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Embodied Carbon Emissions in Shanghai's Power Industry Based on Input-Output Analysis

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Abstract: To improve the authenticity and reliability of emissions accounting for embodied carbon and promote the sustainable development of the PI in the future, this article has taken Shanghai as the object and combined input-output models to conduct in-depth research on its embodied carbon emissions in the PI. This article first analyzed the current development status of the PI in Shanghai, and explored it from the perspectives of energy supply and carbon emissions. Then an embodied carbon emission accounting model was constructed based on the non-competitive input-output table. Finally, through factor analysis, the changes in the emissions of embodied carbon were analyzed. This article conducted experiments from two perspectives: emission accounting and scenario prediction, so that the effectiveness of the input-output model in the emission analysis of embodied carbon in the PI in Shanghai can be verified. The results show that from the proportion of hidden carbon emissions in the power industry to the total hidden carbon emissions in the social industry, the highest proportion of hidden carbon emissions in the power industry can reach 43.69%. The conclusion indicated that the input-output model could achieve objective and accurate accounting of embodied carbon emissions in the PI, which could help to promote green development of the PI.

1. Introduction

With the intensification of global environmental issues such as air pollution, the role and impact of embodied carbon emissions in sustainable development are becoming increasingly prominent [1-2]. The power industry (PI is used instead of expression in the following text) in Shanghai occupies a special position in the city's carbon emissions, with a wide supply chain. Embodied carbon emissions from the industry have a large impact on overall emissions. Traditional analysis methods lack comprehensiveness and accuracy, making it difficult to comprehensively consider the emissions of embodied carbon at all stages of the entire lifecycle of power production and supply. In the development of macroeconomic analysis, input-output analysis methods have achieved considerable achievements in various professional fields such as industrial structure analysis and economic policy evaluation [3]. It has strong comprehensiveness and systematicity, and can comprehensively consider the interrelationships between various parts of the industry system on the basis of providing multi-level data information. Applying it to the analysis of embodied carbon emissions in the PI, comprehensively analyzing all aspects of power production and supply, can provide more accurate carbon emission management strategies, and has important practical value for promoting sustainable energy and low-carbon development.

Quantifying and evaluating carbon emissions at each stage of the power production process is an important way to understand the contribution of power production to carbon emissions [4-5]. Wang Haikun applied the Monte Carlo method and the Kuznets function to simulate the peak per capita emissions, and studied the carbon emissions of 50 cities in China during 2000-2016. His results showed that despite the different carbon emission trajectories of individual cities, there was a strong relationship between per capita emissions and real Gross Domestic Product (GDP) per capita in individual cities [6]. Yang Fuyuan applied the logarithmic mean Divisia index (LMDI) method to identify the properties of factors affecting carbon emission changes. His results suggested that economic activity had been the leading factor in driving the growth of carbon emissions from electricity [7]. Alajmi Reema Ghazi used a structural time series model and LMDI to estimate long-run elasticity. His results suggested that GDP, power generation, and population variables had a significant impact on carbon emissions [8]. Kwakwa Paul Adjei conducted a regression analysis using autoregressive distributed lags and fully corrected ordinary least squares estimation based on the World Bank's 2020 time series data. His results presented that the power crisis had a positive impact on carbon emissions [9]. Although existing analytical methods have certain quantitative capabilities for the carbon emissions and environmental impact of the PI, the data analysis results obtained still cannot fully reflect the actual carbon emissions of the industry.

The development of input-output analysis methods has provided more possibilities for the comprehensive analysis of carbon emissions in the PI. Fan Fengyan analyzed the spatial characteristics of carbon emission intensity in the power sector by adopting the Moran index for 30 provinces in China, and compared the transfer of carbon emissions from electricity at the provincial level in China during 2010 and 2015 based on a multi-regional input-output table. His results demonstrated that between 2010 and 2015, carbon emissions from electricity increased in 20 provinces and carbon intensity decreased in 21 provinces [10]. De Chalendar Jacques A applied an economic input-output model to track the carbon emissions of the power grid. The analysis of multiple publicly available datasets has demonstrated the accuracy of input-output model analysis [11]. Ma Jia-Jun used a structural decomposition analysis method based on input-output subsystem model to explore the sources of incremental emissions in China's PI from 2007 to 2015 [12]. Input-output analysis can fully consider the differences in various components of the PI and the complexity of embodied carbon emissions, achieving objective and comprehensive analysis of carbon emissions, but most studies still have certain limitations in terms of analytical accuracy.

To improve the objectivity and accuracy of the analysis of embodied carbon emissions and provide effective basis for the sustainable development of the PI, this article combined input-output models to study the emissions of embodied carbon in the PI in Shanghai. Using the electricity energy data in Shanghai from 2002 to 2011 as the sample object, embodied carbon emission accounting and scenario prediction were conducted. In terms of emissions accounting for embodied carbon, compared to 2002, its emissions in 2011 only increased by 1.7648 million tons. Although its trend of change was not significant, the emissions were at a relatively high level, and the highest proportion of the total emissions in the social industry could reach 43.69%. From the contribution ratio calculation results, it can be found that the energy production results had a large impact on the emissions of embodied carbon in the Shanghai's PI in 2002, 2007, and 2011. In terms of scenario prediction, compared to the low-speed adjustment in Scenario 3, the emissions of embodied carbon were lower under the high-speed adjustment of energy production structure, electricity consumption intensity, and energy consumption rate. In the analysis of embodied carbon emissions, input-output models can provide more objective and reliable support for the sustainable development of the PI, and effectively promote the high-quality development of emission reduction work in the PI.

2. Embodied Carbon Emissions in Shanghai's Power Industry

2.1 Development of Shanghai's Power Industry

Embodied carbon emissions refer to the direct or indirect emissions of carbon dioxide generated during the production stage of manufacturing a specific product or providing a certain service [13]. The survey results of the *China Energy Report (2008): CO_2 Emissions Research* show that from the 1970s to the early 21st century, carbon dioxide emissions from the power, industrial, and transportation industries dominated the total global industry emissions, accounting for about 70% of the total emissions [14-15].

At present, with the continuous deepening of urban construction in Shanghai, the scale of industrial development is expanding. Its electric PI is developing rapidly, and the demand for energy and electricity is also rising. The cumulative installed capacity is showing an increasing trend year by year, with thermal power generating units accounting for about 85% of the installed power capacity [16]. On the one hand, from the medium and long-term perspective of the PI, there is significant pressure on energy supply and demand in Shanghai. As the carbon peaking and carbon neutrality goals (dual carbon goals) are put forward, the development of energy in Shanghai Petrochemical is restricted, which further increases the pressure on the medium and long-term electricity demand and supply in Shanghai [17]. In terms of achieving the dual carbon goals, provinces and cities in the central and eastern regions are facing enormous pressure, and the electricity load of other provinces and cities around Shanghai far exceeds that of Shanghai. Relying solely on the coordinated allocation and transmission of electricity in east China to support Shanghai and achieve the dual carbon goals is very difficult [18-19]. On the other hand, the technological system for carbon emissions has not yet been fully established. Further improvement is needed in the upstream and downstream of the industrial chain in Shanghai's PI, support for the industrial chain and surrounding services, and integrated development of the industrial chain and innovation chain.

2.2 Construction of Input-Output Model

The input-output analysis method is an economic model that evaluates the interdependence among various departments in the economic system [20]. According to the input-output table, Equations (1) and (2) can be constructed:

$$\begin{cases} x_{11} + x_{12} + \cdots + x_{1n} + Y_1 = X_1 \\ x_{21} + x_{22} + \cdots + x_{2n} + Y_2 = X_2 \\ \cdots \\ x_{n1} + x_{n2} + \cdots + x_{nn} + Y_n = X_n \end{cases} \tag{1}$$

$$\begin{cases} x_{11} + x_{12} + \cdots + x_{n1} + FV\sigma_1 = F_1 \\ x_{12} + x_{22} + \cdots + x_{n2} + FV\sigma_2 = F_2 \\ \cdots \\ x_{1n} + x_{2n} + \cdots + x_{nn} + FV\sigma_n = F_n \end{cases} \tag{2}$$

Assuming $\sigma_{ij} = x_{ij}/x_j$ and $\sigma_{ij} \geq 0$, Equation (1) can be expressed as:

$$\sigma X + Y = X \tag{3}$$

σ_{ij} represents the direct consumption coefficient, which is the required input from various departments when the product output of the PI reaches a certain level. In the input-output table, the change in energy consumption is intuitively reflected in the change of the value of σ_{ij}. Based on this condition, the impact of changes in energy consumption on the production of the electricity industry in the region when the demand for electricity reaches a certain level can be calculated. Vector Y represents the vector of terminal demand, which is the final demand vector, while vector X represents the output of the entire sector in the PI.

The embodied carbon emission matrix of Shanghai's PI can be constructed on the basis of the input-output table to realize the embodied carbon emission accounting. In the specific calculation process, the overall equivalence relationship between input and output is first established, which is expressed as "intermediate use"+"final demand"="total output". Its expression is as Equation (4):

$$\sum_{j=1}^{m+n} X_j + Y_i = X_i, i = 1,2,\cdots m+n \tag{4}$$

The relationship between the complete consumption coefficient τ and the direct consumption matrix can be expressed as Equation (5):

$$\tau = (I-\sigma)^{-1} - I \tag{5}$$

In Equation (5), I represents the identity matrix; $(I-\sigma)^{-1}$ represents the direct and indirect investment required by department i when department j manufactures a product or service. On this basis, the equation is combined with carbon emission intensity to construct an embodied carbon emission input-output model for the PI, which is represented as:

$$C_i = \varphi(I-\sigma^*)^{-1}Y^* \tag{6}$$

In Equation (6), the sum of the row vectors of C_i represents the direct and indirect carbon emissions generated by the PI in the production or service process. The sum of its column vectors represents the embodied carbon emissions generated by the industry during the production process due to the consumption of electricity products or services. The diagonal element of φ is φ_i, which represents the direct carbon emission intensity of various sectors in the PI. Y^* uses cumulative vectors to measure the embodied carbon emissions from the perspective of the power industry production chain, while in the model, it measures the various dimensional vectors of terminal demand after excluding imports.

After excluding internal and external factors, the calculation equation for the non-competitive direct consumption coefficient matrix σ^* is expressed as:

$$\sigma^* = (\mathrm{I}-\mu)\times\sigma \tag{7}$$

Among them, the calculation method for element μ_{ij} in matrix μ is:

$$\mu_{ij} = \frac{I\mu_i}{O_t + I\mu_i - E_v}, i = 1,2,\cdots,n \tag{8}$$

From this, the non-competitive complete consumption coefficient matrix can be obtained by σ^*:

$$\tau^* = (I-\sigma^*)^{-1} - I \tag{9}$$

On the basis of embodied carbon emission accounting under input-output modeling, this article analyzes the impact of carbon emission coefficient, energy consumption rate, energy production structure, electricity consumption intensity, industrial structure, per capita household electricity consumption, per capita GDP, and population on the emissions of embodied carbon in the PI. To reduce computational complexity and improve the feasibility of model accounting, this article takes coal, oil, and natural gas as initial energy inputs (i=1, 2, 3), and agriculture, industry, and urban residential electricity as power consumption sectors (j=1, 2, 3). In the PI of Shanghai, the variation in emissions of embodied carbon can be expressed by Equation (10):

$$\Delta E_c = c^n - c^0 = \Delta c_t + \Delta s_t + \Delta r_t + \Delta I_t + \Delta \alpha_t + \Delta p + \Delta GDP + \Delta p_n \quad (10)$$

Among them, the definition of variables in Equation (10) is shown in Table 1:

Table 1: Definition of variables in Equation (10)

Sequence	Variables	Meaning
1	c^n	Carbon emissions of the power industry in the n-th year
2	c^0	Carbon emissions of the power industry in the base year
3	Δc_t	Emission coefficient contribution value
4	Δs_t	Contribution value of energy consumption rate
5	Δr_t	Contribution value of energy production structure
6	ΔI_t	Contribution value of electricity consumption intensity
7	$\Delta \alpha_t$	Contribution value of industrial structure
8	Δp	Contribution value of per capita electricity consumption to daily life
9	ΔGDP	Contribution value of per capita GDP
10	Δp_n	Contribution value of population

According to the variables in Table 1, when the contribution of the influencing factor is greater than 0, it indicates that this factor has a positive driving effect on the changes in embodied carbon emissions in the PI, representing an increase in total embodied carbon emissions. When the contribution degree of the influencing factor is below 0, it indicates that this factor has a negative driving effect on the changes in embodied carbon emissions in the PI, indicating that it has an inhibitory effect on the growth of total embodied carbon emissions.

3. Accounting and Scenario Prediction of Embodied Carbon Emissions in Shanghai's Power Industry

To analyze the effectiveness of input-output based research on embodied carbon emissions in the Shanghai's PI, this article takes Shanghai's electricity energy data as the sample object and conducts embodied carbon emission accounting and scenario prediction.

3.1 Data Sources

This article uses the *Shanghai Statistical Yearbook* and the *China Energy Statistical Yearbook* as the main sources to conduct statistical analysis on the electricity consumption data of the main consumer sectors in Shanghai's PI from 2002 to 2011, as shown in Table 2. The input-output table is sourced from the National Bureau of Statistics. Based on input-output theoretical analysis, this article mainly focuses on carbon dioxide emissions, and calculates the carbon emission level of Shanghai based on the calculation standards of the *IPCC National Greenhouse Gas Inventory Guidelines (2006)*, as shown in Table 3.

It can be obtained from Table 2 that the trend of electricity consumption in the agricultural consumption sector in Shanghai's PI from 2002 to 2011 was quite complex. Its electricity consumption continued to decline from 2003 to 2008, and showed a significant growth trend since 2008. Except for a downward trend from 2008 to 2009, the overall electricity consumption of industry showed an upward trend. The data on urban residential electricity consumption shows a steady year-on-year increase. Overall, the electricity consumption of the main consumer sectors in Shanghai's PI remained at a high level of demand during this period.

Table 2: Electricity consumption by main consumer sectors in the power industry in Shanghai from 2002 to 2011

Years	Electricity consumption (billion kilowatt hours)	Agriculture (billion kilowatt hours)	Industry (billion kilowatt hours)	Urban residential electricity consumption (billion kilowatt hours)
2002	645.71	6.46	447.46	61.85
2003	745.97	6.75	507.00	82.87
2004	821.44	6.48	555.08	90.64
2005	921.97	5.76	617.59	109.20
2006	990.15	5.34	656.10	122.37
2007	1072.38	5.27	705.90	131.12
2008	1138.22	5.08	727.13	146.55
2009	1153.38	5.39	701.58	152.52
2010	1295.87	6.07	786.61	168.95
2011	1139.62	6.37	805.76	175.22

Table 3: Carbon emission levels in Shanghai from 2002 to 2011

Sequence	Years	Carbon emissions (10000 tons)
1	2002	19616.43
2	2003	21181.18
3	2004	22897.37
4	2005	24998.01
5	2006	26640.29
6	2007	28942.20
7	2008	30094.62
8	2009	30562.39
9	2010	32418.94
10	2011	33194.51

It can be got from Table 3 that the carbon emissions level in Shanghai showed an increasing trend year by year from 2002 to 2011, with carbon emissions reaching 196.1643 million tons in 2002 and increasing to 331.9451 million tons in 2011.

3.2 Emission Accounting for Embodied Carbon

Based on the electricity consumption data of the main consumer sectors in the PI in Shanghai from 2002 to 2011, initial energy input data, and carbon emissions levels in Shanghai from 2002 to 2011, this article combines the input-output model to calculate the emissions of embodied carbon in the PI in Shanghai and its proportion in the total emissions of embodied carbon in the social industry. The results are shown in Figure 1.

In Figure 1, the overall trend of emissions of embodied carbon in the PI in Shanghai from 2002 to 2011 was not significant. Its emission value in 2002 was 31.2567 million tons, and its emission value in 2011 was 33.0215 million tons. Compared to 2002, its emission in 2011 only increased by 1.7648 million tons. Over a longer time span, the increase in emissions was relatively small, but the emissions were at a relatively high level. From the proportion of embodied carbon emissions in the PI to the total embodied carbon emissions in the social industry, the highest proportion of embodied carbon emissions in the PI could reach 43.69%.

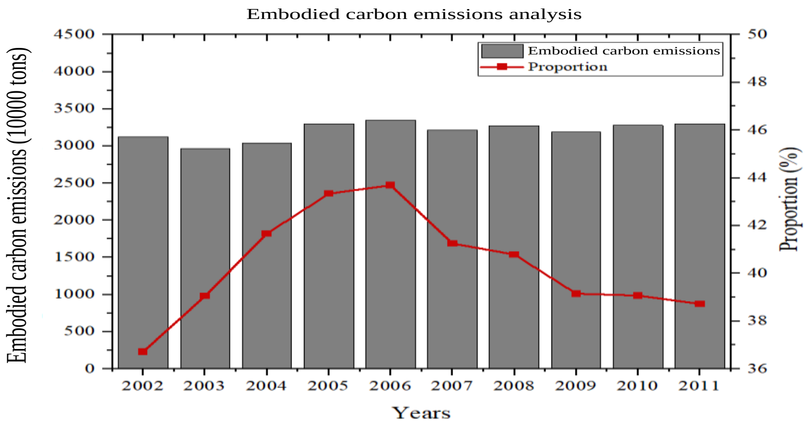

Figure 1: Accounting results of embodied carbon emissions

To conduct an in-depth analysis of the changes in emissions of embodied carbon in Shanghai from 2002 to 2011, this article analyzed the sources of embodied carbon emissions in the PI in Shanghai based on the variables in Table 1. According to Equation (15), the contribution ratios of each influencing factor to the changes in embodied carbon emissions in 2002, 2007, and 2011 were calculated. Figure 2 presents the results:

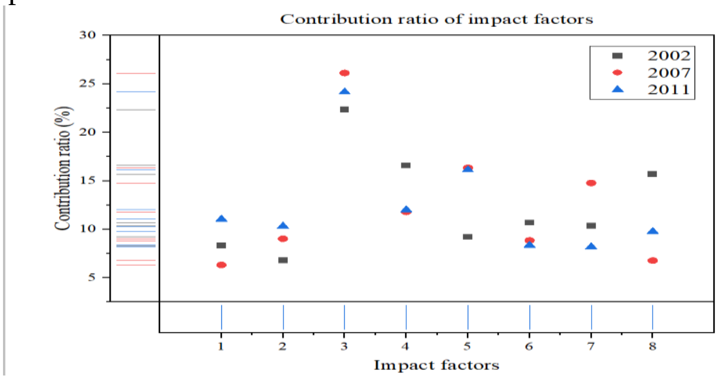

Figure 2: Calculation results of contribution ratio

From the contribution ratio calculation results in Figure 2. In 2002, the factors that contributed the most to emissions were energy production structure, electricity consumption intensity, and population. In 2007, the factors that contributed the most to emissions were energy production structure, industrial structure, and per capita GDP. In 2011, the factors that contributed the most to emissions were energy production structure, energy consumption rate, and electricity consumption intensity.

3.3 Scenario Prediction

According to the contribution ratio of embodied carbon emissions and influencing factors, this article selects representative energy production structure, electricity consumption intensity, population, industrial structure, per capita GDP, and energy consumption rate as key indicators. Due to the fact that population growth is a relatively slow and difficult to directly control factor in actual development and that industrial structure and per capita GDP represent the level and structural characteristics of economic development, this article takes these three types of factors as predetermined values in scenario assumptions and designs and analyzes scenarios based on changes in energy production structure, electricity consumption intensity, and energy consumption rate. The three types of scenarios designed are shown in Table 4.

Table 4: Scenario design

Scenario sequence	Energy production structure	Electricity consumption intensity	Energy consumption rate
Scenario 1	High-speed adjustment	High-speed adjustment	High-speed adjustment
Scenario 2	Medium-speed adjustment	Medium-speed adjustment	Medium-speed adjustment
Scenario 3	Low-speed adjustment	Low-speed adjustment	Low-speed adjustment

Based on the scenario design in Table 4, scenario predictions are made for the emissions of embodied carbon in the PI in Shanghai from 2012 to 2021. The final results are shown in Figure 3.

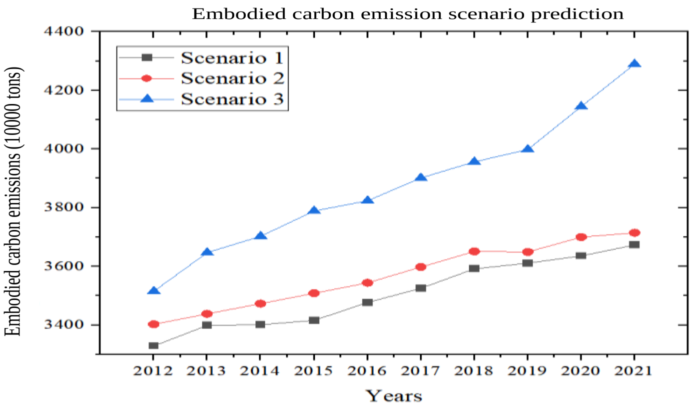

Figure 3: Results of scenario prediction

In Figure 3, it can be found that the predicted emissions of embodied carbon in Shanghai's PI under Scenario 1 in 2012 were 33.2907 million tons; the emission prediction result under Scenario 2 is 34.0276 million tons; the predicted emission under Scenario 3 is 35.1539 million tons. The predicted emissions of embodied carbon in Shanghai's PI under Scenario 1 in 2021 were 36.7296 million tons; the emission prediction result under Scenario 2 was 37.1445 million tons; the predicted emission under Scenario 3 was 42.8969 million tons. Given predetermined population, industrial structure, and per capita GDP, based on the embodied carbon emissions in Scenario 2, the changes in embodied carbon emissions under changes in energy production structure, electricity consumption intensity, and energy consumption rate are analyzed by comparing the predicted results of Scenario 1 and Scenario 3 with those of Scenario 2. It can be seen that compared to the low-speed adjustment in Scenario 3, the emissions of embodied carbon are lower under the high-speed adjustment of energy production structure, electricity consumption intensity, and energy consumption rate.

4. Discussion

To verify the effectiveness of the input-output model based study on the emissions of embodied carbon in the Shanghai's PI, this article conducted experimental analysis from two aspects: accounting for embodied carbon emissions and scenario prediction. From the experimental analysis results of embodied carbon emissions, it can be obtained that the trend of changes in embodied carbon emissions in Shanghai’s PI from 2002 to 2011 was not significant, but its overall emissions remained within a relatively high range. From the results of the contribution ratio of influencing factors, it can be seen that the emissions of embodied carbon are mainly affected by energy production structure, electricity consumption intensity, population, industrial structure, per capita GDP, and energy consumption rate. From the analysis of scenario prediction experiments, it can be seen that in scenario prediction analysis, when the energy production structure, electricity intensity, and energy consumption rate are rapidly adjusted, the results of embodied carbon emissions in the PI are more ideal.

5. Conclusion

As the demand for energy continues to rise, the embodied carbon emissions of the PI are becoming increasingly significant in terms of environmental protection and scientific development. Traditional models lack objectivity and accuracy in accounting work, making it difficult to provide reliable basis for the analysis of embodied carbon emissions. To promote the smooth progress of emission reduction work and the sustainable development of the PI, this article took Shanghai’s PI as the research object and uses input-output models to conduct in-depth research on its embodied carbon emissions from 2002 to 2011. Not only has it achieved objective accounting of embodied carbon emissions, but it has also analyzed the key influencing factors of embodied carbon emissions in the PI. Through scenario analysis, the emissions of embodied carbon in the Shanghai’s PI from 2012 to 2021 under different scenarios were predicted. Based on this, effective suggestions have been provided for its future development in a targeted manner. This article is based on the input-output model to study the emissions of embodied carbon in the Shanghai’s PI. Although it can promote the realization of emission reduction targets to a certain extent, there are still some aspects that require improvement in the research process. In future research, in-depth analysis should be considered from the selection of sample data and regional differences to promote the healthy and sustainable development of the PI.

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