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Allocation Model of Carbon Emission Permits for the Electric Power Industry with a Combination Subjective and Objective Weighting Approach

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Abstract: The electric power industry plays a vital role in carbon emissions reduction efforts. The initial allocation of carbon emission permits to the electric power industry is the key to ensuring the effective operation of the carbon trading market. In this study, the multiple correlated factors that affect the carbon emission permit allocation system were extracted. Then, based on the experts' knowledge and experience, the subjective weight of each index was determined using an improved analytic hierarchy process. Subsequently, the indices were mapped using an improved entropy weight method, and the objective weight of each index was adaptively determined. Finally, the comprehensive weight of each index was determined by optimizing the combination of its subjective and objective weights, and an allocation model of carbon emission permits for the electric power industry was established. A case study of a province by comparative simulation was performed. The simulation results showed that compared with conventional allocation schemes that consider single factors, the theoretical estimates obtained using the proposed model more objectively reflected the actual situation of carbon emissions reduction permits and responsibilities in the region.

Keywords: carbon emission permits; allocation model; electric power industry; analytic hierarchy process; entropy weight method

1. Introduction

The increasing prominence of climate change and energy issues presents serious challenges to ecosystems; accordingly, achieving low-carbon development has become a common goal in various industries [1]. The *Kyoto Protocol*, signed in 1997, aims to reduce carbon emissions through the international carbon trading market [2]. Carbon trading markets have since been established in various regions including Europe and the United States. The practical experiences of various countries demonstrate that carbon emissions trading, particularly carbon emission permits quota transactions, plays a crucial role in meeting carbon emission reduction goals [3].

The electric power industry, as one of the most important energy sectors, plays an important role in reducing emissions [4]. The initial allocation of carbon emission permits for the electric power industry is the critical foundation for ensuring the effective operation of the carbon trading market, which is a multi-objective, multi-level, multi-stakeholder complex project.

Currently, three main ideas exist for the initial allocation of carbon emission permits in the power industry: allocations based on historical emissions, power generation, and power generation intensity. The authors in [5,6] presented the allocation scheme of carbon emission permits based on historical carbon emissions. The historical carbon emission method is an allocation method that uses

the enterprises' historical emissions as the baseline. This approach is useful for heightening market entities' enthusiasm for participating in trading during the initial stage after a carbon trading market has been established. However, this method allows enterprises with high historical emissions to obtain relatively large carbon emission permits, which reduces their incentive to decrease carbon emissions. The authors in [7,8] proposed an allocation method based on power generation, noting that the responsibilities for carbon emissions from power generation should not be completely carried by the power-generating side and provided a regional allocation principle. However, power generation amounts are not equivalent to carbon emissions, which is inadequate for guiding the marketization of clean energy power generation. The researchers in [9,10] proposed an allocation method based on carbon emission intensity (also known as the power generation performance standard, which refers to the amount of CO₂ emitted per unit power output), and noted that carbon emission intensity is an important index for equitably evaluating carbon reduction efficiency. This method actively promotes low-carbon development, but dampens fossil energy power generation enterprises' enthusiasm for market participation. Fossil energy power generation enterprises have high carbon emissions, and will face greater costs participating in carbon market trading. It would be unfair if the costs of carbon emission reductions were entirely borne by the energy-supplier. As a result, the market participation enthusiasm of fossil energy power generation enterprises will be weakened. In the early stage of the establishment of the carbon market, in order to ensure the further perfection of the market, consideration should be given to mobilizing the enthusiasm of participants in each market. Therefore, the single variable method of carbon emission intensity cannot be adopted. As the market becomes more active, the importance of strengthening carbon emission intensity should be considered. The authors in [11] proposed a two-stage carbon emission permits allocation model, which produces the first stage of allocation results based on historical carbon emissions, followed by the second stage of allocation results based on the proportion of clean energy power generation. The authors in [12] also constructed a two-stage allocation model, which performs the first stage of allocation based on the regional development level, and the second stage of allocation is based on the power generation ratio.

Overall, amid the comprehensive promotion of reductions in power supply coal consumption, pollutant emissions, and proportion of coal in energy consumption, none of the historical emissions, power generation, and power generation intensity methods can fairly, effectively, and reasonably allocate carbon emission permits. To develop a fair and reasonable allocation of carbon emission permits for the electric power industry, this study examined the characteristics of carbon emissions in the electric power industry and decomposed the indices to extract multiple correlated factors that affect the carbon emission allocation system. Moreover, the allocation model of carbon emission permits in the power industry was established. Actually, the proposed model has certain limitations. The model accounts for regional differences within countries under the same jurisdiction, but does not work in the international allocation and trade of emission permits due to differences in legal jurisdiction.

2. Multiple Related Factors

The Coase theorem [13] notes that an unclear definition of property permits is the main cause of negative external problems. The primary task of controlling excessive carbon emissions is clarifying the enterprises' permits to use environmental resources. Different regions vary relatively substantially with respect to economic level, endemic resources, energy structure, and emission reduction technologies. Affected by factors such as regional environmental capacity and developmental needs, the power generation capacities of many provinces and cities are unable to meet the local power demand. Therefore, transregional power transmission plays a vital role in ensuring the regional power supply [14]. Under these circumstances, it is unfair for the costs of power generation carbon emissions and carbon emission reductions to be completely carried by the energy-supplying regions. Analyzing the multiple correlated factors that affect electric power industry carbon emissions is critical to formulating a reasonable and fair initial carbon emission rights allocation scheme [15].

Here, the factor decomposition method was used to decompose the electric power industry carbon emissions and analyze the multiple correlated factors that affect the emissions, as shown in Equation (1). Table 1 shows the definition of each symbol in Equation (1).

$$\begin{aligned}
 E &= \sum_{i=1}^m E_i = \sum_{i=1}^m (G_i * \frac{D_i}{G_i} * \frac{P_i}{D_i} * \frac{T_i}{P_i} * \frac{B_i}{T_i} * \frac{E_i}{B_i}) \\
 &= \sum_{i=1}^m (G_i * C_i * M_i * S_i * H_i * F_i)
 \end{aligned}
 \tag{1}$$

Table 1. Definition of each symbol.

Symbol	Meaning
E	Total carbon emissions from the electric power industry within a certain period
E_i	Carbon emissions from the electric power industry in the i th region within the corresponding period
G_i	Gross domestic product (GDP) of the i th region within the corresponding period
D_i	Power consumption of the i th region within the corresponding period
P_i	Power generation of the i th region within the corresponding period
T_i	Thermal power generation of the i th region within the corresponding period
B_i	Coal consumption of the i th region within the corresponding period
C_i	Power consumption per unit GDP of the i th region within the corresponding period
M_i	Ratio of power generation to power consumption of the i th region within the corresponding period
S_i	Proportion of thermal power generation of the i th region within the corresponding period
H_i	Standard coal consumption for thermal power generation of the i th region within the corresponding period
F_i	Carbon emission intensity per unit coal consumption of the i th region within the corresponding period
m	Total number of regions

As no significant short-term change in the coal quality of China is expected to occur, F_i can be assumed to be a constant. Additionally, three other influential factors should be considered when calculating the carbon emission permits for the i th region: transmission loss ratio, historical carbon emissions, and power generation. The importance of historical carbon emissions is evident. Considering the power generation is the result of the neglect of the absolute difference in the proportion index. Failure to limit carbon emissions constraints in high-power generation regions will result in a lack of enthusiasm from power generation industries to reduce emissions. The reason for considering transmission loss is that carbon emissions occur in power production during power transmission and distribution. Based on the relationships between each influential factor and carbon emission reduction responsibilities, the indices were categorized into two types, namely, performance and cost indices, as shown in Table 2.

Table 2. Index types.

Index	Relationship	Index Type
G_i	A higher economic level of a region indicates that more emissions reduction responsibility should be given to that region and smaller carbon emission permits should be allocated to that region.	Cost
C_i	A higher power consumption per unit GDP of a region should result in smaller carbon emission permits allocated to that region.	Cost
M_i	A higher power generation/power consumption ratio of a region indicates that the region exports more power. Thus, the region must reduce its the responsibilities with a high power generation/power consumption ratio and increase its carbon emission permits.	Performance
S_i	To actively guide clean energy power generation, reducing the carbon emission permits for a region with a high proportion of thermal power generation is necessary.	Cost
H_i	To guide and accelerate the elimination of low-efficiency, high-consumption power generation systems, higher standard coal consumption regions for thermal power generation should be allocated smaller carbon emission permits.	Cost
E'_i	Considering the scale of historical carbon emissions, regions with higher E'_i should be allocated higher carbon emission permits.	Performance
P_i	In order to promote high-power generation areas to actively implement energy-saving retrofitting new technologies to reduce emissions, their carbon emission rights allocation should be reduced.	Cost
L_i	To guide technological improvement to reduce transmission loss, higher transmission loss regions should be allocated smaller carbon emission permits.	Cost

Figure 1 shows the key factors affecting the regional carbon emission allocation for the electric power industry.

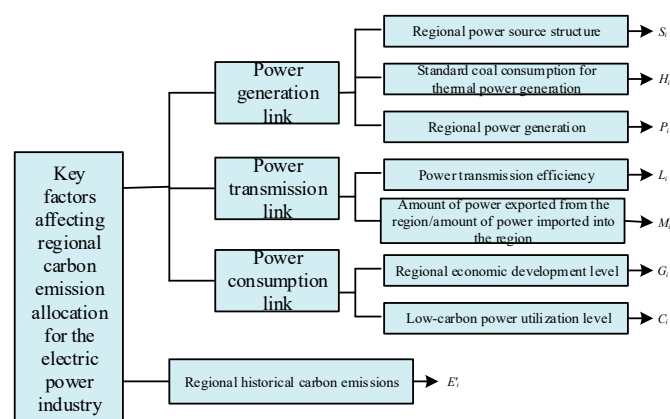


Figure 1. Key factors affecting the regional carbon emissions for the electric power industry.

The combination of subjective and objective weighting methods provides an optimal solution to the problem of weighting multiple correlated factors. The subjective weighting method makes full use of the knowledge and experience of decision makers, but is influenced by subjective preference and

relies too much on the opinions of decision makers. The objective weighting method relies on actual sample data to make judgments, which can better reflect the data information carried by each indicator; however, the method only considers the distribution of the data that cannot reflect the importance of each indicator in reality. Both methods have the problem of information loss, whereas the combination weighting method can minimize the loss of information and make the weighting result as scientific and as reasonable as possible.

3. Subjective Weight

Analytic hierarchy process (AHP), a classical subjective weighting method with the goal of making people's thinking orderly and hierarchical, makes use of less quantitative information to mathematicize the decision-making thinking process using an in-depth analysis of the essence, influencing factors, and their internal relations of decision-making problems. Given the interference by human factors, the traditional AHP is easy to fall into the local optimum in the actual decision-making process, and the consistency of the judgment matrix needs to be checked [16]. This paper optimizes the judgment matrix to prevent it from being unable to pass the consistency test and fall into the local optimum.

The decision makers are experts that should cover all relevant fields including government, energy, power, environmental protection, etc. They work in authoritative institutes in the field and have many years of relevant work experience. For experts from the same field, take only their average or weighted average to participate in the synthesis. To ensure the effectiveness of the review, appropriate specifications should be established so that experts use the same criteria for the measurements. Additionally, the experts should be asked to give detailed reasons for the evaluation results. In order to ensure that the evidence is independent of each other, conditions and facilities for independent review by experts will be provided. Experts will independently review in accordance with the law, and no unit or individual may illegally interfere. The number of experts is generally an odd number.

According to the decision makers' knowledge and experience, the multi-correlated influencing factors in Table 2 are sorted in descending order of importance to establish a decision matrix. To illustrate the universality of the method, n indices are assumed.

$$X = [x_1, x_2, \dots, x_j, \dots, x_n] = [x_{i,j}]_{m \times n}, \quad (2)$$

where $x_{i,j}$ is the j th index of the i th region. A total of m regions with n indices exist. According to the experts' opinions, the importance of the j th indicator (marked as ϕ_j) and the $(j + 1)$ th indicator (marked as ϕ_{j+1}) are compared in pairs. The comparative value of importance $\sigma_j (j = 1, 2, \dots, n - 1)$ is shown in Table 3.

Table 3. The comparative value of importance.

The Comparative Value of Importance	Comparing ϕ_j with ϕ_{j+1}
1	Equally important
1.2	Slightly important
1.4	Greatly important
1.6	Strongly important
1.8	Extremely important
1.1, 1.3, 1.5, 1.7,	Intermediate value of two adjacent judgments

Then, a judgment matrix is established.

$$\rho_{s,t} = \begin{cases} \prod_{j=s}^{t-1} \sigma_j & s < t \\ 1 & s = t \\ \prod_{j=t}^{s-1} \sigma_j & s > t \end{cases}, \quad (3)$$

where $\prod_{j=s}^{t-1} \sigma_j = \sigma_s * \sigma_{s+1} * \dots * \sigma_{t-2} * \sigma_{t-1}$, which shows that

$$\rho_{s,r} * \rho_{r,t} = \prod_{j=s}^{r-1} \sigma_j * \prod_{j=r}^{t-1} \sigma_j = \prod_{j=s}^{t-1} \sigma_j = \rho_{s,t}, \quad (4)$$

Therefore, any element in the judgment matrix satisfies $\rho_{s,r} * \rho_{r,t} = \rho_{s,t}$, and the judgment matrix is consistent. Then, the subjective weight value of the j^{th} indicator can be calculated.

$$\mu_j = \frac{\sqrt[n]{\prod_{t=1}^n \rho_{j,t}}}{\sum_{j=1}^n \sqrt[n]{\prod_{t=1}^n \rho_{j,t}}}, \quad (5)$$

4. Objective Weight

The multiple correlated factors differ relatively significantly in both dimension and numerical value. Extracting features from the real number series of these indices is very difficult. However, investigating the effective feature parameters of indices is generally easier by using a certain method to uniformly map them to a certain feature space to construct a new identification parameter system. The information entropy method is considered a simple but very effective spatial mapping method that can reflect the spatial structure of original data and show more visual, conspicuous feature relationships between the factors.

The concept of entropy first appeared in thermodynamics and was used to measure the uniformity of energy distribution in a system. More uniformly distributed energy results in greater entropy [17]. In information theory, the function of information is to eliminate uncertainty in the understanding of a matter. Entropy was introduced into information theory to measure the uncertainty of the system state [18]. Assuming that a system has n states and the probability for the system to be in each state is $p_j (j = 1, 2, \dots, s)$, the information entropy of the system is

$$d = -\sum_{j=1}^s (p_j * \ln p_j), \sum_{j=1}^s p_j = 1, 0 < p_j < 1, \quad (6)$$

When the system is in the equal-probability state (i.e., $p_j = \frac{1}{s}$), the entropy has the maximum value ($d = \ln s$), which is referred to as its extremum property.

Information entropy is objectively determined by a system's internal attributes. From a statistical perspective, greater entropy results in a more disorderly system; smaller entropy results in more abundant and effective information being provided for formulating a scheme. Therefore, among all of the indices, those with small entropy should have a high weight [19]. Based on this approach, an improved entropy weight method was employed to determine the weight of each correlated influential factor.

4.1. Normalize the Indicator

Normalize the indicator using the dispersion method, and when an index is a performance index,

$$r_{i,j} = \frac{x_{i,j} - x_{\min,j}}{x_{\max,j} - x_{\min,j}}, \quad (7)$$

When an index is a cost index,

$$r_{i,j} = \frac{x_{\max,j} - x_{i,j}}{x_{\max,j} - x_{\min,j}}, \quad (8)$$

4.2. Calculation of the Information Entropy Output by Each Index

The information entropy d_j of the j^{th} index is

$$d_j = -\frac{1}{\ln m} \sum_{i=1}^m (y_{i,j} * \ln y_{i,j}), \quad (9)$$

$$\text{where } y_{i,j} = \begin{cases} r_{i,j} / \sum_{i=1}^m r_{i,j} & r_{i,j} \neq 0 \\ 0 & r_{i,j} = 0 \end{cases}.$$

4.3. Calculation of the Attribute Weight Vector of Each Index

The weight of the j^{th} index calculated using the conventional entropy weight method is

$$\lambda_j = \frac{|1 - d_j|}{\sum_{j=1}^n |1 - d_j|}, \quad (10)$$

Relevant research demonstrates that when entropy is within a certain range, a small difference in entropy may cause a several-fold change in the entropy weight, which is inconsistent with the information carried by the entropy. To prevent this issue from occurring, an improved entropy weighting method is employed to calculate the weight of the j^{th} index:

$$\lambda'_j = \frac{\sum_{k=1}^n d_k + 1 - 2d_j}{\sum_{l=1}^n (\sum_{k=1}^n d_k + 1 - 2d_j)}, \quad (11)$$

5. Comprehensive Weight

The correct evaluation of weights should consider the subjective judgment of the evaluator and the objective information transmitted by the indicators. Here, the linear weighted combination method is used to calculate the comprehensive weights of the indicators.

$$\omega_j = \delta \mu_j + (1 - \delta) \lambda'_j, \quad (12)$$

The value of δ is based on the final decision-maker's preference for subjective judgment and objective results. If subjective judgment is preferred, then $0.5 < \delta < 1$. If objective results are preferred, then $0 < \delta < 0.5$; otherwise, $\delta = 0.5$.

The weight of the carbon emission permits in the i^{th} region is determined by the comprehensive weight of each indicator.

$$\alpha_i = \sum_{j=1}^n (y_{i,j} * \omega_j), \quad (13)$$

Assuming that Q is the total amount of carbon emission permits that can be used for the allocation, then the carbon emission permits that can be allocated in the i^{th} region are as shown.

$$Q_i = \alpha_i * Q, \quad (14)$$

6. Case Study

In this section, the proposed carbon emission permits allocation scheme is illustrated using an example. Table 4 shows the value of each index for five regions of a certain province in 2018.

Table 4. Index values for five regions in a certain province.

Index Region	E'_i (10,000 tons)	H_i (g/kWh)	S_i (%)	M_i (%)	C_i (kWh/CNY)	L_i (%)	G_i (CNY 100 million)	P_i (100 million kWh)
1	18,736	312	0.6	0.9	0.04	0.05	19,610	384
2	9648	257	0.02	1	0.07	0.03	8630	576
3	14,326	304	0.7	20	0.13	0.07	3202	553
4	7954	366	1	0.2	0.09	0.03	1045	180
5	2543	287	0.4	3.2	0.1	0.045	976	276

Note: G_i , C_i , S_i , H_i , L_i and P_i are the cost indices and M_i and E'_i are the performance indices. These indicators in descending order of importance are as follows: E'_i , G_i , P_i , H_i , S_i , M_i , C_i and L_i .

According to the experts' opinions or experiences, the importance of the two adjacent indicators is compared. Table 5 shows the comparative value of importance for adjacent indicators.

Table 5. Comparative value of importance for adjacent indicators.

σ_j	Value of Importance	Meanings
σ_1	1.1	Importance of E'_i to G_i is between equally important and slightly important
σ_2	1.2	G_i is slightly more important than P_i
σ_3	1.4	P_i is greatly important than H_i
σ_4	1	H_i is equally important to S_i
σ_5	1.5	The importance of S_i to M_i is between greatly important and strongly important
σ_6	1.6	M_i is strongly important relative to C_i
σ_7	1.8	C_i is extremely important relative to L_i

Set the preference coefficient as $\delta = 0.5$. The calculated subjective, objective, and comprehensive weights are shown in Table 6.

Table 6. Weight of each indicator.

Weights Indicators	μ_j	λ'_j	ω_j
E'_i	27.99%	8.45%	18.22%
G_i	24.03%	20.88%	22.46%
P_i	17.95%	12.58%	15.27%
H_i	10.48%	7.11%	8.79%
S_i	10.48%	8.83%	9.65%
M_i	5.48%	26.50%	15.98%
C_i	2.58%	8.41%	5.50%
L_i	1.01%	7.24%	4.13%
sum	100%	100%	100%

Thus, the proportion of each component of carbon emission permits in each region can be calculated according to the subjective and objective weights, as shown in Figure 2.

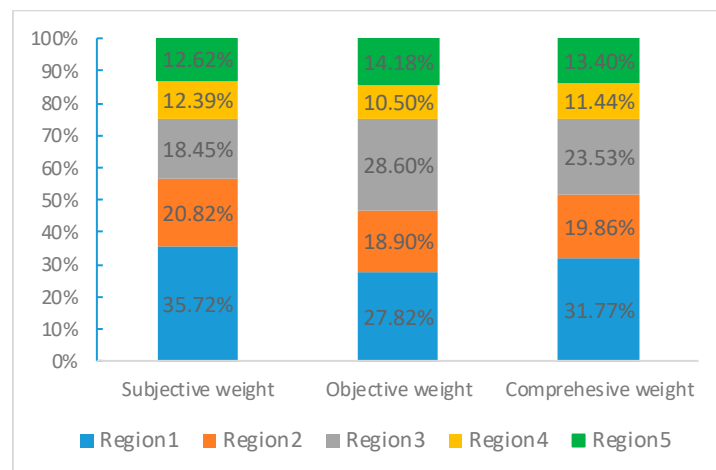


Figure 2. Proportion of carbon emission permits of each region based on subjective and objective weights.

Figure 3 summarizes the allocation results obtained using the historical carbon emission method, the carbon emission intensity method, the power generation method, and the proposed method.

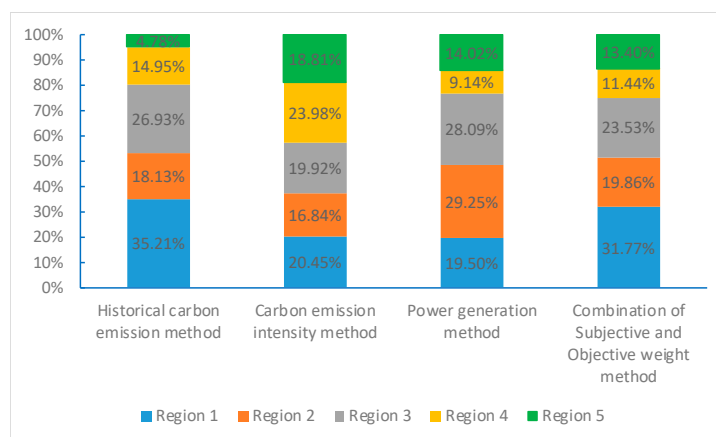


Figure 3. Carbon emission permits allocation results.

Region 1 has the highest historical carbon emissions, an indicator that is considered to be the most important by experts and that should be allocated with the largest number of carbon emission permits when considering the historical carbon emission scale. However, given its relatively high economic development level, region 1 should carry a relatively higher level of the carbon emission reduction responsibility. The subjective weight allocation ratio was the largest, and the objective weight allocation ratio was also larger; therefore, ultimately, the number of carbon emission permits allocated to the region was the largest, accounting for 31.77% of all such permits.

Region 2 generates a relatively large amount of power, but had the lowest carbon emission intensity. Additionally, the region has a relatively small proportion of thermal power generation and generates most of its power using clean energy. The region has a relatively high economic development level and should thus carry a higher level of the carbon emissions reduction responsibility. However, to actively guide clean energy power generation, it is necessary to increase the region's carbon emission permits. Through comprehensive consideration, region 2 was ultimately allocated a medium level of carbon emission permits, accounting for 19.86% of the total carbon emission permits.

Region 3 has the highest ratio of power generation to power consumption (20) and exports most of its generated power to other regions; consequently, its carbon emission reduction responsibility should be lowered. Moreover, region 3 has a relatively large historical carbon emission scale; therefore, it should be allocated a relatively large number of carbon emission permits. Although the region had

the largest transmission loss, according to the experts' experience, the proportion of carbon emissions corresponding to transmission loss was very small. Therefore, the final carbon emission permits in region 3 are not strongly affected by transmission loss. Given the largest objective weight allocation proportion, the proportion of the final carbon emission permits of region 3 was the second largest (23.53%).

Region 4 has the highest standard coal consumption for thermal power generation (366 g/kWh). To guide and accelerate the elimination of power generation systems with low-efficiency and high-consumption, reducing the carbon emission permits allocated to this region is necessary. Additionally, most of the power consumed in region 4 relies on long-term exports from other regions. Therefore, region 4 should carry a relatively higher level of carbon emission reduction responsibility. Thus, region 4 was allocated the fewest carbon emission permits, accounting for 11.44% of all such permits.

Region 5 has a relatively low economic development level and exports a certain amount of power to other regions. However, region 5 has the lowest historical carbon emissions. To support the region's economic development, the allocation amount should be increased appropriately. As the objective weight occupies a certain proportion of the allocation, through comprehensive consideration, region 5 was allocated a relatively small number of carbon emission permits, corresponding to a comprehensive weight of 13.4%.

Figure 3 also indicates that the proposed subjective and objective allocation method of the carbon emission permits allocation scheme comprehensively considers the multi-correlated influencing factors, and the final allocation result falls within the interval of considering the distribution result of a single factor, which is scientific and reasonable. This final allocation result was also a more acceptable solution for the allocation.

The proposed carbon emission permits allocation scheme based on the subjective and objective weighting method reasonably apportions permits based on an in-depth analysis of the carbon emission process in the electric power industry. Thus, this scheme considers the fundamental function of power in economic development, the environmental costs of energy bases, the contribution of the power supply to society, and the uneven distribution of resources among regions. Such an approach allows the transfer of reasonable carbon emission permits from regions rich in clean power-generating resources to regions deficient in these resources, thereby ensuring each region's permits to fairly use clean power-generating resources. Additionally, the proposed scheme can help actively guide the transition of the regional power source structure to clean energy power generation and facilitate the implementation of national policies for the electric power industry. For regions that largely rely on power imports, their external carbon emission reduction responsibilities are internalized, which can help mobilize their enthusiasm for supporting power supply regions. For relatively less-developed regions, the proposed scheme can help reduce their power generation costs and carbon emissions reduction pressure, facilitating the sustainable and healthy development of their energy structures and economies.

In summary, the proposed carbon emission permits allocation scheme for the electric power industry based on the subjective and objective weighting method can organically combine the objective information transmitted by the index sample data with the knowledge and experience of decision makers and fully embody the scientificness and fairness of the allocation scheme.

7. Conclusions

The carbon emission permits allocation scheme of the power industry based on the subjective and objective weighting method proposed in this paper cannot only overcome the disadvantage of inconsistency between the entropy value and the transmitted information in the traditional entropy weighting method. However, the scheme also prevents the problem that the judgment matrix in the AHP cannot pass the consistency test, leading to the decision-making problem. By optimizing the combination of subjective and objective weights, the combined weighting method not only highlights

the inherent differences in the attributes of the sample data, but also pays enough attention to the indicators that experts believe need to be focused on, and obtains the comprehensive quantitative value of multi-correlated indicators, thus avoiding one-sided evaluation results that are too subjective or too objective. Compared with the traditional method of considering a single factor, the method proposed in this paper, considering the influence of multi-correlated factors, the theoretical calculation results are consistent with the actual emissions reduction responsibility.

The established model considers the fundamental function of power in economic development and the environmental costs of energy bases. Through the reasonable allocation of carbon emission permits, this model achieves the following: reasonable reallocation of carbon emission reduction responsibilities between regions; improvements in the developed regions' enthusiasm for supporting energy bases in reducing carbon emissions; assisting with increasing the proportion of clean energy in power generation; and promotion of energy restructuring and coordinated regional economic development. For regions that largely rely on imported power, external carbon emission responsibilities are internalized to stimulate enthusiasm for energy conservation and carbon emissions reduction. For relatively less-developed regions, the proposed method can help reduce carbon emissions reduction pressure and facilitate sustainable and healthy economic development. Such a model can also be used as a theoretical basis for regional carbon emission permits allocation in the electric power industry to facilitate joint regional carbon emissions reduction efforts and the realization of national carbon emissions reduction goals.

Author Contributions: X.P. and H.L. conceived of the presented idea. X.P. developed the theory and performed the computations. J.H. verified the analytical methods. Y.S. and H.H. was encouraged to investigate a specific aspect and supervised the findings of this work. All of the authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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