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Responsibility Allocation of Provincial Industry Emission Reduction from the Perspective of Industrial Linkages—A Case Study of Shanxi Province

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Abstract: The allocation of emissions reduction responsibilities in a fair and efficient manner is the key to achieving optimal overall reductions in emissions. However, existing studies have not adequately considered the impact of industry linkages. To fill this gap, this study constructed a carbon emissions reduction responsibility allocation model from the perspective of industry linkages using the TOPSIS (a technique for order preference by similarity to an ideal solution) comprehensive evaluation method based on entropy weights. A typical resource-based province, Shanxi, was selected to broaden the scope of the related research to the provincial level. The indicator system designed in this study also compensates existing studies that have lacked consideration of industry linkages. The results show that traditional energy-intensive industries will be significantly less responsible by incorporating indirect emissions responsibility into the equity principle, while the 'coal mining and washing' and 'construction' industries will be more responsible. By incorporating the impact of industry linkages on the overall emissions reduction effect into the efficiency principle, traditional energy-intensive industries with overly intensive emissions reduction tasks will limit the overall efficiency, while industries with strong emissions reduction potential or able to support low-carbon economic development will be able to take on more responsibilities. These findings are expected to provide the government with references to formulate mitigation policies in China and in other countries.

Keywords: CO_2 emissions; emissions reduction; responsibility allocation; equity principle; efficiency principle; industrial linkages

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1. Introduction

As the world's largest emitter of carbon dioxide (CO_2), China has a key role to play in global climate change mitigation [1]. China has pledged to meet its carbon peak target by 2030 [2], and the scientifically justifiable carbon reduction plan is essential to achieve this goal [3]. The allocation of carbon emissions reduction responsibilities has become the focus of interest among industries [4]. The key issue that needs to be addressed is how to allocate the responsibility for emissions reduction in a fair and efficient manner to achieve the best overall reduction [5].

Scholars have conducted extensive research that has positively enhanced emissions reduction and reduced abatement [5]. In terms of research objectives, existing studies have mainly been conducted at the national level [6]. For example, Zhao et al. [7] and Han et al. [8] investigated the allocation of emissions reduction responsibilities to the building materials industry and the transportation industry, respectively, which provided a reference for the design of carbon emissions trading mechanisms and the adjustment of carbon emissions allowance purchase schemes. Zhang and Hao [9] allocated carbon emissions quotas among the 39 sectors of China's industry in 2020 and employed the input-oriented ZSG-DEA model to examine the efficiency of allocation solutions. Based on

1992–2012 input–output tables and the direct carbon emissions of China, Hou et al. [10] calculated the embodied carbon transfer within 28 industries. They characterized the embodied carbon transfer structure among different industries in China, which addresses some shortcomings in production responsibility, thus providing a new perspective for carbon emissions reduction.

In terms of research perspectives, scholars generally agree that carbon reduction responsibilities should be allocated in terms of both the principle of equity and the principle of efficiency [5,11]. This is because considering the two principles for allocation can avoid both the loss of efficiency caused by considering only the principle of equity, [8,12] and the "Matthew effect" caused by considering only the principle of efficiency [13]. In terms of indicators to measure the equity principle, existing studies have mainly used indicators such as the historical emissions of each industry as a reflection of the fair distribution of emissions reduction responsibilities [14,15], lacking consideration of the impact of the embodied carbon emissions of each industry on fair distribution from the perspective of industrial linkages [16]. In terms of indicators to measure the efficiency principle, existing studies have mainly used indicators such as value added and carbon intensity to assess the carbon efficiency of each industry [17], failing to take into account the impact of industrial linkages on overall emissions reduction efficiency [18]. In addition, some scholars point out that the carbon diffusion coefficient and carbon-inducing coefficient can reflect the close relationship between carbon emissions, economic growth, and industrial structure [19], and help to deal with the relationship between development and emissions reduction, on the whole and on a local scale, but no previous research has yet selected these two indicators for the study of emissions reduction responsibility allocation.

There are still some issues that need to be addressed. In terms of research objectives, studies have been conducted mainly at the national level [20], while further research is needed to be conducted at the provincial level to provide a more practical allocation [21]. In terms of research perspectives, studies have not been conducted from the perspective of industrial linkages. First, consideration of the impact of indirect emissions embedded in industries' final demand on equitable allocation is lacking [22]. Second, the impact of the reduction in emissions of each industry on the overall emissions reduction efficiency has not been adequately included in previous analytical framework [23].

To address these issues, this study constructs a model for the distribution of carbon emissions reduction responsibilities among provincial industries using the entropy-based TOPSIS (a technique for order preference by similarity to an ideal solution) comprehensive evaluation method, and distributes carbon emissions reduction responsibilities among provincial industries to provide a case study for the distribution of carbon emissions reduction responsibilities among provincial industries. The influence of industry linkages is reflected in the design of the emissions reduction responsibility allocation indicators. The historical carbon emissions and embodied carbon emissions of each industry are used as indicators to measure the equity principle. The value added, the ratio of the actual carbon intensity of the industry to the advanced carbon intensity of the industry, the carbon impact factor, and the carbon inductance factor are used to measure the principle of efficiency. This study aims to provide a more comprehensive analytical perspective to enhance the reliability of the allocation of the CO_2 emissions reduction responsibility.

Shanxi Province is a suitable case study for several reasons. As a typical resource-based province, Shanxi Province has long taken coal resources as the core to drive local economic development [24]. In 2019, Shanxi Province's CO_2 emissions per unit of GDP energy consumption was 3.10 tons per CNY 10,000, about 3.28 times higher than the national level. Under the carbon peak target, Shanxi Province faces a more intense conflict on how to balance carbon emissions reduction and economic development compared to other provinces, so it is more valuable to select this province for the study [25]. In view of this, this paper discusses the characteristics and differences in the allocation of carbon emissions reduction responsibilities among various industry segments in Shanxi Province from the perspective of industry and industrial linkages, respectively, based on the principle of equity and the comprehensive principle of "equity + efficiency".

This study contributes to the existing literature in two ways. First, in terms of the research object, this study aims to provide a research case for allocation among provincial industries. This overcomes the shortcomings of existing studies that are too macro in the allocation of emissions reduction responsibilities, which can hardly provide a practical reference for policy makers. Second, in terms of the research perspective, the impact of industry linkages is incorporated in the design of the indicators. Such an increase is necessary to reflect the impact of embodied CO_2 emissions to enhance the fairness of the allocation. Meanwhile, it compensates for the fact that existing studies have not adequately addressed the impact of each industry's own emissions reduction practices on the overall reduction efficiency.

The remainder of this paper is structured as follows: Section 2 presents the methodology and data sources; Section 3 provides the results and discussion; Section 4 suggests relevant future policies; and, finally, Section 5 presents the conclusions.

2. Research Methodology and Data

This section discusses the basis for selecting and calculating the allocation of carbon emissions reduction responsibility indicators from the industry perspective and the industrial linkages perspective, respectively, as well as the models for allocating emissions reduction responsibilities to provincial-level sub-sectors from the two perspectives.

2.1. Design of Carbon Emissions Reduction Responsibility Allocation Indicator System from Industry Perspective

From the industry perspective, in terms of the equity principle, the direct emissions responsibility for the direct consumption of fossil energy is mainly considered, and the historical emissions of each industry is used as an indicator for allocation [26].

In terms of the efficiency principle, the emissions reduction ability and potential are mainly considered. The allocation is made according to the added value of the industry and the ratio of actual carbon intensity to the advanced level of each industry [17].

2.2. Design of Carbon Emissions Reduction Responsibility Allocation Indicator System from Industrial Linkages Perspective

Under the industrial linkages perspective, this study improves the indicator system to compensate previous studies that lacked consideration of the industrial linkages on CO_2 emissions.

2.2.1. Design of the Equity Principle Indicator System from Industrial Linkages Perspective

Under the equity principle, the indirect emissions responsibility is additionally considered. Historical and embodied emissions are jointly considered for a fair allocation. Embodied CO_2 emissions represent the CO_2 emissions generated by upstream industries driven by the final consumption of the products of a certain industry [27]. The larger the indicator is, the more indirect emissions the industry has and thus should be more responsible for emissions reduction. In this way, the responsibility undertaken by each industry includes not only the direct emissions responsibility, but also the indirect emissions responsibility [28]. The specific calculation process of embodied carbon emissions is as follows:

Based on the basic relationships of 'Leontief' non-competitive input–output table, the following model is established:

$$x = (I - A_d)^{-1} y = L_d y \tag{1}$$

where x represents the total output vector, A_d represents the provincial direct consumption coefficient matrix, L_d represents the provincial Leontief inverse matrix, and y represents the provincial final demand vector.

The carbon intensity coefficient matrix F is defined as a diagonal matrix, and each element on the diagonal is equal to the CO_2 emissions per unit added value of each industry; $1'F$ is defined as the row vector of each industry's carbon intensity. The embodied carbon emissions of each industry can be expressed as:

$$C = 1'F\hat{k}L_d diag(y) \tag{2}$$

where k represents the vector of value-added rate, and $\hat{k}$ represents its diagonal matrix. $diag(y)$ represents the diagonal matrix of the final demand vector within the province.

2.2.2. Design of the Efficiency Principle Indicator System from Industrial Linkages Perspective

Under the efficiency principle, the impact of industrial linkage on the CO_2 emissions of each industry is considered. The indicators of the carbon diffusion coefficient and carbon-inducing coefficient are included for efficiency allocation. By adding these two indicators, the allocation of the responsibility for emissions reduction can not only analyze the emissions reduction efficiency reflected to each industry's own emissions reduction ability and potential, but also the interactive influence between industries [29]. The specific calculation process is as follows:

With the help of the carbon intensity coefficient matrix F and the provincial Leontief inverse matrix L_d, the provincial complete demand matrix of carbon emissions E_d can be calculated as:

$$E_d = C \cdot L_d \tag{3}$$

The carbon diffusion coefficient δ_j can be calculated as:

$$\delta_j = \frac{\sum_{i=1}^{n} e_{ij}}{\sum_{j=1}^{n} \sum_{i=1}^{n} e_{ij}\alpha_j} \tag{4}$$

where α_j represents the proportion of the final consumption demand of sector j in the total final consumption demand of the national economy. The larger δ_j of j sector is, the greater the carbon emissions consumed to meet the increase in the final products of the sector. By strengthening the emissions reduction responsibility, the industries with a larger carbon diffusion coefficient can be encouraged to reduce their demand from energy-intensive industries, thus accelerating the reduction in the carbon emissions of the overall industrial chain.

The carbon-inducing coefficient θ_i is defined as:

$$\theta_i = \frac{\sum_{j=1}^{n} e_{ij}\alpha_j}{\frac{1}{n}\sum_{j=1}^{n} \sum_{i=1}^{n} e_{ij}\alpha_j} \tag{5}$$

Among them, the larger the θ_i of sector i is, the more greenhouse gases the sector emits to meet the growth of the national economy. By strengthening the emissions reduction responsibility of industries with a larger carbon-inducing coefficient, the induced effect of the development of the national economy on the carbon emissions of these industries can be weakened, preventing them from becoming new industries with a high level of carbon emissions.

The indicator design of the allocation of responsibility for emissions reduction from different perspectives is shown in Table 1. The principles of equity and efficiency are considered in both perspectives. First, in terms of the industry perspective, indicators are determined according to existing studies. The equity principle is represented by historical carbon emissions, while the efficiency principle is represented by added value and the ratio of industrial actual carbon intensity to an advanced level.

Table 1. Design of emissions reduction responsibility allocation indicators from the perspectives of equity and efficiency principles, respectively.

Perspective	Industry Perspective	Industrial Linkages Perspective
Equity principle	Historical carbon emissions	Historical carbon emissions Embodied carbon emissions
Efficiency principle	Added value Industrial actual carbon intensity/advanced level of industrial carbon intensity	Added value Industrial actual carbon intensity/advanced level of industrial carbon intensity Carbon diffusion coefficient Carbon-inducing coefficient

Second, in terms of the industrial linkages perspective, the impact of industry linkages on CO_2 emissions is further included. Under the equity principle, there is additional consideration of each industry's embodied CO_2 emissions. Under the efficiency principle, the indicators of the carbon diffusion coefficient and carbon-inducing coefficient are included.

2.3. A Provincial Inter-Industry Model for Emissions Reduction Responsibility Allocation

In terms of research methods, the commonly used methods mainly include the optimization method [30], game theory [31], mixed method [32], and indicator methods [33]. Among the optimization methods, the DEA technique is often used to maximize the efficiency of carbon quota allocation due to its advantage of reflecting the comprehensive performance of multiple factors [34]. However, this method lacks consideration of equity, and the input–output indicator data mostly need to be predicted based on past trends, lacking consideration of the impact of changes in the external conditions on the indicators [35]. Game theory and mixed methods suffer from a lack of transparency and are too complex to be widely used [36]. In contrast, the indicator method is often used to integrate multiple principles for the design of abatement responsibility allocation schemes because it is simple and easy to understand and can better balance the principles of equity and efficiency [37,38]. Bathrinath et al. [39] used the fuzzy COPRAS (complex proportional assessment) technique to decipher the factors disturbing the sustainable performance of a shipping port. Wang et al. [40] constructed a model for empirically testing the policy effect of China's carbon emissions trading pilot based on the entropy-weighted TOPSIS comprehensive evaluation method. This improvement compensated for the shortcomings of the indicator method in terms of the unreasonable design of indicator weights, and also provided a reference for this study.

In this paper, the TOPSIS comprehensive evaluation method and entropy method are used to construct a provincial inter-industry emissions reduction responsibility allocation model. The allocation of emissions reduction responsibility is conducted, respectively, from the perspectives of industry and industrial linkages.

First, a two-dimensional data matrix consisting of n sub-industries and m allocation indicators is established:

$$X = \begin{bmatrix} x_{11} \, x_{12} & \cdots & x_{1m} \\ x_{21} \, x_{22} & \cdots & x_{2m} \\ \cdots \; \cdots & \cdots & \cdots \\ x_{n1} \, x_{n2} & \cdots & x_{nm} \end{bmatrix} = (x_{ij})n \cdot m \quad (6)$$

where x_{ij} represents the original data and represents the value of the j metric for the i industry $(i = 1, 2, \cdots n,\ j = 1, 2, \cdots, n)$.

Second, the original data were standardized to eliminate the dimensions of each indicator to achieve comparability. In this paper, the selected indicators from the perspective of industry and industrial linkages are all efficiency-based indicators, and the specific processing formula is as follows:

$$y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}}, i = 1,2,\cdots n;\ j = 1,2,\cdots m \tag{7}$$

where $\max x_{ij}$ and $\min x_{ij}$ are the maximum and minimum values of the indicators in the j column of matrix X, respectively, and y_{ij} is the normalized data of each indicator.

The third step is to construct a weighted standardized matrix and to objectively calculate the weight of each index using the entropy weight method to distinguish the influence and relative importance of each indicator on the system. According to Formulas (8)–(10), the weight of the i industry under the j indicator p_{ij}, the entropy value of the j indicator H_j, and the entropy weight of the j indicator w_j can be obtained, respectively.

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}}, (i = 1,2,\cdots n;\ j = 1,2,\cdots,m) \tag{8}$$

$$H_j = -k\sum_{i=1}^{n} p_{ij}\log p_{ij}, (i = 1,2,\cdots n;\ j = 1,2,\cdots,m) \tag{9}$$

$$w_j = \frac{1 - H_j}{m - \sum_{j=1}^{m} H_j}, (i = 1,2,\cdots n;\ j = 1,2,\cdots,m) \tag{10}$$

$$Z = \begin{bmatrix} y_{11}\, y_{12} & \cdots & y_{1m} \\ y_{21}\, y_{22} & \cdots & y_{2m} \\ \cdots\ \cdots & \cdots & \cdots \\ y_{n1}\, y_{n2} & \cdots & y_{nm} \end{bmatrix} \begin{bmatrix} w_1 & 0 & \cdots & 0 \\ 0 & w_2 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & w_m \end{bmatrix} = \begin{bmatrix} z_{11}\, z_{12} & \cdots & z_{1m} \\ z_{21}\, z_{22} & \cdots & z_{2m} \\ \cdots\ \cdots & \cdots & \cdots \\ z_{n1}\, z_{n2} & \cdots & z_{nm} \end{bmatrix} \tag{11}$$

where the value of k is calculated by the formula $k = 1/\log(n)$ to ensure $0 \le H_j \le 1$. z_{ij} indicates the weighted normalized indicator value of j for the i industry $(i = 1,2,\cdots n;$ $j = 1,2,\cdots,m)$.

The fourth step is to calculate the distances from each distribution scheme to the positive and negative ideal schemes d_i^+ and d_i^-, which are calculated as follows:

$$d_i^+ = \sqrt{\sum_{j=1}^{m} (z_{ij} - z_j^+)^2}, i = 1,2,\cdots n \tag{12}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m} (z_{ij} - z_j^-)^2}, i = 1,2,\cdots n \tag{13}$$

where $z_j^+ = \max_{1\le i\le n}\{z_{ij}\}$, $z_j^- = \min_{1\le i\le n}\{z_{ij}\}$, $(i = 1,2,\cdots n)$. The smaller the value of d_i^+ is, the closer the industry's allocation scheme is to the positive ideal scheme. In this case, this industry's emissions reduction potential is greater and should undertake greater responsibility. The larger the value of d_i^- and the farther away from the negative ideal scheme, the greater the amount of responsibility which should be undertaken.

The fifth step is to calculate the ideal discount level for each allocation option at D_i. The greater the value of D_i is, the greater the potential of the industry to reduce emissions and to take more responsibility for carbon emissions reduction. The specific calculation is as follows:

$$D_i = \frac{d_i^-}{d_i^+ + d_i^-}, i = 1,2,\cdots n \tag{14}$$

Finally, the percentage of the allocation of responsibility for carbon emissions reduction to each industry is derived from the share of the ideal discount level for each industry P_i, which is calculated as follows:

$$P_i = \frac{D_i}{\sum\limits_{i=1}^{n} D_i}, i = 1, 2, \cdots, n \tag{15}$$

2.4. Data Source and Processing

Twenty-nine sub-sectors in Shanxi Province were selected as the assignment objects of carbon emissions reduction responsibility. The input–output data were obtained from the input–output Table of China's Regions (2017) complied by the Department of National Economic Accounting of the National Bureau of Statistics. The carbon emissions data were obtained from the China Carbon Accounting Database (CEAD). The study did not involve the carbon emissions data of Hong Kong, Macao, Taiwan, and Tibet in view of data availability. The data used in the emissions reduction responsibility accounting model are shown in Table 2.

Table 2. Accounting indicators for emissions reduction responsibility of various industries in Shanxi Province.

Industry Code	Industry Name	Equity Principle		Efficiency Principle			
		Actual Carbon Emissions (Million Tons)	Embodied Carbon Emissions (Million Tons)	Value Added (Billions of Dollars)	Carbon Emissions Intensity /Advanced Level	Influence Coefficient	Sensitivity Coefficient
S1	Agriculture, forestry, and fisheries	437.47	780.10	764.06	4.57	0.33	0.20
S2	Coal mining and washing industry	1229.99	8738.52	2290.20	0.65	0.89	0.57
S3	Oil and gas extraction industry	0.32	148.80	28.89	0.06	1.42	0.00
S4	Metal mining industry	46.17	149.70	89.07	3.90	1.60	0.04
S5	Non-metallic and other mineral mining industry	0.20	3.61	1.37	1.39	0.50	0.00
S6	Food processing and tobacco manufacturing	16.85	306.29	256.11	1.19	0.25	0.02
S7	Textile industry	2.28	37.24	6.69	6.27	0.76	0.01
S8	Textile, apparel, and leather manufacturing	0.40	9.66	8.29	2.27	0.20	0.00
S9	Wood processing and furniture manufacturing	0.04	18.63	13.50	0.09	0.30	0.00
S10	Paper, printing, and education and sports manufacturing	12.11	31.85	17.99	4.88	0.69	0.02
S11	Petroleum processing, coking, and nuclear fuel processing industry	4041.23	4269.20	389.89	13.29	2.08	2.42
S12	Chemical industry	473.95	926.84	352.23	10.18	1.16	0.28
S13	Non-metallic mineral products industry	1653.72	768.68	171.42	2.85	2.48	0.96
S14	Metal smelting and rolling processing industry	8524.56	5526.48	829.56	3.09	3.36	5.77
S15	Metal products industry	28.53	74.89	97.56	4.57	1.18	0.02
S16	General equipment manufacturing	18.48	176.08	54.01	6.04	0.92	0.02

Table 2. *Cont.*

Industry Code	Industry Name	Equity Principle		Efficiency Principle			
		Actual Carbon Emissions (Million Tons)	Embodied Carbon Emissions (Million Tons)	Value Added (Billions of Dollars)	Carbon Emissions Intensity /Advanced Level	Influence Coefficient	Sensitivity Coefficient
S17	Specialized equipment manufacturing	319.85	285.12	70.62	5.59	1.17	0.33
S18	Transportation equipment manufacturing	18.84	342.89	92.43	5.48	0.66	0.03
S19	Electrical machinery and equipment manufacturing	0.67	166.26	65.08	0.44	0.65	0.00
S20	Communications equipment, computers, and other electronic equipment manufacturing	21.58	688.10	203.35	12.14	0.53	0.02
S21	Instrument manufacturing	0.12	19.68	8.53	1.02	0.30	0.00
S22	Scrap waste, equipment repair, and other manufacturing	31.06	111.63	53.13	17.22	0.66	0.02
S23	Electricity, heat production, and supply industry	29,277.15	8936.69	572.50	3.13	8.61	17.09
S24	Gas production and supply industry	0.21	175.25	87.32	0.07	0.97	0.00
S25	Water production and supply industry	0.24	11.92	11.49	2.03	1.34	0.00
S26	Construction	207.88	10,640.78	1019.84	3.54	0.97	0.19
S27	Wholesale, retail trade and accommodation, and catering	1946.39	1940.10	1480.31	2.45	0.51	0.69
S28	Transportation, storage, and postal industry	451.77	1620.16	1052.14	2.23	0.60	0.19
S29	Other Services	411.85	2268.74	5440.85	3.48	0.30	0.13

3. Research Results and Discussion

3.1. Allocation Results of Carbon Emissions Reduction Responsibility from Industrial Linkages Perspective

The emissions reduction responsibility of each sub-industry in Shanxi Province under the equity principle and comprehensive principle is shown in Figure 1.

From the two perspectives, the key industries that undertake a share of emissions reduction higher than 5% under both principles are relatively similar, namely the "coal mining and washing industry" (S2), "petroleum processing, coking and nuclear fuel processing industry" (S11), "metal smelting and rolling processing industry" (S14), "electricity, heat production and supply industry" (S23), "construction industry" (S26), etc. Combined with Table 2, the above industries share characteristics of high direct or embodied carbon emissions. These industries typically directly consume fossil energy in the production process or drive other industries to consume fossil energy to meet demand. However, there are certain differences between these industries. For example, S2 and S26 have a greater indirect emissions responsibility as their production activities drive the fossil energy consumption of upstream industries, although their direct emissions are lower. S11, S14, and S23 have significantly lower emissions reduction responsibilities after considering their embodied carbon emissions but are still higher than other industries; therefore, they need to take on more emissions reduction responsibilities. This result also supports the view of He, Yang, Liu, Wang, Ji, and Yi [22] in that the formulation of emissions reduction policies should focus on the 13 sectors with the highest CO_2 emissions.

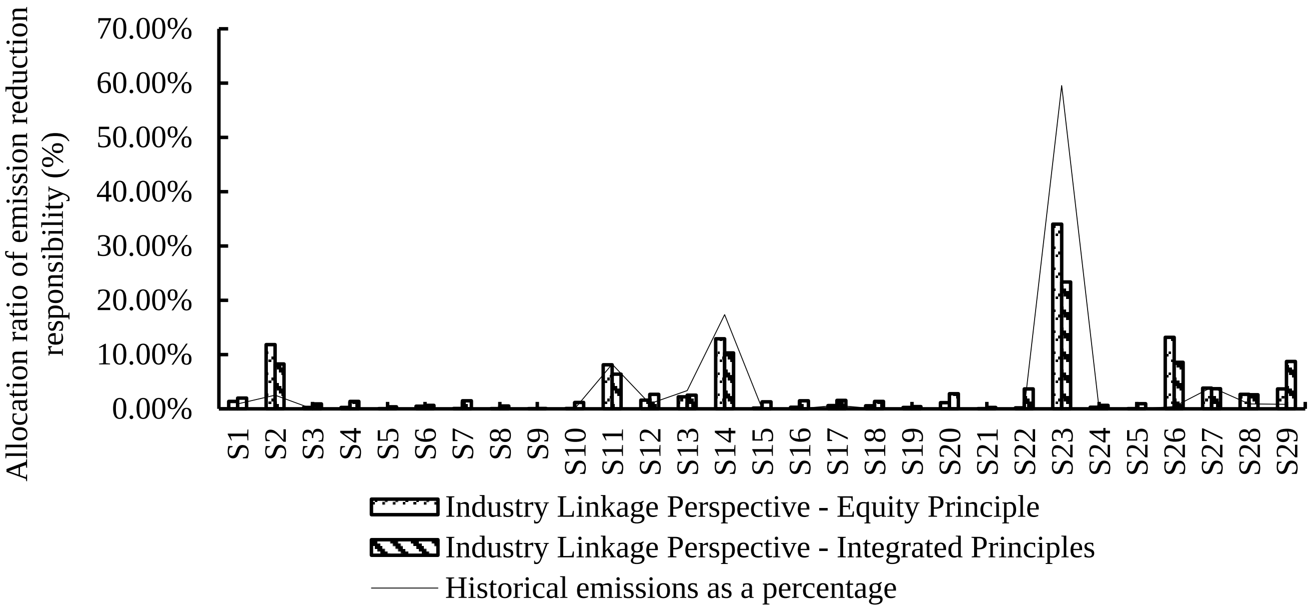

Figure 1. The proportion of carbon emissions reduction responsibilities by industry in Shanxi Province from industrial linkages perspective. Note: See Table 2 for each industry code in the table.

From the changes in the emissions reduction responsibilities of each industry under the two principles, the responsibility of traditional energy-intensive industries with large direct emissions will decrease after considering the indirect emissions responsibility and emissions reduction efficiency. The change in S23 is particularly prominent. The historical emissions percentage of this industry is 59.54%, which is characteristic of a high-emissions industry. Further, after considering the emissions driven by the demand of other industries, its emissions reduction responsibility will drop significantly to 34.02%. Further, after considering the differences in the emissions reduction efficiency among industries, the responsibility of this industry will decrease to only 23.36% to maximize the overall efficiency. It can be seen that there is often a "mismatch" between the emissions reduction responsibility and emissions reduction efficiency in traditional energy-intensive industries. If the emissions reduction responsibility is determined simply by the proportion of direct emissions, the indirect emissions responsibility that should be borne by downstream industries will be ignored, which will easily cause excessive pressure on energy-intensive industries and undermine the fairness of responsibility allocation. At the same time, it also lacks consideration of the impact of industrial linkages on overall emissions reduction, making it difficult to maximize the emissions reduction efficiency. Zhang et al. [41] also verified this by quantifying Beijing's production-, supply-, and consumption-based electricity-related carbon emissions. Compared to them, this study has a broader perspective, incorporating more industries into the analytical framework.

Industries with lower direct emissions can often take several times their own reduction responsibility, reducing the burden on energy-intensive industries. The increase in the emissions reduction responsibility of "scrap, equipment repair and other manufacturing" (S22) and "other services" (S29) is particularly prominent under the comprehensive principle. Combining Table 2 and Figure 1, the emissions reduction responsibility of S22 will increase from 0.18 % under the equity principle to 3.50 % under the comprehensive principle, which is related to the backward emissions level of this industry. Compared with the advanced level in China, the ratio of S22 is 17.22, which is the highest among all industries in Shanxi Province, indicating that the energy efficiency level of the industry is relatively backward and should be assigned a higher emissions reduction responsibility to stimulate it to improve energy conservation and emissions reduction. The emissions reduction responsibility of S29 increased from 3.65% under the equity principle to 8.73% under the comprehensive principle, which is mainly related to its strong capability for low-carbon development. The added value of S29 is CNY 544.085 billion, which is the highest among all industries. Furthermore, the carbon diffusion coefficient and carbon-inducing coefficient of the industry are both low at 0.30 and 0.13, respectively. This indicates that this industry has less influence in terms of driving other industries to produce carbon emissions, and the overall development of the national economy has a small induced effect on this industry. It is appropriate to take it as an important pillar to support the development of the low-carbon economy.

3.2. Differences and Links of Each Industry's Emissions Reduction Responsibility from Different Perspectives

In order to further analyze the effect of industrial linkages, the emissions reduction responsibility allocation scheme based on the comprehensive principle under the industrial linkages perspective is compared with the industry perspective, as shown in Figure 2. It can be seen that there is a significant difference in the emissions reduction responsibilities required by each industry under the two principles.

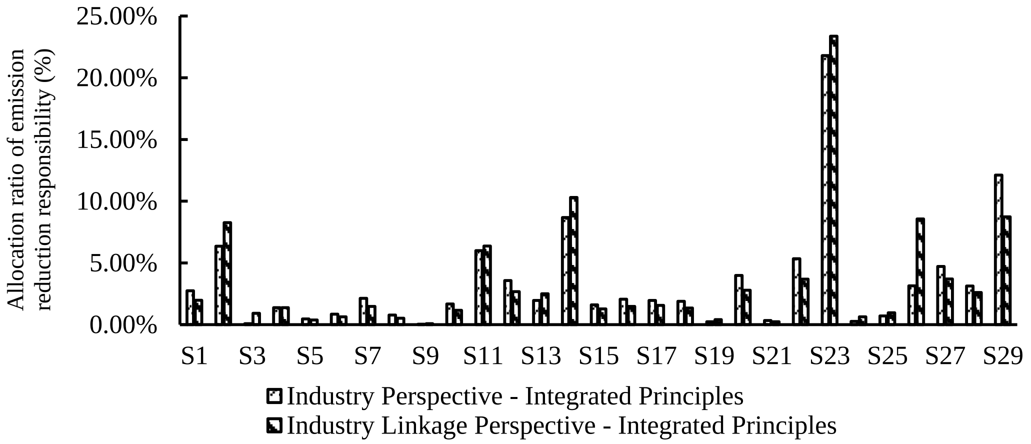

Figure 2. Comparison of the allocation of carbon emissions reduction responsibilities based on equity principle under two perspectives. Note: See Table 2 for each industry code in the table.

First, among the industries with higher emissions reduction responsibilities from the perspective of industrial linkages, "coal mining and washing" and "construction" are more prominent. Combining Table 2, it can be found that both S2 and S26 are characterized by high embodied carbon emissions. This indicates that these industries drive upstream industries to consume fossil energy to meet their production, thus leading to high CO_2 emissions. Therefore, the emissions reduction responsibilities of the above two industries will increase, meaning they need to take more responsibility for emissions reduction. This result supports the view of Hung et al. [42] that the construction industry requires significant intermediate inputs from the upstream sector and that they generate high CO_2 emissions, with the inclusion of quantitative data from Shanxi Province.

Second, industries with a lower emissions reduction responsibility under the industrial linkages perspective mainly include "communication equipment, computer and other electronic equipment manufacturing" (S20), "scrap, equipment repair and other manufacturing" (S22), "wholesale, retail and accommodation and catering" (S27), and "other services industries" (S29), with decreases of 1.20%, 1.66%, 1.02%, and 3.39%, respectively. According to Table 2, the common feature of the above industries is a small carbon diffusion coefficient and carbon-inducing coefficient. The interesting cases are S20 and S22. Compared with the national advanced level, the carbon emissions intensity of these two industries is 12.14 and 17.22, respectively. This indicates that the low-carbon production capacity of the two industries is relatively backward, and the emissions reduction potential is relatively greater. Therefore, they take more responsibility from the industry perspective. However, the carbon impact coefficients of these two industries are only 0.53 and 0.66, meaning they are in the middle and lower levels among all industries. In other words, the development of these two industries has a weak degree of influence on the CO_2 emissions of other industries, and it is difficult to promote overall carbon emissions reduction by pressurizing them. At the same time, the carbon inductance coefficients of these two industries are only 0.02, meaning they are also in the middle and lower levels among all industries. This indicates that the development of these two industries has a weak impact on other industries. This study compensates for the shortcomings of Zhou and Jin [43] who only considered direct emissions and carbon intensity; we provide a more comprehensive perspective on the allocation of responsibility for emissions reduction.

4. Policy Recommendations

A comprehensive carbon responsibility accounting system should be constructed. Our research results show that the traditional high-energy-consuming industry's emissions reduction responsibility will decline after considering indirect emissions responsibility. The existing accounting system, which only considers direct carbon emissions responsibility, is not reasonable. For example, the accounting method adopted in China's "Guidelines for the Preparation of Provincial Greenhouse Gas Inventories" is a modified producer responsibility method. In addition to direct CO_2 emissions generated from the fossil energy consumed by each industry, this method only accounts for the indirect CO_2 emissions generated from the electricity and heat consumed. Therefore, in order to enhance the fairness of the emissions reduction responsibility, this paper suggests that both producer responsibility and consumer responsibility should be considered together, and the indirect emissions generated from upstream industries driven by each industry's final demand still need to be further accounted for.

The number of industries covered by carbon emissions trading should be increased. Our research results show that among industries with smaller direct carbon emissions, some industries have greater indirect carbon emissions responsibilities, and other industries with a smaller carbon diffusion coefficient and carbon-inducing coefficient have a relatively backward low-carbon production capacity and bear more emissions reduction responsibilities. The involvement of industries with greater responsibility and more efficiency in the carbon emissions trading market could relieve pressure on energy-intensive industries. However, China's current carbon emissions trading market contains only eight industries, including the petrochemical industry, iron and steel industry, power industry, etc. Therefore, this paper suggests that while focusing on energy-intensive industries, efforts should also be made to explore the potential of other industries to share the pressure of energy-intensive industries to reduce emissions. Additionally, we should strive to avoid shutdowns and production restrictions in energy-intensive industries due to excessive responsibility, as well as maintain the stability of industrial structure.

5. Conclusions

This study constructs a carbon emissions reduction responsibility allocation model and allocates responsibility by industry in Shanxi province based on the principle of equity and the comprehensive principle of "equity + efficiency", respectively. As a distinctive feature, this study emphasizes the incorporation of industry linkages between industries in terms of carbon emissions into the allocation model. By adopting the typical resource-based region of Shanxi province as the case study, this study provides theoretical support for balancing the emissions reduction pressure between traditional energy-intensive industries and achieving low-carbon development. The main results of this study are as follows.

(1) The responsibility of traditional energy-intensive industries to reduce emissions may have been overestimated. After considering indirect CO_2 emissions, traditional energy-intensive industries, such as "electricity, heat production and supply industry" and "metal smelting and rolling processing industry", usually have significantly lower embodied carbon emissions than direct emissions. From the perspective of equity principles, the responsibility of these industries should be mitigated. From the perspective of the

efficiency principle, the excessive concentration on the responsibility of energy-extensive industries also tends to waste the emissions reduction efficiency and undermine the overall reduction effect due to the influence of industrial linkages between industries in terms of carbon emissions.

(2) Industries with lower direct emissions may need to take more responsibility for reducing emissions. Some industries with lower direct emissions, such as "coal mining and washing" and "construction", are driving significant carbon emissions from upstream industries to meet their own demands. From the perspective of the equity principle, these industries should take more responsibility. From the perspective of the efficiency principle, industries such as 'scrap, equipment repair and other manufacturing' and 'other services' have a greater energy saving potential or can support the low-carbon economy. Therefore, these industries need to take more responsibility.

As for the limitations of this study and future research directions, there is still much related work to be conducted. First, the input–output relationship between industries will change with economic development. The input–output data between industries are also the basis for calculating the three indicators of embodied carbon emissions, the carbon diffusion coefficient, and the carbon-inducing coefficient in this study. However, limited by the frequency of data publication, the latest data available for this study are for 2017. Therefore, the scope of the study can be extended in the future to validate and enhance the scientific validity of this study's methodology by incorporating new input–output data published by provinces. Second, the availability of data limits the extent of this study. Limited by the precision of the data, only 29 industry segments were analyzed in this study. However, a further assessment of the impact of industry linkages between industries can be conducted once the related data are available, such as allocation at a finer level.

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