Carbon emission quota allocation of high energy consumption industries in undeveloped areas – A case study of Inner Mongolia Autonomous Region

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A R T I C L E   I N F O

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A B S T R A C T

With the approaching of the target year of carbon peak, all world countries have gradually strengthened carbon emission reduction actions. However, most of the undeveloped countries or regions do not belong to the Annex I countries in the Kyoto Protocol, and the development of carbon emission trading mechanisms is relatively slow. Therefore, setting emission quota standards for industries in undeveloped regions is necessary. Considering the principles of fairness, efficiency, and sustainability, we establish a “multi-objective information entropy allocation model” (I.E., IEMMA method) for undeveloped areas. Take China’s Inner Mongolia Autonomous Region as an example, and the allocation results show that: (1) The “historical emissions”, “carbon emission intensity”, “cumulative emissions”, “energy structure”, and “energy intensity” are assigned higher weights. Such industries will carry a higher responsibility for emissions reductions, they should gradually transfer emission quotas to industries with smaller historical emissions to increase enthusiasm for reducing emissions. (2) Compared with the historical emissions allocation scheme, the IEMMA model can increase the emission limits for industries with large historical emissions. For industries with relatively small emissions, their emission quotas can be appropriately relaxed to promote the sustainable development of the industry. (3) Under the allocation scheme of the IEMMA model, the difference in the reduction of carbon emission intensity of different industries is small. Carbon emission intensity becomes a relative emission reduction indicator, which reflects the fairness of allocation while maintaining economic development. (4) The “quota gap” formed by the allocation plan of the IEMMA model is large, which is conducive to promoting the active emission reduction of high-emission enterprises. Larger “allowance gaps” are conducive to increasing the activity of the carbon trading market. In summary, the IEMMA model is conducive to achieving long-term emission reduction goals in undeveloped regions and is more suitable for the allocation of quotas to high-energy-consuming industries.

1. Introduction

Under the challenge of economic growth and environmental constraints, the demand for the green transformation of energy utilization is increasingly urgent (Wang et al., 2022). Carbon trading mechanisms aim at optimizing the allocation of resources and achieving emission reduction targets (Ren, 2021). Since 2011, China has established a pilot market for carbon emission trading in more developed regions such as Beijing and Shanghai, has set up industries to be included in the control for these pilot regions, and allocated corresponding carbon emission quotas to the included industries to control the carbon emissions of the industry. For underdeveloped regions such as Inner Mongolia, Xinjiang, and Tibet, although the total carbon emission and carbon intensity of these regions are relatively high, China has not established a carbon emission trading market in these regions. Scientific allocation can clarify carbon emission responsibilities. At present, undeveloped countries have gradually begun to establish carbon emission trading markets (Tan and Lin, 2022, Liang and School, 2017). The study of carbon quota allocation schemes between different countries or regions is mature. China adopts the “top-down” carbon emission quota allocation method. According to the energy use of each region, the carbon emission quota is first allocated to each province, and then it is allocated to industries according to the energy consumption or the production process (Lo et al., 2022). This two-stage allocation method realizes the comprehensive consideration of the characteristics of regional and
industrial energy consumption, making the quota allocation more operable and achievable.

At present, China’s carbon emission trading pilot markets mainly realize the allocation of carbon quotas in different industries through the “historical total emission method”, the “historical intensity decline method”, and the “baseline method”. The “Historical Emission Method” is suitable for industries with complicated production and complex characteristics (Pan and Pan, 2018). The shortcoming of the historical method is that it does not reflect the differences in emission characteristics and emission reduction potential of different industries. During the operation of the carbon trading market, some pilot markets have adjusted the allocation of quotas and compliance methods promptly by considering the implementation of emission reduction actions before the compliance period, adopting the compliance method, and setting up industry adjustment coefficients. The purpose is to make the quota allocation results of enterprises more in line with the actual emission situation of enterprises and to better realize the fairness and efficiency of allocation while encouraging enterprises to carry out energy conservation and emission reduction actions. The historical intensity reduction method formulates the emission reduction rate by comprehensively considering the previous carbon emission reduction of the enterprise (Abadie et al., 2015). The baseline method calculates the total quota by setting the industry benchmark and allocates the quota based on the production facilities (Liu and Cui, 2018, Horowitz and Just, 2013). With the expansion of the national carbon emission trading market, more enterprises will be included in the carbon emission trading market, and the shortcomings of the existing methods are highlighted. The carbon quotas acquired are highly correlated with the historical emissions of the company. When an enterprise suddenly increases or decreases production, the emission quotas obtained will vary greatly from the actual demand. The historical intensity reduction method may produce unfair results for established or newly established enterprises that have achieved certain carbon emission reduction results. The newly formed companies are in the development stage in the first three years, and then enter the development stage of rapidly increasing productivity, and the annual carbon emission intensity has a large gap. If the “historical intensity reduction method” continues, enterprises will likely generate more than 50% of the surplus emission quotas and affect the carbon emission trading market. The baseline method has higher requirements for the industry emission calculation process, the production process, and the production facilities (Chang et al., 2016).

The current international representative allocation principles include fairness, efficiency, polluter-pay, and the “Common but differentiated responsibility (CBDR)”. Under these international principles, scholars have carried out research on carbon emission quotas for different industries. Under the CBDR principle, carbon emissions trading markets conduct more cost-effectively entities. Developed countries should carry out greater responsibility for emission reduction. The power industry is the key object in the process of carbon quota allocation (Li et al., 2019). Domini et al. (2019) analyzed Australia’s carbon emission reduction targets and pointed out that the government should implement strict emission control in the power industry. Sheng et al. (2018) analyzed the operation of electricity sectors in all EU member states, proposed to limit carbon emissions using differentiated emission reduction, and established a carbon emission quota allocation method using the Shapely value model. Taking into account the principle of efficiency, Yu et al. (2020) used a two-step goal programming allocation model to allocate carbon emission quotas to the Danish power industry considering the relevant policy. Key and Ho (2021) defined the industry’s total carbon emission quota target as a function of output value, but many scholars have different opinions on this view. Abatemarco (2017) believed that the allocation of carbon emission quotas should consider the future development and emission reduction capacity of the industry, and comprehensively consider the industry’s emission reduction responsibilities and potential capabilities. In recent years, scholars have drawn lessons from the game theory of “zero-sum income”, using the DEA model (Cui et al., 2020, Han et al., 2017), Malmquist measurement method (Lin and Du, 2015; Shi and Chen, 2016) and various modeling ideas combined with SBM model (Fang et al., 2022, Meng et al., 2018) to realize the reasonable decomposition of the goal of carbon emission reduction in different regions, and systematically analyze the resource utilization efficiency and technological efficiency. The fairness principle is mostly considered from the process and results of quota allocation. García and Padfield (2018) used the “ICLIPS model” to study the path construction of inter-temporal carbon emission reduction. Most undeveloped areas are still in the initial stage of industrialization and urbanization, and the task of eliminating poverty and developing the economy is still heavy. However, there are few studies on the allocation of carbon emission quotas for different industries in the same region, and most of them focus on a certain industry (i.e., the power industry, the transportation industry, etc.). The proportion of high energy-consuming industries in underdeveloped areas is large, and the efficiency of energy resource utilization is low. The situation for carbon emission reduction is grim. Since undeveloped regions mainly undertake low-end industrial links, the economic and technological levels could not be effectively improved. The allocation of carbon emission quotas among industries should consider the emission reduction capacity to decompose emission reduction targets better.

The main objective of this study is to set a reasonable carbon emission quota allocation of high-energy-consuming industries in underdeveloped areas to better achieve carbon emission reduction goals. Determine the reasonable allocation, and design a reasonable allocation method for covering industries. Make the operation of the entire trading system more effective and fair, to achieve sustainable development of China’s low-carbon economy. The innovation of this paper is to make up for the lack of current research on the quota allocation of high-energy-consuming industries, and put the research perspective in underdeveloped areas of China, which enriches the research on carbon emission quota allocation of the carbon emission trading market, promotes the energy efficiency of high-energy-consuming industries. The arrangement of the article is as follows: Section 2 describes the experimental design of the study. Section 3 describes the results and discussion of the study. In this part, we make a comparative analysis of the different plans. Section 4 describes the conclusion and limitations of the study.

2. Experimental

2.1. Research object introduction

Inner Mongolia is one of the provincial administrative regions with more neighboring provinces in China, which spans the three major regions of Northeast China, North China, and Northwest China and is adjacent to eight provinces. Inner Mongolia belongs to the inland underdeveloped areas in China, whose status of the carbon emission system is more prominent than that of coastal developed areas. According to the statistics of the Inner Mongolia Autonomous Region Bureau of Statistics (2021), energy consumption in Inner Mongolia increased by 6.89% in 2020 and ranks first among 31 provinces in China. We study Inner Mongolia Autonomous Region as an example, analyzing the allocation of carbon emission quotas in high-energy-consumption industries. The map of Inner Mongolia is shown in Fig. 1.

The Inner Mongolia Autonomous Region now consists of 9 cities and 3 alliances. The 9 cities are Huhhot, Baotou, Wuhai, Chifeng, Tongliao, Erdos, Hulunbeier, Ulanqab, and Bayanzhuoer, and the 3 alliances are Xing’an league, Alashan, and Xilingol. The Inner Mongolia Autonomous Region is an important energy strategic resource base in China. Inner Mongolia has not established a regional carbon trading market but has gradually started cross-regional carbon emissions trading, participating in the Beijing carbon emissions trading market and the national carbon emissions trading market.
2.1.1. Industry structure analysis

According to the Inner Mongolia Statistical Yearbook, the industrial added value above the scale of Inner Mongolia increased by 23.8% in 2020, industry growth is further expanded, and the pillar industries are growing. Fig. 2 shows the energy consumption of major industries in the Inner Mongolia Autonomous Region in 2020.

It can be seen that the industrial industry generates high carbon emissions. In the more mature international carbon emissions trading market (i.e. European Union Emission Trading Scheme, EUETS), the higher energy consumption in the industrial sector is covered in the quota allocation. EUETS is the world’s first multi-country emission trading system. It allocates the emission reduction targets under the Kyoto Protocol to each member state. EUETS covers more than 12,000 power stations, factories, and other industrial facilities, and is the world’s largest total carbon emission control and trading system. At the same time, the transportation, warehousing, and postal industries account for 11% of the energy consumption in the Inner Mongolia Autonomous Region. Considering the current situation of China’s carbon emission...
quota trading pilot market, the pillar industries, and the traditional advantageous industrial system in undeveloped regions, we choose the following 13 industries (see Fig. 3) as high-energy-consuming industries for analysis. Total energy consumption and its proportion in different industries in Inner Mongolia Autonomous Region are analyzed as shown in Fig. 3.

We count the proportion of total energy consumption in 13 sectors in Inner Mongolia from 2018 to 2020, as shown in Fig. 4-6.

From the results in Fig. 4 to Fig. 6, it can be found that the proportion of the industry changes little with time, and the top four industries account for a large proportion of the overall carbon emissions of the industry. The industrial output (Billion yuan) and the energy structure (Represented by the Consumption Proportion of Coal Energy) of these industries as shown in Fig. 7 and Table 1.

The Figure and the Table show the changes in the energy structure and energy consumption of various industries in the Inner Mongolia Autonomous Region, in general, the proportion of coal consumption in the total energy consumption shows a decreasing trend. However, the energy structure changes in the non-ferrous metal smelting and rolling processing industry and rubber and plastic products industry are small, and they are heavily dependent on coal. The proportion of coal consumption in some industries has increased slightly.
Table 1. Energy Structure of High Energy Consumption Industry in Inner Mongolia.

| Energy structure (%) | D44-D46 | C30 | C31 | C25 | C26 | C32 | C17 | C22 | C28 | C29 | C13 | C39 | G53-G56 |
|----------------------|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|
| 2018                 | 65.19   | 53.22 | 54.73 | 40.54 | 51.23 | 41.45 | 38.57 | 59.45 | 57.23 | 61.27 | 39.94 | 28.57 | 48.25   |
| 2019                 | 64.22   | 45.64 | 44.31 | 36.26 | 48.43 | 40.95 | 32.53 | 57.35 | 58.17 | 60.38 | 37.57 | 26.44 | 47.52   |
| 2020                 | 53.55   | 49.43 | 42.17 | 36.42 | 45.34 | 39.87 | 35.16 | 56.84 | 55.67 | 58.82 | 36.81 | 26.07 | 46.63   |

Table 2. Total Carbon Emissions (10,000 tonnes) and Intensity of Carbon Emissions (tonnes/million yuan) from Energy-intensive Industries in the Inner Mongolia Autonomous Region.

| High-energy-consuming industries | Total carbon emissions | Carbon emissions intensity |
|-----------------------------------|------------------------|---------------------------|
|                                   | 2018 | 2019 | 2020 | 2018 | 2019 | 2020 |
| D44-D46                           | 16336.28 | 16669.65 | 17812.62 | 1.381 | 5.3445 | 5.2539 | 5.4083 |
| C30                               | 7768.54 | 7927.05 | 8469.41 | 0.755 | 4.2983 | 4.4358 | 4.5348 |
| C31                               | 7514.13 | 7667.46 | 8191.98 | 1.658 | 4.7843 | 5.0285 | 4.6049 |
| C25                               | 6194.47 | 6320.83 | 6752.84 | 1.385 | 4.2186 | 4.1784 | 4.3155 |
| C26                               | 3381.35 | 3450.3 | 3685.11 | 0.867 | 3.3319 | 3.6164 | 3.6473 |
| C32                               | 2466.7 | 2517.01 | 2687.7 | 0.531 | 2.7246 | 2.9488 | 2.9883 |
| C17                               | 1454.57 | 1484.23 | 1583.97 | 0.215 | 2.0343 | 2.1024 | 1.9825 |
| C22                               | 1381.84 | 1410.01 | 1504.64 | 1.160 | 3.0092 | 3.5019 | 3.3951 |
| C28                               | 883.54 | 901.54 | 961.25 | 0.735 | 2.1804 | 2.6282 | 2.5474 |
| C29                               | 854.22 | 871.62 | 929.29 | 0.175 | 1.5377 | 2.8208 | 2.5769 |
| C13                               | 564.92 | 576.4 | 613.79 | 0.081 | 2.362 | 2.4823 | 2.8219 |
| C39                               | 531.44 | 542.24 | 577.26 | 0.033 | 2.5428 | 2.3516 | 1.6151 |
| G53-G56                           | 118.69 | 121.07 | 127.15 | 0.087 | 2.7341 | 2.2437 | 2.9304 |

Fig. 6. The Proportion of Comprehensive Energy Consumption in Different Industries in Inner Mongolia in 2020.

2.1.2. Carbon emissions status

According to energy consumption data and carbon emission coefficient, the total carbon emission of the industry is estimated. Among them, the carbon emission coefficient uses the data published by the National Development and Reform Commission (General rules for the calculation of the comprehensive energy consumption, National Standards of China, GB/T 2589-2020). After calculating the total carbon emissions, the carbon emission intensity of the industry can be further calculated according to the industrial output value. According to the energy emission coefficient, the total industry carbon emissions can be converted from the total energy consumption of the industry, and further, calculate the carbon emission intensity as shown in Table 2.

From Table 2, we can see that the total carbon emissions and carbon emission intensity of key energy consumption industries in Inner Mongolia from 2018 to 2020 are calculated. The carbon emission intensity of some industries is high, and the total carbon emission has a further increasing trend soon. High-energy-consuming industries should be gradually integrated into the future national unified carbon emissions trading market, and more reasonable quota allocation schemes should be designed to restrict and guide carbon emissions.

2.2. Model

2.2.1. Method

We construct the IEMMA Allocation Model for the industry carbon emission quota. Considering the information entropy model and the multi-factor mixed weighted allocation method, the criterion layer and the index layer are established to calculate the comprehensive coefficient of the evaluation object. The weight of each index calculated by the information entropy principle reduces the influence of subjective factors and makes the evaluation results more objective. At the same time, the multi-factor mixed weighting model can consider a variety of factors that affect the level of carbon emissions, and the impact on the evaluation object makes the decision-making results more accurate and comprehensive.

The IEMMA Allocation Model technically processes multiple single indicators that reflect the evaluated things, to obtain a comprehensive indicator that can fully reflect the overall situation of the evaluated things. The steps of the multi-index comprehensive evaluation method generally include the selection of indicators, the construction of the index system, the selection of evaluation methods, the standardization of data, and the determination of index weights. In the process of the comprehensive evaluation, selecting an evaluation index and constructing an evaluation system constitute the important foundation of comprehensive evaluation. According to the nature of the research object, it is further decided to select the evaluation method and standardize the data. The weight of each index can reflect the difference in index importance. Finally, the difference of each index weight coefficient directly determines the evaluation results. The index selection of the comprehensive multi-index multi-objective decision-making method is guided
by the multi-objective direction and comprehensively considered in multiple directions.

(1) Information Entropy Principle

In the development of information economics, Shannon (1948) pointed out that information is redundant and solved the problem of information quantification from the perspective of probability theory. The information entropy principle is that for any random variable \( F(X) \), if it satisfies continuity, symmetry, and additivity, there is the following unique expression:

\[
F(Q_1, \ldots, Q_n) = -A \sum Q(x_i) \log Q(x_i)
\]

Continuity: \( F(Q, 1 - Q) \) is a continuous function of \( Q \), \((0 \leq Q \leq 1)\); Symmetry: the order of \( F(Q_1, \ldots, Q_n) \) and \( Q_1, \ldots, Q_n \) is independent; Additivity: if \( Q_n = R_1 + R_2 > 0 \), and \( R_1, R_2 \geq 0 \), then,

\[
F(Q_1, \ldots, Q_{n-1}, R_1, R_2) = F(Q_1, \ldots, Q_{n}) + Q_n F(R_1/Q_n, R_2/Q_n)
\]

where \( A \) is a positive integer, usually \( A = 1 \).

The essence of information entropy is the mathematical expectation of a random variable. When measuring the system, information measures the order degree of the system and entropy measures the disorder degree of the system. The greater the probability of an event in the system, if it can be judged in advance, the higher the degree of order, the smaller the amount of information contained, and the lower the information entropy value. The calculation principle of the entropy weight method is to determine the amount of information of the relevant indicators according to the nature of the research object and the required objectives and determine the entropy value, and then determine the index weight. The size of the entropy weight can reflect the contribution of the index to the research object. The larger the information entropy of an index is, the more reference information the index value can provide for decision-makers, and the larger the index weight is when constructing a comprehensive evaluation index system. In recent years, the information entropy model has been widely used in system evaluation and comprehensive decisions in the field of engineering economics.

(2) Multi-factor Mixed Weighted Allocation Method Based on Information Entropy

A multi-factor mixed weighted allocation model based on information entropy can be constructed by combining the multi-factor mixed weighted allocation method and information entropy principle. The model is used to allocate the carbon emission quota of the industry in the region. Based on the historical carbon emissions, the index system of carbon emission quota allocation among industries based on the total quota is constructed. The comprehensive coefficient and distribution coefficient of the carbon emission quota of each industry are further obtained by the index weight. Under the constraint of the total quota target, the carbon quota allocation of the industry is calculated according to the historical total carbon emission and distribution coefficient.

A flowchart of the experiment is shown in Fig. 8.

### 2.2.2. Parameters

1. Determine the Index Entropy Weight

First, the indicators are standardized. The different promotion directions of entropy determine that the indicators are divided into positive indicators and negative indicators. The methods of standardizing the two indicators are as follows:

**Positive indexes:**

\[
Y_{ij} = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}}
\]

**Negative indexes:**

\[
Y_{ij} = \frac{\max X_{ij} - X_{ij}}{\max X_{ij} - \min X_{ij}}
\]

where, \( i \) represents the industry, \( j \) represents the index. \( i = 1, 2, 3, \ldots, m; j = 1, 2, 3, \ldots, n \).

- \( Y_{ij} \): The normalized value of the \( j \)th index of the industry \( i \), there are \( m \) industries and \( n \) indexes in the region.
- \( X_{ij} \): Value of indicator \( j \) of industry \( i \).
- \( \max X_{ij} \) and \( \min X_{ij} \) represent the maximum and minimum values in the original matrix, respectively.

Standardized matrix after normalization: \( Y = (y_{ij})_{mxn}, \ 0 \leq y_{ij} \leq 1 \).

Step 1: Calculate the proportion of indicator values:

\[
P_{ij} = Y_{ij}/\sum_{i=1}^{m} Y_{ij}
\]

Step 2: Calculate the entropy \( e_j \) of index \( j \):

\[
e_j = -k \sum_{i=1}^{m} P_{ij} \ln P_{ij}
\]

\( k = 1/\ln m \)

\( P_{ij} \): The proportion of evaluation indicator \( j \) in the industry \( i \). When \( P_{ij} = 0 \), let \( \ln P_{ij} = 0 \). When the difference of index data is larger, the effective information provided by the index is larger, the entropy value is smaller, the corresponding entropy weight is larger, and the proportion in the evaluation index is higher.

The amount of information of indicator: \( h_j = 1 - e_j \)

Entropy weight of index \( j \): \( w_j = h_j / \sum_{j=1}^{n} h_j \)
The value range of entropy weight $W_j$ is $[0, 1]$, which reflects the effective information provided by index $j$ in the comprehensive evaluation. The index entropy weight which provides relatively more effective information is larger and closer to 1.

(2) Determine the Final Weight $W_j$

We use the information entropy model to assign values to the index layer, and then use the AHP method to calculate the index weight in the criterion layer. $W_j$ is the weight value given by the criterion $a$, and $a$ is the number of criterion layers.

Step 1: Construct a pairwise comparison matrix

Starting from the second layer of the hierarchical structure model, for the same layer of factors that belong to (or affect) each factor in the previous layer, a pair comparison matrix is constructed by using the pair comparison method and the 1-3 comparison scale until the lowest level.

Step 2: Calculate the weight of the evaluation index.

$$
\begin{align*}
\alpha_i &= \sum_{i=1}^{n} a_{ij} \\
\omega_i &= \sum_{i=1}^{n} \alpha_i
\end{align*}
$$

where,

- $\mu$ denotes index weight,
- $a$ denotes the data in the judgment matrix,
- $n$ denotes the order of the judgment matrix

Step 3: A consistency test.

Calculating the Maximum Eigenvalue $\lambda_{\text{max}}$ and Consistency Index $CI$.

The relative weight of the compared element to the criterion is calculated by the judgment matrix, and the consistency of the judgment matrix is tested:

$$
CR = \frac{CI}{RI}
$$

Table 3. Reference table for the partial value of average random consistency index $RI$ in the analytic hierarchy process.

| $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----|---|---|---|---|---|---|---|---|---|
| $RI$ | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.21 | 1.32 | 1.41 | 1.45 |

$$
CI = (\lambda_{\text{max}} - n)/(n - 1)
$$

$$
\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \alpha_{ij} \times \omega_j
$$

where,

- $CRI$ represents a consistency ratio;
- $CI$ represents a coincidence indicator;
- $RI$ represents the number of consistent tests;
- $\lambda_{\text{max}}$ represents the maximum eigenvalue of the judgment matrix;  
- $n$ represents the order of the judgment matrix; 
- $\mu$ represents the weight of the indicator.

Find the average random consistency index $RI$ according to Table 3. When $CR < 0.1$, the consistency test can be passed, otherwise the judgment matrix needs to be reconstructed.

Step 4: Calculate the final weight.

$$
W_j = \omega_a \times \omega_j
$$

(3) Determine the Allocation factor: $T_i$

The industry with a higher score will get a smaller factor. Then it should increase emission reduction efforts. By formulating relevant policies, the industry can obtain fewer carbon quotas through allocation, and use the quota limit to promote energy conservation and emission reduction of the industry.

Calculating Index score $K$:

$$
K = Y \times W = \begin{bmatrix} Y_{1,1} & \cdots & Y_{1,n} \\ \vdots & \ddots & \vdots \\ Y_{m,1} & \cdots & Y_{m,n} \end{bmatrix} \times \begin{bmatrix} W_1 \\ \vdots \\ W_n \end{bmatrix} = \begin{bmatrix} K_1 \\ \vdots \\ K_n \end{bmatrix}
$$

$$
T_i = 1/k_i
$$
(4) Calculate the Incremental Emission Allocation

Based on the actual total carbon emissions in the base year and the target year, the inter-industry allocation of carbon emission increments is carried out. The carbon quota change allocation of industry \( i \) in the target year is set as \( \Delta C^i_0 \), and the actual carbon emissions of industry \( i \) in the base year are set as \( C^i_{base} \), then the carbon quota change allocation of industry \( i \) in the target year is the product of the actual carbon emissions of the base year and the allocation factor.

\[
\Delta C^i = C^i_{base} \times T^i
\]

In the case of a certain total quota, the total amount of carbon quota changes in the industry is the sum of the total quota changes in the region. The total quota change in the target year compared with the base year is set to \( \Delta C \), and the adjustment coefficient \( f \) is introduced.

\[
\Delta C = \sum_i \Delta C^i = C_{target}^i - C_{base}^i
\]

\[
f = \frac{\Delta C}{\sum_i \Delta C^i}
\]

The carbon quota variable (adjusted) of each industry in the target year is expressed as \( \Delta C^i \):

\[
\Delta C^i = \Delta C^i \times f
\]

(5) Calculate the Total Industry Quota

Calculate the amount of allocation in the target year:

\[
C^i_{target} = C^i_{base} + \Delta C^i = C^i_{base} + C^i_{base} \times T^i \times f
\]

2.3. Empirical analysis

2.3.1. Construction of allocation index system

The “Kyoto Protocol” has made it clear in a legal form that each country should bear “Common but differentiated responsibilities” for carbon emission reduction targets, which has become an important principle for the sharing of emission reduction responsibilities and the allocation of carbon emission quotas among countries in the world (Abadie et al., 2019; Shao et al., 2018). Considering industry characteristics, emission reduction basis, and the fairness of allocation. Given the “Common but differentiated” responsibilities, the effectiveness of allocation, and China’s national conditions, the principle of fairness, efficiency, and sustainability are taken into account in the allocation of carbon quotas among industries in each region.

(1) Fairness Principle

At present, for the allocation of carbon quotas, the principles of fairness that scholars agree on mainly include the principle of equal per capita carbon emission quotas (Cui et al., 2022), the principle of historical emission considering the historical cumulative emissions of enterprises, and the principle of development opportunities considering the future development space of the industry (Fogarassy et al., 2015; Huang et al., 2018). The carbon emission reduction responsibility is allocated according to the payment ability of different enterprises in each industry when the quota is insufficient (Wang et al., 2019). The design of the fairness principle of carbon emission quota is related to the future development and economic benefits of the industry, so the fairness principle is the basic principle that the allocation process should follow.

(2) Efficiency Principle

The efficiency principle of environmental governance refers to maximizing economic benefits with minimal resource consumption and fewer pollutant emissions (Nowzari et al., 2017; Obeed et al., 2019). There are certain differences in the historical carbon emission level and carbon emission reduction potential and capacity among different industries (Garcia and Padfield, 2018; Zhao et al., 2017). To achieve the effectiveness of allocation, we should fully consider the differences among industries, and set carbon emission quotas according to the characteristics and heterogeneity of industries (Li and Lu, 2015; Torabi et al., 2015). Give full play to the carbon emission reduction capacity of various industries to explore the maximum carbon emission reduction efficiency, to achieve the effectiveness of allocation (Qian and Jxa, 2020).

(3) Sustainability Principle

Sustainable development is an objective requirement for economic development (Gao and Zhou, 2017; Piper et al., 2017). The principle of sustainable development can be further subdivided into the feasibility and enforceability of emission reduction (Wilson et al., 2018; Zhang et al., 2021b). The feasibility requires that the allocation of quotas is economically, technically, and managerially feasible. Enforceability means that the allocation scheme and the final result can be recognized by the allocation object, taking into account the historical emission level of each industry and the sustainable and stable development of the industry in the future (Zhang et al., 2022a,b). The principle of sustainable development is an important guarantee for the implementation of allocation programs.

Therefore, we comprehensively consider the above three basic principles to design the carbon emission quota allocation scheme for various industries in the region. Combined with the research results and evaluation indicators of literature, and considering the availability of data, we choose the “historical emissions”, “carbon emission intensity”, “per capita output value”, and other indicators. Among them, “Historical emission \( A_1 \)”, “Carbon emission intensity \( A_2 \)”, and “Cumulative emissions \( A_3 \)” are used to measure the fairness principle, “Per capita output \( B_1 \)”, “Energy structure \( B_2 \)”, and “Industrial energy intensity \( B_3 \)” are used to measure the efficiency principle, “Openness \( C_1 \)” “Profitability \( C_2 \)” “Research input \( C_3 \)”, “The comprehensive utilization rate of solid waste \( C_4 \)” and “Fiscal Expenditure on Energy Conservation and Environmental Protection \( C_5 \)” are used to measure the sustainability principle. Using the information entropy model to build an inter-industry carbon emission quota allocation index system is shown in Table 4. If the index is positive, the index is proportional to the contribution of carbon emission reduction and inversely proportional to the allocation.

Based on the principle of fairness, effectiveness, and sustainability, we construct the carbon emission quota allocation index system for high-energy-consuming industries through the information entropy model.

2.3.2. Calculation of the parameter

(1) Determine the Index Entropy Weight

Based on the above model and the original data, the Allocation coefficient of each industry can be calculated, and the carbon emission quota of each industry in 2030 can be calculated based on the total carbon emission of the Inner Mongolia Autonomous Region in 2020. According to China’s goal of reducing carbon emission intensity by 60%-65% in 2030 compared with 2005, the carbon emission intensity reduction target is set to be 65%, and the carbon emission intensity of the Inner Mongolia Autonomous Region in 2030 will be 2.021. According to the average economic growth rate of the Inner Mongolia in the past three years (Inner Mongolia Statistical Yearbook, 2021; Inner Mongolia Statistical Yearbook, 2020; Inner Mongolia Statistical Yearbook, 2019), the economic growth rate of Inner Mongolia Autonomous Region in 2020-2025 is set to be 1.5%. Based on the economic development plan proposed in the “14th Five-Year” Energy Development Plan of the Autonomous Region-People’s Government of Inner Mongolia Autonomous Region, the sustainable development of industrial carbon emissions will be calculated.
Table 4. Carbon Emission Quota Allocation Index System for High Energy Consumption Industries.

| Secondary index | Tertiary index | Index type | Index selection basis | Index measurement |
|-----------------|----------------|------------|-----------------------|-------------------|
| Fairness A      | Historical emission $A_1$ | Positive | Avoiding polarization of inter-industry carbon emission quotas | Carbon emissions in the base year: industries with larger historical emissions bear greater responsibility for emission reductions |
| Carbon emission intensity $A_2$ | Positive | Force industries to achieve emission reduction targets | Total carbon emissions / industrial output |
| Cumulative emissions $A_3$ | Positive | Reflecting on the Historical Responsibility of Industry and the Development Process of Industrialization | Set start year to calculate industry cumulative emissions |
| Efficiency B    | Per capita output $B_1$ | Positive | The ability of the industry to create economic value | Per capita main business income |
| Energy structure $B_2$ | Positive | Guiding the Transformation of Coal-Based Energy Structure | Coal consumption / total energy consumption |
| Industrial energy intensity $B_3$ | Positive | Encourage industries to improve energy efficiency | Energy consumption / industrial output |
| Sustainability C | Openness $C_1$ | Negative | Encourage industries to improve openness and develop an export-oriented economy to introduce advanced technology and management experience | Energy consumption / industrial output |
| Profitability $C_2$ | Negative | Balance their development and emission reduction targets | Total profit / net assets |
| Research input $C_3$ | Negative | Reflect the Intensity of Technological Innovation in the Industry | R&D expenditure / main business cost |
| The comprehensive utilization rate of solid waste $C_4$ | Negative | Encourage Industry to Realize Green Low Carbon Sustainable Development | Comprehensive utilization amount of industrial solid waste / (production amount of industrial solid waste + storage amount of comprehensive utilization) |
| Fiscal Expenditure on Energy Conservation and Environmental Protection $C_5$ | Negative | Encourage enterprises to increase expenditure on energy conservation and environmental protection to achieve energy conservation and management and comprehensive utilization of resources | Fiscal expenditure on energy conservation and environmental protection / industrial output value |

Region (2022), the economic growth rate from 2025 to 2030 is set as 1.0%, then the total GDP of Inner Mongolia Autonomous Region in 2030 will be 3,693,289 billion yuan. The total emission quota target will be 746,414 million tons. Compared with 2020, the increase in total carbon emissions is 207,444 million tons. The original data are processed to obtain the normalized index matrix as follows:

$$Y_{ij} = \frac{1000 \cdot 1000 \cdot 0.500 \cdot 1.000 \cdot 0.813 \cdot 0.502 \cdot 0.688 \cdot 1.000 \cdot 0.746 \cdot 0.609 \cdot 0.745}{0.550 \cdot 0.394 \cdot 0.935 \cdot 0.763 \cdot 0.755 \cdot 1.000 \cdot 0.156 \cdot 0.853 \cdot 0.751 \cdot 0.719 \cdot 0.785}$$

The index value proportion of industry $i$ is as follows:

$$P_i = \begin{bmatrix} 0.319 & 0.319 & 0.160 & 0.319 & 0.259 & 0.160 & 0.211 & 0.319 & 0.238 & 0.194 & 0.238 \\ 0.176 & 0.088 & 0.191 & 0.198 & 0.096 & 0.281 & 0.033 & 0.166 & 0.098 & 0.102 & 0.126 \\ 0.158 & 0.196 & 0.042 & 0.119 & 0.101 & 0.081 & 0.084 & 0.119 & 0.097 & 0.110 & 0.161 \\ 0.145 & 0.171 & 0.039 & 0.108 & 0.046 & 0.132 & 0.060 & 0.079 & 0.035 & 0.126 & 0.123 \\ 0.069 & 0.089 & 0.048 & 0.058 & 0.088 & 0.051 & 0.035 & 0.042 & 0.097 & 0 & 0.058 \\ 0.039 & 0.067 & 0.023 & 0.075 & 0.050 & 0.034 & 0.007 & 0.007 & 0.102 & 0.119 & 0.005 \\ 0.025 & 0.019 & 0.129 & 0.063 & 0.039 & 0.028 & 0 & 0.174 & 0.131 & 0.091 & 0.033 \\ 0.037 & 0.073 & 0.014 & 0.020 & 0.120 & 0.058 & 0.037 & 0.094 & 0.100 & 0.020 & 0.066 \\ 0.018 & 0.047 & 0 & 0.111 & 0.053 & 0.148 & 0.001 & 0.071 & 0.141 & 0.141 & 0.141 \\ 0.011 & 0.017 & 0.038 & 0.012 & 0.126 & 0.061 & 0.094 & 0 & 0.003 & 0.055 & 0 \end{bmatrix}$$

The information entropy, information content, and entropy weight of each index are calculated in different industries. The information entropy value of each index reflects the different degrees of each index. The greater the difference in the index data, the more information the index can provide, and should be given greater weight. The entropy weight of the index is calculated by the entropy value of the index. The index entropy weight is calculated from the index entropy value.

(2) Determine the Final Weight $W_i'$. In this part, we calculate the weight of indicators at the criterion level. In the Analytic Hierarchy Process (AHP), 9 scales are used to compare the indexes, which are difficult to estimate. So we improve the analytic hierarchy process and reduce the scale to 3. In the improved analytic hierarchy process, when comparing the indicators in pairs, if $A$ and $B$ are equally important, they are expressed as ‘1’; if $A$ is more important than $B$, it is denoted as ‘2’; if $A$ is not as important as $B$, it is denoted as ‘0’. Taking the method of expert investigation, 25 experts in the field of environment, ecology, and resource utilization with certain academic attainments were consulted. Experts were invited to give the relative ranking of each index in the hierarchical structure. According to the comparative scale of 1-3, the judgment matrix was constructed:

$$A = \begin{bmatrix} 1 & 3 & 1/2 \\ 1/3 & 1 & 2 \\ 2 & 1/2 & 1 \end{bmatrix}$$

Calculate the weight of the evaluation index:

Through the above equation, we can obtain that $u_A = 0.398$, $u_B = 0.292$, $u_C = 0.310$.

A consistency test is performed:

The maximum eigenvalue $\lambda_{\text{max}}$ of the matrix is 3.039. $CI = (3.039)/(3-1) = 0.0195$. When $n = 3$, $RI = 0.52$. $CR = 0.0195/0.52 = 0.039 < 0.1$, which meets the requirements.

The total weight is calculated by combining the subjective weighting method and the objective weighting method, and the results are shown in Table 5.

(3) Calculate the Incremental Emission Allocation

Based on the actual total carbon emissions of 30 provinces in China in 2020, and with 2030 as the target year. The carbon quota change allocation of industry $i$ in the target year (2030) is set as $\Delta C_i>0$, and the actual carbon emissions of industry $i$ in the base year (2020) are set as $C_i<2020$, then the carbon quota change allocation of industry $i$ in 2030
is the product of the actual carbon emissions of the base year and the allocation factor.

\[ T_i = \frac{1}{k_i} \]

\[ \Delta C_i^0 = C_{i,2020} \times T_i \]

\[ \Delta C = \sum_{i=1}^{m} \Delta C_i = C_{2030} - C_{2020} \]

\[ f = \frac{\Delta C}{\sum_{i=1}^{m} \Delta C_i} \]

\[ \Delta C_i = \Delta C_i^0 \times f \]

(4) Calculate the Total Industry Quota

\[ C_{i,2030} = C_{i,2020} + \Delta C_i = C_{i,2020} + C_{i,2020} \times T_i \times f \]

Based on the principle of fairness, effectiveness, and sustainability, we construct the carbon emission quota allocation index system for high-energy-consuming industries through the information entropy model and calculate the total industry quota in 2030.

3. Results and discussion

Using the carbon emission quota evaluation index system established above, we allocate carbon emission quotas to high energy-consuming industries in Inner Mongolia. The impact of different allocation schemes is further discussed.

3.1. Results

3.1.1. Index weight results

From Table 4, we can see that the total emission and per capita output value have the greatest impact on the allocation of carbon emission quotas among industries when considering fairness. The score of the evaluation index system of carbon emission quota in high-energy-consuming industries can reflect the responsibility of different industries. These following indicators should be focused.

### Table 5. Information Entropy, Information Value, Entropy Weight, and Index Weight of Each Index.

| Indicators | A₁ | A₂ | A₃ | B₁ | B₂ | B₃ | C₁ | C₂ | C₃ | C₄ |
|------------|----|----|----|----|----|----|----|----|----|----|
| Information entropy value | 0.727 | 0.719 | 0.788 | 0.789 | 0.759 | 0.709 | 0.713 | 0.758 | 0.752 | 0.746 | 0.813 |
| Information value | 0.273 | 0.281 | 0.212 | 0.211 | 0.241 | 0.291 | 0.287 | 0.242 | 0.248 | 0.254 | 0.187 |
| Entropy weight | 0.356 | 0.367 | 0.277 | 0.284 | 0.324 | 0.392 | 0.236 | 0.199 | 0.204 | 0.209 | 0.154 |
| Index weight | 0.142 | 0.146 | 0.110 | 0.083 | 0.095 | 0.114 | 0.073 | 0.062 | 0.063 | 0.065 | 0.048 |

### Table 6. Carbon Emission Quota Allocation of High-energy-consuming Industries in Inner Mongolia Autonomous Region in 2030 (10000 tons).

| Industry | The IEMMA allocation | Historical Emission Method |
|----------|----------------------|---------------------------|
|           | Total carbon emission quota | Carbon emission intensity | Total carbon emission quota | Carbon emission intensity |
| ID44-ID46 | 18563.10 | 2.142 | 24658.15 | 2.845 |
| C30      | 10670.10 | 2.379 | 11725.91 | 2.614 |
| C31      | 10881.20 | 1.976 | 11341.91 | 2.060 |
| C25      | 9566.33  | 1.944 | 9350.00  | 1.900 |
| C26      | 8442.94  | 2.065 | 5103.84  | 1.248 |
| C32      | 4192.68  | 1.268 | 3723.26  | 1.126 |
| C17      | 3561.16  | 1.168 | 2195.54  | 0.720 |
| C22      | 2760.17  | 2.030 | 2085.76  | 1.534 |
| C28      | 1906.86  | 1.458 | 1333.62  | 1.020 |
| C29      | 1759.29  | 1.373 | 1289.37  | 1.006 |
| C13      | 1014.44  | 2.069 | 852.70   | 1.739 |
| C39      | 1036.08  | 1.021 | 802.16   | 0.790 |
| G53-G56  | 287.03   | 1.218 | 179.15   | 0.760 |

Historical emission (A₁): industries with historically large emissions should make more emissions reductions to avoid polarization of emission quotas between industries.

Carbon emission intensity (A₂): this indicator reflects the efficiency of creating economic value from carbon emissions. Based on the principle of fairness, industries with lower carbon emission intensity have higher energy efficiency and should be encouraged to maintain lower emission intensity. At the same time, industries with higher carbon emission intensity should be forced to make corresponding technology innovations and other measures to reduce the carbon intensity in the future.

Cumulative emissions (A₃): this indicator reflects the cumulative emissions of the industry. The historical cumulative emissions reflect the responsibility for the emission reduction. The industry should actively carry out carbon emission reduction actions to achieve the goal of greenhouse gas emission control.

Energy structure (B₁): this indicator reflects the use of different types of energy in various industries and the actual situation of carbon emissions from different energy sources.

Industrial energy intensity (B₂): industries with higher energy intensity should increase energy conservation and emission reduction to gradually reduce energy consumption and further improve the energy efficiency.

3.1.2. Industry quota allocation results

In this section, we calculate the industry quota allocation and carbon emission intensity results in the target year (2030) under the Historical Emission Method and the IEMMA Model for Inner Mongolia. The results are shown in Table 6.

3.2. Discussion

3.2.1. Analysis of impact on carbon emission

We calculate the carbon emission quota of Inner Mongolia under the Historical Emission Method and the IEMMA Model, respectively. Under the IEMMA model, the total carbon emission reduction and carbon emission intensity reduction of high-energy-consuming industries are calculated as shown in Fig. 9.
In the IEMMA model, “Petroleum, coal, and other fuel processing (C25)” ’s total carbon emissions grew the most (129.11%), while “Electricity, heat, gas, and water production and supply (D44-D46)” ’s total carbon emissions grew the least (only 4.21%). The IEMMA model highlights the emission restrictions on industries with large historical emissions, thus reducing the dependence on energy consumption to a certain extent. The relatively small emissions industries focus on sustainable development. From the perspective of carbon emission intensity, the change in carbon emission intensity is similar, but under the information entropy model, most industries failed to achieve a 60%-65% decline. The IEMMA model has higher restrictions on high-emission industries. Only “Electricity, heat, gas, and water production and supply (D44-D46)” can achieve a 60.39% reduction in carbon emission intensity in 2030.

Under the Historical Emission Method, the total carbon emission reduction and carbon emission intensity reduction of high-energy-consuming industries are shown in Fig. 10.

Under the Historical Emission Method, high-emission industries can obtain higher carbon emission quotas. From the perspective of total carbon emissions, the increase in total carbon emissions in different industries is nearly the same (about 40%). Dominated by carbon emissions in historical years, the increase in total carbon emissions is relatively close. This method indirectly encourages high-emission industries and ignores industry heterogeneity, which makes the industry lack the motivation to explore energy conservation and emission reduction, and is not conducive to the realization of emission reduction targets. At the same time, it has certain inequities for low-emission industries. For industries with high energy efficiency, there is relatively little room for future emissions reductions. From the perspective of carbon emission intensity, the decline of carbon emission intensity in different industries is quite different. The carbon emission intensity of “Transportation (G53-G56)” decreases the most (up to 74.06%), and the carbon emission intensity of “Agricultural and sideline food processing (C13)” decreased the least (38.37%)

We can see that the IEMMA model plays an important role in regulating the future carbon emission increment of different industries. The allocation principles of fairness, efficiency, and sustainability are reflected in the carbon emission allocation coefficient, thus realizing the aim of achieving the goal of peaking carbon emissions in 2030.

**3.2.2. Analysis of impact on emission reduction cost**

The IEMMA model focuses on the nature and development potential of the industry. What are emission reduction costs in this model? What is the impact on the carbon emissions trading market? The following analysis is discussed.
Under the IEMMA model, the industry with higher carbon emissions face lower total carbon emission growth. Therefore, the "Electricity, heat, gas, and water production and supply (D44-D46)" has a greater responsibility for the emission reduction. Under the principle of sustainability, these industries rely on profitability and openness to increase the innovation of emission reduction technologies, vigorously improve the production efficiency, and achieve carbon emission reduction targets. The current environmental protection has become an important direction of China's power industry. The high-carbon emission industry gradually improves the energy conversion efficiency. The adjustment and optimization of energy structure can promote development of economic growth and energy saving. The IEMMA model is more suitable for achieving long-term emission reduction targets.

The Historical Emission Method is based on the historical emission of each industry. This allocation method indirectly encourages high-emission industries, which may lack the motivation to explore active energy conservation and emission reduction, which is unfair to industries that have invested in energy conservation and emission reduction funds and developed environmentally friendly equipment in historical years.

By comparing the two allocations, under the same overall emission reduction cost, the emission reduction cost of high energy-consuming industries under the IEMMA model is higher. This "emission gap" can promote the active participation in the carbon trading market to achieve emission reduction targets while improving low-carbon technologies to reduce carbon emissions.

4. Conclusion

Based on the principle of fairness, effectiveness, and sustainability, the information entropy model is established. The carbon emission quota allocation of high energy-consuming industries in the Inner Mongolia Autonomous Region shows that: (1) Under the effectiveness principle, the IEMMA model considers the development gap of different industries and has a promoting effect on carbon emission reduction. The model achieves circular development of energy saving and consumption reduction and control emissions in high energy-consuming industries. (2) Under the fairness principle, the IEMMA model promotes high energy-consuming industries to take measures in low-carbon transformation, industrial structure upgrading, and the cleanliness of energy structures in underdeveloped areas. (3) Under the sustainability principle, the IEMMA model gives full play to the potential of the industry in a long-term process. The IEMMA model is suitable for the expansion of the coverage of industries to achieve the overall carbon emission reduction target. Therefore, the IEMMA model is conducive to promoting high energy-consuming to actively reduce emissions and activate the carbon trading market. This study still has some limitations. The development and improvement of the carbon emissions trading mechanism is a long process. First, using the IEMMA model to allocate carbon emission quotas for different industries in the region combines more indicators and more steps in the calculation. With the increasing inclusion of the industry, the complexity of the calculation will increase. Second, the model is more suitable for the allocation of quotas for high-energy-consuming industries, and less consideration is given to the heterogeneity of the industry. In the future, the model can be further improved according to the characteristics of the industry and to formulate distribution methods suitable for different stages.

Declarations

Author contribution statement

Xiufan Zhang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Fan Decheng: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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