Effectively allocating emission control targets is critical for China to achieve its emission reduction goals. This study researched the efficiency of total carbon dioxide (CO₂) emission control target allocations during the 13th Five-Year Plan period (2015–2020). The efficiency of carbon intensity reduction targets, allocated by the National Development and Reform Commission in 30 regions, was assessed using a Directional Distance Function (DDF) model. Then, a Zero-Sum Gains (ZSG)-DDF model was constructed to determine how to optimally allocate total CO₂ emission, under the premise of maximizing economic benefits and minimizing CO₂ emissions. The results showed that in the case of fixed total CO₂ emissions, to improve the resource allocation efficiency, the quota should be increased in the regions with high efficiencies, and the quota should be reduced in the regions with low efficiencies. The results in this paper can help guide the future allocations of total CO₂ emission in China.

1. Introduction

Climate change has attracted increasing attention worldwide, as both an environmental and economic problem. The United Nations Framework Convention on Climate Change (UNFCCC) has stated that a long-term goal is keeping the gas concentrations of the atmosphere greenhouse at a fixed level; this requires individual countries to control the emissions of greenhouse gas. In China’s Work Plan for Controlling Greenhouse Gas Emission during the 13th Five-Year Plan Period (2015–2020), the National Development and Reform Commission set a target to reduce CO₂ emission per unit of gross domestic product by 18 percent from 2015 levels by 2020.

There are three ways to identify and allocate more specific CO₂ emission reduction goals. (1) The carbon intensity (that is, the CO₂ emission per unit of GDP) reduction target can converted into a total CO₂ emission reduction target using the scenario analysis method. The total CO₂ emission target can then be decomposed for each region. Finally, each region can break down its carbon targets across industries. (2) After converting the carbon intensity reduction target into the total CO₂ emission reduction target, the target can be directly allocated to different industries. (3) Carbon intensity reduction targets can be allocated directly to provinces, municipalities, and autonomous regions across the country or can be allocated directly to different industries [1]. The National Development and Reform Commission selected the third option, directly distributing the national target for reducing carbon intensity to provinces, municipalities, and autonomous regions during the 13th Five-Year Plan period.

There was currently no specific, universally accepted, worldwide scheme for allocating the total amount of CO₂. Researchers around the world have put forward different allocation principles, with research mainly focusing on two core principles: equity and efficiency [2]. The equity principle means that subjects participating in the allocation of total CO₂ emission should have equal rights [3]. The most widely used indicators to assess this include the population,
the gross domestic product (GDP) level, and the level of historical emissions (that is, the grandfather method) [4, 5]. The efficiency principle means that the allocation should maximize the economic benefit while also allocating the total amount of CO2 emissions.

To capture the resource allocations and production efficiencies, researchers apply the Data Envelope Analysis (DEA) method to create multiple constraints and to establish a production possibility set including multiple input-output indicators. Some researchers have used the DEA derivative models to allocate the total amount of CO2 emissions [6–9]. The Zero-Sum Gains DEA (ZSG-DEA) can achieve the maximum allocation efficiency in the case of fixed total amount. This method is widely used to allocate total CO2 emissions.

During production, the target product is desirable output, and CO2 is often treated as a pollutant, known as an undesirable output. Producers generally want to simultaneously maximize the desirable output and minimize the undesirable output. However, the ZSG-DEA model cannot currently solve this problem on its own. As such, the contribution of this paper was to combine a DDF (Directional Distance Function) with a ZSG-DEA model to construct a ZSG-DDF model. The model was used to examine approaches for optimally allocating total CO2 emissions, under the premise of maximizing economic benefits and minimizing CO2 emissions. This involved establishing different improvement directions of desirable output and undesirable output [10–12].

The rest of this paper is organized as follows. Section 2 introduces the input-output indicators and data sources and describes the construction of the ZSG-DDF model. Section 3 provides the empirical results and analysis. First, the DDF model was used to examine the regional allocation efficiency of China’s current CO2 emission control targets. Then, the ZSG-DDF model was applied to adjust the initial allocation results to optimize the allocation efficiency. Section 4 summarizes the conclusions.

2. Data Sources and Research Method

2.1. Indicator Selection and Data Sources. This study examined 30 provinces, municipalities, and autonomous regions in China. Tibet, Hong Kong, Macao, and Taiwan were not included because part or all of the data were not available. Input-output data for 2015 were used as a baseline to calculate the relevant data for 2020. During production, capital, labor, and energy are usually used for input, producing economic benefit and CO2 emissions. Therefore, the input-output indicators set consisted of capital stocks, labor, energy consumption, regional GDP, and CO2 emissions.

Data on capital, the labor force, and regional GDP were obtained from the China Statistical Yearbook; data on the amount of different energy were obtained from the China Energy Statistical Yearbook. The amount of CO2 was measured using the relevant data and method from Guidelines for Provincial Greenhouse Gas Inventories, published by the National Development and Reform Commission of China. The specific indicators and growth rate were calculated as follows.

1. Capital Stocks. This indicator was denoted by the total capital formation data. In this study, the annual development speed of capital during the “13th Five-Year Plan” period was measured as the average development speed of total capital formation during the “12th Five-Year Plan” period.

2. Labor. This indicator was measured as the number of employed persons per urban unit. In this study, the annual development speed of labor during the “13th Five-Year Plan” period was measured as the average growth rate of the number of employed persons during the “12th Five-Year Plan” period.

3. Energy Consumption. The amount of different energy consumption was converted into the amount of standard coal consumption, respectively. The values were then added according to the standard coal coefficient of energy conversion. Four kinds of fossil energy with high carbon levels were selected to represent the regional energy consumption: raw coal, coke, petroleum energy, and natural gas. The amount of energy consumption in 2020 was measured using the unit GDP energy consumption reduction target during the “13th Five-Year Plan” period. Where data were not available for specific regions, the national reduction target was used.

4. Regional GDP. The economic development levels differed across different regions in China, and the caliber of regional accounting differed from the caliber of national GDP accounting. Further, the Chinese economy has recently slowed. Therefore, the lower limits in the GDP growth target during the 13th Five-Year Plan period were selected to compute the regional GDP in 2020.

5. CO2 Emissions. The reduction target of CO2 emissions intensity in each region was established during the 13th Five-Year Plan period. As such, the target growth rate of CO2 emissions at the end of 13th Five-Year Plan was computed by the growth rate of regional GDP.

2.2. Methods. For this study, 30 regions in China were selected as Decision-Making Units (DMUs), represented by \( i = 1, 2, \ldots, 30 \). The input indicators included capital \((x^1)\), labor \((x^2)\), and energy \((x^3)\). The output indicators included regional GDP (i.e., desirable output \( y \)) and CO2 emissions (i.e., undesirable output \( b \)). The meaning of DDF value is as follows. At the current output level, the maximum possible proportion of desirable output increases and undesirable output decreases. The direction vector of undesirable output is generally negative. Therefore, the direction vector was defined as \( g = (y, -b) \); that is, the output vector of the evaluated DMU was set as the direction vector. When the direction vector took the output value of the evaluated DMU, the efficiency value of the evaluated DMU was \( \theta = 1/(1 + \beta) \). In this study, the output-oriented ZSG-DEA...
model was selected, and the proportional reduction strategy was used to reallocate the total CO₂ emissions. When the efficiency of DMU \( k \) was lower, the amounts of CO₂ emissions for DMU \( k \) need to reduce, and the amounts of CO₂ emissions for other DMUs could increase because of a fixed total amount. Then, the increased amounts of CO₂ emissions for DMU \( j \) \( (j \neq k) \) were calculated as

\[
b_{jk} = \frac{b_j}{\sum_{\mu \neq k} b_j} \times b_k \left( 1 - \frac{1}{1 + \beta} \right).
\]  

Therefore, the ZSG-DDF model was expressed as

\[
\bar{D}_0(x, y, b; g_y, g_b) = \text{Max} \beta,
\]

\[
\text{s.t. } \sum_{i=1}^{n} \lambda_i x_i \leq x_k, \quad \sum_{i=1}^{n} \lambda_i y_i \geq y_k + \beta g_y, \quad \sum_{i=1}^{n} \lambda_i y_i \geq y_k + \beta g_y,
\]

\[
\beta \geq 0, \lambda_i \geq 0, \quad \sum_{i=1}^{n} \lambda_i \leq 1.
\]  

3. Empirical Results and Analysis

3.1. Statistical Description of Input-Output Data of 30 Regions in China in 2015. The calculations of energy consumption and CO₂ emissions in 2020 depend on the associated data in 2015 (i.e., the end of 12th Five-Year Plan). As such, the specific data for 2015 are listed in Table 1. In a DDF model, the DMU will have a higher efficiency when the inputs yield more desired output and less undesired output. Comparing with other regions, Shandong Province had the largest amount of capital input, showing there were more capital-intensive industries. Qinghai Province had invested the lowest labor and energy; however, it also had the lowest accompanying outputs. This led to a production efficiency that was lower. Guangdong Province had invested the most labor and the amount of GDP was highest, indicating that it had more labor-intensive industries. Shanxi Province consumed abundant energy and produced the highest amount of CO₂ emissions, showing that Shanxi Province had more opportunities to conserve energy conservation and reduce CO₂ emission.

3.2. Initial Allocation Efficiency of Chinese Total CO₂ Emission in 2020. Previous studies have mostly used DEA-derived models to research the direct allocation of total carbon emission among regions or industries. Few studies, however, have examined the allocation efficiency of carbon intensity emission reduction targets among regions allocated by the National Development and Reform Commission. Using the given carbon intensity reduction targets for different region in the Work Plan for Controlling Greenhouse Gas Emission (2015–2020), the specific values of CO₂ emission were calculated. Based on the specific data for 2015 and the accompanying growth rate, the DDF model was applied to obtain the initial allocation efficiency of total CO₂ emissions in 30 regions of China (specific results could be seen in Table 2).

The efficiency value of 9 regions was 1, that is, these regions were situated at the production frontier (the production frontier is the boundary in the optimal state, and the efficiency is highest when the combination of input and output is on the production frontier); the efficiency values of 4 regions were 0.9–1, which meant that the 4 regions nearly reached the production frontier, and 6 regions could not reach the production frontier, with efficiency values of less than 0.7. This indicated that the allocation plan based on China’s total carbon emission control of the National Development and Reform Commission (2015–2020) had not yet optimally allocated resources.

Among the 13 regions with higher efficiency values, most were located in the east and central regions [13] and had relatively developed economies, abundant levels of capital investment, and high energy utilization efficiencies [8] (Inner Mongolia also had a high efficiency but is located in a different geographic area). In contrast, the regions with low efficiency were mostly western regions with relatively underdeveloped economic levels and production capacities [14–17]. The technological innovation level should be improved to improve the levels of energy utilization efficiency and to reduce CO₂ emissions.

3.3. Adjustment Results of Total CO₂ Emission Allocation Based on the ZSG-DDF Model. Total CO₂ emissions are fixed at a country level. Allocating the carbon intensity levels across regions based on established reduction targets may result in unreasonable resource allocations in many regions, highlighting the need to further improve allocation efficiencies. To obtain the optimal allocation of resources at the end of the 13th Five-Year Plan period and to optimize the relative efficiency of each region in the total CO₂ emission allocation scheme, this study used the ZSG-DDF model to reallocate the total CO₂ emissions in 2020.

After three iterations, the CO₂ emission quotas were adjusted: the amount of CO₂ emissions for the regions with lower efficiency values was reduced. The amount of CO₂ emissions was increased for the regions on the production frontier because of their higher input-output efficiency. This was consistent with the idea of zero-sum benefits based on a fixed total amount of CO₂ emissions, whereby efficient regions receive increasingly higher quotas and inefficient regions receive increasingly lower quotas. The average efficiency value of all regions increased to 0.91, improving the efficiency of resource allocations across all regions.

Table 3 shows that after the first iteration, the mean value of input-output efficiency increased from 0.85 to 0.87. There were still only 9 regions with an allocation efficiency of 1;
however, the number of regions nearly reaching the production frontier increased from 4 to 7. After the second iteration, the mean value of input-output efficiency increased to 0.89; the number of regions with efficiency values above 0.9 remained unchanged. After the third iteration, the mean value of input-output efficiency increased to 0.91; the number of regions with an efficiency value of 1 remained unchanged, and the number of regions nearly reaching the production frontier increased to 8. The efficiency values for other regions improved significantly; however, the efficiency values for Shanxi, Ningxia, Gansu, and Xinjiang remained low.

To improve the input-output efficiency of the 30 regions, 9 regions with high allocation efficiency should be allocated a

### Table 1: The descriptive analysis of input-output data of 2015.

<table>
<thead>
<tr>
<th></th>
<th>Mean value</th>
<th>Standard deviation</th>
<th>Maximum value</th>
<th>Minimum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital stock (100 million yuan)</td>
<td>13444.08</td>
<td>8106.99</td>
<td>35587.40</td>
<td>2317.10</td>
</tr>
<tr>
<td>Labor (10^4 persons)</td>
<td>600.97</td>
<td>419.29</td>
<td>1948</td>
<td>62.7</td>
</tr>
<tr>
<td>Energy consumption (10^4 tons of standard coal equivalent)</td>
<td>18012.36</td>
<td>13600.96</td>
<td>60987.46</td>
<td>2367.15</td>
</tr>
<tr>
<td>GDP (100 million yuan)</td>
<td>24162.10</td>
<td>17737.61</td>
<td>72812.60</td>
<td>2417.10</td>
</tr>
<tr>
<td>CO₂ emission (10^4 tons)</td>
<td>44909.45</td>
<td>35261.21</td>
<td>161297.8</td>
<td>5501.25</td>
</tr>
</tbody>
</table>

### Table 2: The efficiency of CO₂ emission allocations.

<table>
<thead>
<tr>
<th>Carbon intensity reduction targets for the 13th Five-Year Plan period (%)</th>
<th>The initial values of allocation</th>
<th>Iterative adjustment efficiency</th>
<th>The degree of decline in carbon intensity</th>
<th>Allocation efficiency by historical emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing 20.5</td>
<td>0.00</td>
<td>1.00</td>
<td>-11.5%</td>
<td>1.00</td>
</tr>
<tr>
<td>Tianjin 20.5</td>
<td>0.05</td>
<td>0.95</td>
<td>-1.2%</td>
<td>0.94</td>
</tr>
<tr>
<td>Hebei 20.5</td>
<td>0.14</td>
<td>0.88</td>
<td>23.0%</td>
<td>0.88</td>
</tr>
<tr>
<td>Shanxi 18.0</td>
<td>0.65</td>
<td>0.60</td>
<td>71.8%</td>
<td>0.60</td>
</tr>
<tr>
<td>Inner Mongolia 17.0</td>
<td>0.00</td>
<td>1.00</td>
<td>-16.4%</td>
<td>1.00</td>
</tr>
<tr>
<td>Liaoning 18.0</td>
<td>0.00</td>
<td>1.00</td>
<td>-15.0%</td>
<td>1.00</td>
</tr>
<tr>
<td>Jilin 18.0</td>
<td>0.10</td>
<td>0.91</td>
<td>10.4%</td>
<td>0.91</td>
</tr>
<tr>
<td>Heilongjiang 17.0</td>
<td>0.33</td>
<td>0.75</td>
<td>41.5%</td>
<td>0.75</td>
</tr>
<tr>
<td>Shanghai 20.5</td>
<td>0.00</td>
<td>1.00</td>
<td>-11.5%</td>
<td>1.00</td>
</tr>
<tr>
<td>Jiangsu 20.5</td>
<td>0.00</td>
<td>1.00</td>
<td>-11.5%</td>
<td>1.00</td>
</tr>
<tr>
<td>Zhejiang 20.5</td>
<td>0.00</td>
<td>1.00</td>
<td>-11.5%</td>
<td>1.00</td>
</tr>
<tr>
<td>Anhui 18.0</td>
<td>0.20</td>
<td>0.84</td>
<td>26.4%</td>
<td>0.84</td>
</tr>
<tr>
<td>Fujian 19.5</td>
<td>0.07</td>
<td>0.93</td>
<td>2.5%</td>
<td>0.93</td>
</tr>
<tr>
<td>Jiangxi 19.5</td>
<td>0.25</td>
<td>0.80</td>
<td>31.1%</td>
<td>0.81</td>
</tr>
<tr>
<td>Shandong 20.5</td>
<td>0.00</td>
<td>1.00</td>
<td>-11.5%</td>
<td>1.00</td>
</tr>
<tr>
<td>Henan 19.5</td>
<td>0.27</td>
<td>0.79</td>
<td>34.3%</td>
<td>0.80</td>
</tr>
<tr>
<td>Hubei 19.5</td>
<td>0.03</td>
<td>0.97</td>
<td>-6.4%</td>
<td>0.98</td>
</tr>
<tr>
<td>Hunan 18.0</td>
<td>0.00</td>
<td>1.00</td>
<td>-15.0%</td>
<td>1.00</td>
</tr>
<tr>
<td>Guangdong 20.5</td>
<td>0.00</td>
<td>1.00</td>
<td>-11.5%</td>
<td>1.00</td>
</tr>
<tr>
<td>Guangxi 17.0</td>
<td>0.15</td>
<td>0.87</td>
<td>11.8%</td>
<td>0.87</td>
</tr>
<tr>
<td>Hainan 12.0</td>
<td>0.38</td>
<td>0.73</td>
<td>36.3%</td>
<td>0.73</td>
</tr>
<tr>
<td>Chongqing 19.5</td>
<td>0.14</td>
<td>0.88</td>
<td>13.2%</td>
<td>0.91</td>
</tr>
<tr>
<td>Sichuan 19.5</td>
<td>0.13</td>
<td>0.88</td>
<td>12.9%</td>
<td>0.88</td>
</tr>
<tr>
<td>Guizhou 18.0</td>
<td>0.53</td>
<td>0.65</td>
<td>54.2%</td>
<td>0.66</td>
</tr>
<tr>
<td>Yunnan 18.0</td>
<td>0.31</td>
<td>0.76</td>
<td>34.3%</td>
<td>0.77</td>
</tr>
<tr>
<td>Shaanxi 18.0</td>
<td>0.47</td>
<td>0.68</td>
<td>54.8%</td>
<td>0.68</td>
</tr>
<tr>
<td>Gansu 17.0</td>
<td>0.60</td>
<td>0.63</td>
<td>59.2%</td>
<td>0.63</td>
</tr>
<tr>
<td>Qinghai 17.0</td>
<td>0.40</td>
<td>0.71</td>
<td>38.3%</td>
<td>0.72</td>
</tr>
<tr>
<td>Ningxia 12.0</td>
<td>0.47</td>
<td>0.68</td>
<td>56.7%</td>
<td>0.68</td>
</tr>
<tr>
<td>Xinjiang 12.0</td>
<td>0.71</td>
<td>0.58</td>
<td>64.4%</td>
<td>0.59</td>
</tr>
</tbody>
</table>

### Table 3: The iterative change process of the ZSG-DDF model.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>The mean value of input-output efficiency</td>
<td>0.87</td>
<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>Number of regions reaching the production frontier</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Number of regions nearly reaching the production frontier</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Number of regions far from the production frontier</td>
<td>9</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>
higher CO₂ emission quota, while the CO₂ emission quota should be reduced in regions with low efficiency (such as Shanxi, Guizhou, Shaanxi, Gansu, Ningxia, and Xinjiang). These changes could lead to a significant increase in the ability to reach a higher carbon intensity reduction target. The regions with high efficiency levels were mostly those with high levels of economic development. These regions placed relatively high importance on the environment and were able to effectively control environmental pollution. Therefore, higher input-output efficiency should be associated with a higher CO₂ emission quota allocation.

From the regional 13th Five-Year Plan, the average GDP growth rate of Shanxi Province was the lowest, and the reduction targets of energy consumption intensity and CO₂ emission intensity were not high. However, Shanxi Province consumed largest energy and produced highest amount of CO₂ emissions in 2015. This indicates that there were significant opportunities for conserving energy conservation and reducing CO₂ emission. Guizhou, Shaanxi, Gansu, Ningxia, and Xinjiang had a low proportion of GDP compared to the country overall; they also have underdeveloped economies, heavy industrial structures, high energy consumption levels, and relatively poor environmental governance. To improve the input-output efficiency, there should be a reduction in these regions’ CO₂ emission quotas.

Each region’s proportion of historical CO₂ emissions, as a percentage of the entire country’s emissions, was used to recalculate new allocations of CO₂ emission quotas for each region in 2020. The allocated efficiencies were essentially consistent with the efficiencies allocated in light of the carbon intensity reduction targets in the 13th Five-Year Plan. This is because the original allocation of China’s CO₂ emission intensity reduction target primarily considered the CO₂ emissions of different region in the past; it was those levels that determined the required region-specific emission reductions.

During the 13th Five-Year Plan period, the CO₂ emission allocation plan of the National Development and Reform Commission, which was under the total emissions control, did not give higher quotas to efficient regions but rather gave them to inefficient regions [18–20]. In other words, the economically developed regions had higher resource allocation efficiency, and the CO₂ emission reduction targets were correspondingly higher. However, the CO₂ emissions in a region have a close relationship to its speed of economic growth. China’s economic growth in CO₂ emissions cannot be completely decoupled in short time. The allocation of CO₂ emissions should therefore consider a region’s economic development level. A more developed economy should be associated with a greater demand for CO₂ emissions.

4. Conclusion

Allocating CO₂ emissions plays an important role in developing carbon trading markets and in the ability of countries to realize national CO₂ emission reduction targets. This paper makes the following main contributions to the field. First, the efficiencies of carbon intensity reduction targets allocated by the National Development and Reform Commission in 30 regions were assessed using a DDF model. Second, a ZSG-DDF model was constructed to study approaches for optimizing the allocation efficiency of total CO₂ emissions, under the premise of maximizing economic benefits and minimizing CO₂ emissions.

The results showed the following. (1) The initial allocation efficiency of China’s total CO₂ emissions in 2020 was not optimal. In the case of fixed total CO₂ emissions, to improve the allocations, regions with a high efficiency level should receive higher quotas, and regions with a low efficiency level should receive lower quotas. (2) The CO₂ emission intensity reduction targets of the National Work Plan for Controlling Greenhouse Gas Emission in the 13th Five-Year Plan primarily used CO₂ emissions in the past for each region as the reference basis. Some regions were assigned CO₂ emission quotas that were inconsistent with their resource allocation efficiency, resulting in lower efficiency levels. Economically developed regions had a higher level of resource allocation efficiency and higher carbon intensity reduction targets. The allocation scheme prioritized equity with respect to historical emissions and regional equity. That scheme did not give priority to the optimal efficiency of regional resource allocation or the maximum emission reduction effect achieved with the minimum level of input.

This study highlighted implications for future regional allocations of CO₂ emissions. (1) The principle of prioritizing efficiency should be considered when allocating CO₂ emissions among different regions in the future planning. On the premise of sustaining economic growth, the principle could encourage regions with significant levels of energy consumption and environmental pollution to change the mode of economic growth, strengthen energy conservation and emission reductions, and adjust the industrial structure. It would also encourage regions to prioritize the development of the green economy and to promote an ecological civilization, further improving the production efficiency. (2) In the long run, the allocation plan developed to allocate national total CO₂ emission control targets among different regions needs to be executable, considering both regional equity and allocation efficiency. It is particularly important to determine which indicators best represent regional equity. This is needed to guarantee the smooth achievement of the national CO₂ emission reduction targets; encourage the smooth operation of the CO₂ emission trading market; and achieve the carbon peak and carbon neutrality at an early date.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Acknowledgments

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References


