for a small proportion, with low-carbon agriculture as the mainstay, with low carbon intensity; less population and less GDP	Attract talent and speed up economic development
	Hubei, Sichuan, Anhui, Hunan, Guizhou, Guangxi, Yunnan, Jiangxi, Gansu	Central provinces	Many mountains, high forest cover, low level of economic development, with low-carbon agriculture as the mainstay	While raising the level of economic development, carbon emissions should not grow too quickly

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