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Decoupling Analysis of China's Product Sector Output and Its Embodied Carbon Emissions—An Empirical Study Based on Non-Competitive I-O and Tapio Decoupling Model

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Abstract: This paper uses the non-competitive I-O model and the Tapio decoupling model to comprehensively analyze the decoupling relationship between the output of the product sector in China and its embodied carbon emissions under trade openness. For this purpose, the Chinese input and output data in 2002, 2005, 2007, 2010, and 2012 are used. This approach is beneficial to identify the direct mechanism for the increased carbon emission in China from a micro perspective and provides a new perspective for the subsequent study about low-carbon economy. The obtained empirical results are as follows: (1) From overall perspective, the decoupling elasticity between the output of the product sector and its embodied carbon emissions decreased. Output and embodied carbon emissions showed a growth link from 2002 to 2005 and a weak decoupling relationship for the rest of the study period. (2) Among the 28 industries in the product sector, the increased growth rate of output in more and more product sectors was no longer accompanied by large CO_2 emissions. The number of industries with strong decoupling relationships between output and embodied carbon emissions increased. (3) From the perspective of three industries, the output and embodied carbon emissions in the second and third industries exhibited a growth link only from 2002 to 2005; the three industries presented weak or strong decoupling for the rest of the study period. Through empirical analysis, this paper mainly through the construction of ecological and environmental protection of low carbon agriculture, low carbon cycle industrial system, as well as intensive and efficient service industry to reduce the carbon emissions of China's product sector.

Keywords: trade openness; product sector; embodied carbon emission; non-competitive I-O model; Tapio decoupling model

1. Introduction

The development of world economy and the rapid expansion of population, and as the population of many countries tends to be older, increasing consumption throughout the life cycle (Lugauerand Jensen and Sadler 2014; Zagheni 2011) [1,2], have expanded the demand for energy resources. Such demand triggers a series of serious environmental problems, such as climate warming. There is considerable scientific evidence that CO_2 is the most important anthropogenic greenhouse gas (IPCC 2007) [3]; this phenomenon arouses serious concerns all over the world. The problem of carbon emissions has become the focus of the world since the issue of Kyoto Protocol in 1997 (Huang et al., 2008) [4]. Since then, many countries have conducted relevant research actively on climate change and involved in climate change and mitigation actions, taken decarburization as their ultimate objective in social-economic development (Żuk 2016) [5]. In 2016, 175 countries signed the agreement on the first day of the opening of the Paris Agreement, highlighting the global consensus on climate governance. The international community has reached a broad consensus that sustained carbon reduction is the primary measure for addressing climate change (Haminand Gurran 2009) [6]. At the beginning of the reform and opening, China vigorously developed its economy and drove for industrialization but ignored the environmental problems; this phenomenon led to excessive energy consumption and the increase in carbon emissions. According to statistics, the carbon emissions in the United States always ranked first in the world from 1971 to 2006; however, the carbon emissions in China surpassed those of the United States and became the highest in the world in 2007 (IEA 2009) [7]. As the largest developing country, China also became the top energy consumer in the world in 2010 (Guan et al., 2012) [8]. According to the "Global Carbon Budget Report 2015" released by the Global Carbon Project, the annual emissions in China are larger than the sum of those in the United States and the European Union. This report shifts the global focus to China, thereby posing high pressure and leaving China at a disadvantage in negotiations. To adapt to climate change and its own development, and as soon as possible complete the commitment to reduce carbon intensity by 40–45% in 2020 based on the level of 2005 at the Copenhagen climate conference (Yang et al., 2017) [9], China urgently needs to develop low-carbon economy, establish low-power, low-emission, and low-pollution growth mode; and eliminate economic growth dependency on energy consumption. However, carbon emission differs from other pollutions in terms of its global externalities. Such characteristic must be considered in taking mitigation measures. The vigorous development of the international trade has led to the transfer of polluting industries to developing countries, which leads to the serious trade carbon leakage (Ederington, Levinson and Minier 2004) [10]; therefore, trade openness has undeniably significantly impacted the global carbon emissions. The product sector is the major source of carbon emission. Therefore, the relationship between the output of the Chinese product sector and its embodied carbon emissions must be analyzed to realize economic structure transformation and provide guidance for coordinating environmental development.

2. Literature Review

At present, several econometric models and research methods have been applied to the field of economics of climate change, such as the LMDI decomposition method (Ang and Choi 1997; Wang et al., 2005; Liu et al., 2007) [11–13], VAR analysis (Xu and Lin 2015; Xu and Lin 2016) [14,15], DEA analysis (Zhou et al., 2013; Goto M et al., 2014) [16,17], STIRPAT Model analysis (Fan et al., 2006; Wang et al., 2013; Kang et al., 2016) [18–20], and the decoupling elasticity coefficient (Laha and Luthy 2014) [21]. All of these models and methods have their own merits in analyzing different issues. Many countries choose to develop low-carbon economy because of the increasingly growing carbon emissions. The so-called low-carbon economy is a way of decoupling economic growth from carbon emissions. Thus, the decoupling elastic analysis method has attracted much attention from scholars.

"Decoupling" was first used in physics, and it means eliminating the corresponding relationship between two or more physical quantities by a certain method. Given that the meaning of decoupling has been extended, its application has also expanded. The concept has been applied in the environmental field in evaluating the relationship between environmental stress and economic growth (Yin et al., 2014; Wang and Yang 2015; Zhang et al., 2015) [22–24]. The most commonly used definition of decoupling in this field is the interpretation of the OECD (2002) that decoupling refers to breaking the link between economic growth and its impact on resources and environment or changing the speed of resource consumption and pollution to contradict with the speed of economic growth [25]. To date, the output of the product sector shows over-reliance on energy resources, thereby resulting in energy shortage and serious environmental damage. Therefore, decoupling analysis has attracted considerable attention as an important method for determining the relationship between economic development and environmental impact.

Juknys (2003) defined the decoupling between economic growth and natural resources as primary decoupling, and the decoupling between natural resources and environmental pollution as secondary decoupling. He also analyzed the decoupling relationship between environmental resources and economic growth in Lithuania [26]. Using the decoupling method, the decoupling or non-decoupling property of the two elements can be identified; however, the degree of decoupling between them and the type they belong to cannot be determined. To correct this shortcoming, Tapio extended this method and proposed the Tapio decoupling model, which significantly improves objectivity and accuracy. Tapio (2005) used his model in analyzing the relationship among economic developments, transportation volume, and greenhouse gas emission in Europe from 1970 to 2001. The results showed three types of decoupling relationship: connection, decoupling, and negative decoupling [27]. Gray et al. (2006) used the Tapio decoupling model to analyze the decoupling relationship among economic growth, transportation volume, and carbon emissions in Scotland [28]. Lu et al. (2007) compared the decoupling relationship among economic growth, carbon emission, and energy consumption in Germany, Japan, Korea, Taiwan, and other countries and regions from 1990 to 2002 [29]. Freitas and Kaneko (2011) explored the decoupling relationship between economic development and CO_2 emissions in Brazil, and they found that carbon intensity and energy structure are the most critical factors leading to CO_2 emissions [30]. Sorrell et al. (2012) studied the decoupling relationship between energy consumption in British highway freight transportation and economic growth from 1989 to 2004 [31]. Andreoni and Galmarini (2012) investigated the decoupling relationship among economic growth, energy consumption, and CO_2 emissions in Italy from 1998 to 2002 [32]. Fiorito (2013) analyzed the decoupling relationship between economic growth and resource consumption in 133 countries from 1960 to 2010 [33]. Yu et al. (2013) explored the decoupling relationship between the economic growth and environmental pressure in China from 1978 to 2010 [34]. Wang et al. (2013) examined the decoupling relationship between economic growth and CO_2 emissions in Jiangsu Province, China from 1995 to 2009. The results reflected that these components showed no decoupling property from 2003 to 2005, strong decoupling from 1996 to 1997 and 2000 to 2001, and weak decoupling for the rest of the years [35]. Chen and Zhu (2014) used the decoupling methods of OECD and Tapio to analysis the relationship between Shanghai industrial economic growth and carbon emissions [36]. Lu et al. (2015) showed the industry of Jiangsu was in a weak decoupling state from 2005 to 2012 [37]. Zhang et al. (2015) combined the decoupling method with LMDI decomposition methods to analyze the decoupling relationship between economic growth and energy consumption in China from 1991 to 2012, and the factors contributing to carbon emissions. The results showed four types of decoupling relationship, namely, weak decoupling, growth link, growth negative decoupling, and strong decoupling [38]. The possibility and feasibility of economic decoupling are still debated and need further research (Kallis 2011; Nicholas 2014) [39,40]. The decoupling method is undoubtedly the most effective tool for evaluating sustainable development currently and provides useful information for policy makers.

In summary, numerous scholars have conducted in-depth research on different regions using the decoupling method and have made many achievements. However, the method can still be extended and improved inthe following aspects: (1) The decoupling relationship between economic growth and carbon emissions has been analyzed from the regional (macro level) and spatial (meso level) perspectives only. Such approach ignores the micro level. Given that each industry in the product sector interacts with one another, the sector influences the economic activity and impacts the carbon emission. The I-O method can quantitatively analyze the correlation among production, distribution, and delivery in each industry in the product sector. Therefore, this study combines the I-O method with the decoupling method and analyzes the decoupling relationship between the output of the product sector and its carbon emissions from a micro perspective; this approach is beneficial in identifying the direct mechanism for the increased carbon emission in China. The proposed approach provides a new perspective for the subsequent study on low-carbon economy and operational measures for reducing carbon emission in the future. (2) When analyzing the decoupling relationship between economic growth and carbon emissions, carbon emission is usually measured using the IPCC emission coefficient method. However, the method results in low accuracy of estimation owing to the significant differences in production, life, and technology. Its calculation method is also problematic. The changes of the emission system result in poor processing capacity. IPCC only calculates the direct energy consumption but ignores the indirect part, thereby causing an underestimation of carbon emission. Consequently, the trends between economic growth and carbon emissions over time cannot be analyzed. The I-O model can be used to decompose and analyze the background of the embodied carbon emissions and improve the accuracy and scientificity of decoupling analysis between economic growth and carbon emission. (3) When calculating the embodied carbon emissions, the data from the product sector and the international trade are calculated separately, calculating the combined data is rare. Foreign trade is one of the "three carriages" that stimulate national economic growth, and it plays an important role in the increase in output. Considering that large amount of carbon emissions from the output is attributed to the rapid growth of foreign trade, trade and carbon emissions are closely related. The development of Chinese economy has facilitated the increase in production of the product sector in the middle part of the input products. However, this part of emission does not occur in China, if added into China's total carbon emission, the real figure absolutely will rise, thereby resulting in biased decoupling analysis. The present study utilizes the Chinese I-O data in 2002, 2005, 2007, 2010, and 2012 and calculates the embodied carbon emissions in each industry in the product sector using the non-competitive I-O model. Based on these figures, the Tapio decoupling model is used to analyze the decoupling relationship and the degree of the decoupling relationship between the output of the Chinese product sector and its embodied carbon emissions. Finally, the trend of decoupling is discussed from the overall perspective, product sector perspective, and three-industries perspective. The findings provide support for improving production efficiency in the product sector and developing a low-carbon development policy. The rest of this paper is organized as follows. Section 3 details the application of I-O model in embodied carbon emission measurement and the method of measuring the elastic modulus of decoupling. Section 4 describes the data sources and processing. Section 5 discusses the decoupling relationship between China's product sector output and its embodied carbon emissions from 2002 to 2012. Section 6 provides conclusions and policy recommendations.

3. Research Method and Model Construction

3.1. Application of I-O Model in the Estimation of Embodied Carbon Emissions

3.1.1. Model Construction of Competitive Embodied Carbon Emissions

When using the I-O model in the environmental field, the carbon emissions from the product sector can be expressed as

$$C_i = \sum_{k=1}^{n} C_{ik} = \sum_{k=1}^{n} (\theta_{ik} \times \phi_k) \quad (i, k = 1, 2, \cdots, n) \tag{1}$$

where C_i is the amount of CO_2 produced by the direct consumption of energy by the i_{th} product industry, C_{ik} is the amount of CO_2 produced by the k_{th} energy source for the i_{th} product industry, $\sum_{k=1}^{n} C_{ik}$ is the total amount of CO_2 emissions for i_{th} the product sector to consume $k = n$ species of energy, θ_{ik} is the consumption of the k_{th} energy in the i_{th} product industry, $\sum_{k=1}^{n} \theta_{ik}$ is the consumption of $k = n$ species of energy in the i_{th} product industry, and ϕ_k is the CO_2 emission coefficient of the k_{th} energy source.

The direct emission coefficient of CO_2 is E_i $(i = 1, 2, \cdots, n)$, which refers to the i_{th} sector of per unit output of direct emissions of CO_2. The equation is expressed as

$$E_i = C_i / X_i = \sum_{k=1}^{n} C_{ik} \Big/ X_i = \sum_{k=1}^{n} (\theta_{ik} \times \phi_k) \Big/ X_i \tag{2}$$

If the row vector E is used to represent the direct emission coefficient of CO_2 matrix, then the equation for the embodied carbon C of a country to satisfy the final demand Y is

$$C = EX = E(I - A)^{-1}Y \tag{3}$$

The form of Equation (3) can be transferred as

$$C/Y = E(I - A)^{-1} \tag{4}$$

F_i $(i = 1, 2, \cdots, n)$ presents the embodied carbon emission coefficient of CO_2 in each industry in the product sector, which refers to the i sector of per unit output of the complete carbon emissions, including direct carbon emissions and indirect carbon emissions; the record row vector F is the matrix of the embodied carbon emission coefficient, and $F = C/Y$. Therefore, the embodied carbon emission coefficient matrix of each product sector is

$$F = E(I - A)^{-1} \tag{5}$$

3.1.2. Construction of Non-Competitive Embodied Carbon Emission Model

According to the foregoing description, the competitive I-O model can be represented by $X = (I - A)^{-1}Y$. In this formula, X is the total output of the product sector; I is the unit matrix; A is the direct consumption coefficient matrix; $(I - A)^{-1}$ is the Leontief inverse matrix; and Y is the amount of end-use value. The competitive I-O model cannot be directly used to distinguish between the intermediate inputs of domestic production and foreign imports under an open economic system. Therefore, a non-competitive I-O model must be constructed. The direct consumption coefficient matrix is expressed as $A = A^d + A^m$, where A^d is still the direct consumption coefficient matrix in the competitive I-O table; A^m is the direct consumption coefficient matrix of imported product sector; and the corresponding element a_{ij}^m represents the value of the goods or services imported by the i_{th} product industry. This value is directly consumed by the total output of the unit in the j th product or product industry in the production and operation process. A^m is substracted from the imported intermediate inputs of the method and $A^m = M \times A$ to ensure the accuracy of measurement. In the formula, M is the import coefficient matrix, which is used to observe and measure the degree of dependence of the product sector on imported products. The product sector i adopts the same import intermediate input proportion in the inputs for all other product sectors j. Therefore, $M = \begin{bmatrix} m_{11} & 0 & \cdots & 0 \\ 0 & m_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_{nn} \end{bmatrix}$ is a diagonal matrix, and the diagonal matrix element $m_{ij} = IM_i/(X_i + IM_i - EX_i)$ $(i, j = 1, 2, \cdots, n$; and $i \neq j$, $m_{ij} = 0)$. In this equation, X_i is the output of the i_{th} product sector; IM_i is the import volume of the i_{th} product sector; and EX_i is the export volume of the i_{th} product sector. Therefore, the domestic direct consumption coefficient matrix is $A^d = (I - M)A$. At this point, the embodied carbon emission coefficient for each product sector is

$$F = E(I - A^d)^{-1} \tag{6}$$

3.2. Method for Calculating the Elastic Coefficient of Decoupling

3.2.1. OECD Decoupling Index Model

OECD (2002) constructed the decoupling index and decoupling factor [25]. The basic equation is expressed as

$$S = 1 - D = 1 - \frac{EP_{t_i}/DP_{t_i}}{EP_{t_0}/DP_{t_0}} \quad (7)$$

where S is the decoupling factor; D is the decoupling index; EP is the index value of the environmental pressure, which can be expressed by energy consumption or waste discharge; DP is the index value of the driving force, which is represented by GDP or output in most cases; t_0 is the base year; and t_i is the final year. The value of the decoupling factor S is in the range of $[-\infty, 1]$. When S is higher than 0, a decoupling relationship exists between resource consumption and economic growth. Large value of S means strong decoupling relationship between them; that is, absolute decoupling ($S > 0$, and close to 1) or relative decoupling ($S > 0$, and close to 0). If the value of S is lesser than or equal to 0, a certain degree of coupling exists between resource consumption and economic growth, that is, no decoupling exists ($S \leq 0$).

3.2.2. Tapio Decoupling Elastic Model

Many elasticities, such as ecological elasticity (Richard York et al., 2003) [41], price elasticity (Vander Voet et al., 2005) [42] and income elasticity (Steinberger et al., 2010) [43], are used to empirically analyze the relationship between environmental load and other driving forces. Given that the "decoupling index" of OECD presents several shortcomings, Tapio (2005) proposed the concept of "decoupling elasticity" for measuring the decoupling relationship between the freight volume growth and economic growth [27]. The equation is expressed as

$$H = \frac{\%\Delta VOL}{\%\Delta GDP} \quad (8)$$

where H is the decoupling elasticity coefficient, $\%\Delta VOL$ is a percent change of transport volume, $\%\Delta GDP$ is a percent change of GDP or output. According to the size of the decoupling elasticity, Tapio divided the decoupling relationship into three kinds: negative decoupling, decoupling, and connection relationship. On this basis, Tapio further subdivided the decoupling relationship into eight categories: weak negative decoupling, strong negative decoupling, growth negative decoupling, recession decoupling, strong decoupling, weak decoupling, recession connection, and growth link.

3.2.3. Decoupling Model of Product Sector Output and Its Embodied Carbon Emissions

Unlike the "decoupling index" of OECD, the "decoupling elasticity" model of Tapio comprehensively considers two types of indicators: total quantity change and relative quantity change; thus, this model further improves the objectivity, scientificity, and accuracy of decoupling relationship measurement and analysis (UNEP, 2011) [44]. On this basis, the present study uses the Tapio decoupling elasticity to analyze the decoupling relationship between the output of the product sector and its embodied carbon emission. The equation is

$$DI = \frac{(C_t - C_{t-1})/C_{t-1}}{(G_t - G_{t-1})/G_{t-1}} = \frac{\Delta C/C}{\Delta G/G} = \frac{\%\Delta C}{\%\Delta G} \quad (9)$$

where DI is the decoupling elasticity coefficient; $\%\Delta C$ is a percent change of CO_2 emissions from energy consumption; $\%\Delta G$ is a percent change of product sector output; t refers to the current period; C_t and G_t refer to the current CO_2 emissions and product sector output, respectively; $t - 1$ refers to the base period; C_{t-1} and G_{t-1} refers to the base period of CO_2 emissions and product sector output, respectively; ΔC represents the current CO_2 emission difference from the base period; and ΔG represents the output difference between the current and the base product industries. According to the positive and negative change rates of CO_2 emissions and product sector output and using the classification criteria of Tapio (2005), the decoupling relationship between product sector output and its embodied carbon emissions in the present study is divided into eight categories (Table 1).

Table 1. Grade Classification of Decoupling of Product Sector Output and Its Embodied Carbon Emissions.

Decoupling Relationship		Decoupling Index		Elastic Coefficient DI
First Level Index	**Second Level Index**	**%ΔCO_2**	**%ΔGDP**	
Negative Decoupling	Weak Negative Decoupling	<0	<0	0 < DI < 0.8
	Strong Negative Decoupling	>0	<0	DI < 0
	Growth Negative Decoupling	>0	>0	DI > 1.2
Decoupling	Recession Decoupling	<0	<0	DI > 1.2
	Strong Decoupling	<0	>0	DI < 0
	Weak Decoupling	>0	>0	0 < DI < 0.8
Connection	Recession Connection	<0	<0	0.8 < DI < 1.2
	Growth Link	>0	>0	0.8 < DI < 1.2

Notes: Data sources: The 27th reference.

4. Data Sources and Processing

4.1. Division and Adjustment of Product Department

To ensure detailed, unified, and reliable data, this study uses the national I-O questionnaire (value type) and the I-O extension table (value type) from 2002 (42 industries), 2005 (42 industries), 2007 (42 industries), 2010 (41 industries), and 2012 (42 industries). The energy consumption data for each industry in the product sector in 2002, 2005, 2007, 2010, and 2012 are also employed. (Five years is selected as research time to discuss the impact of trade on carbon emissions in the second years after China's accession to the WTO, and because China's input–output table and input–output extension table are released every five years, and the 2012 input–output table is the latest.) As a result, the data of import sector in 2002, 2005, 2007, 2010, and 2012 are obtained for estimating the trends of the embodied carbon emissions of the product sector of China over time under trade openness. These I-O tables and I-O extended tables are from the Department of National Economic Accounting, National Bureau of Statistics (2006, 2009, 2011, 2013, and 2015), and "China Statistical Yearbook" from the National Bureau of Statistics (2003, 2006, 2008, 2011, and 2014). "I-O Table" and "China Statistical Yearbook" are based on the National Economic Industry Classification Standard for classifying the energy consumption of the product sector. However, some discrepancies are observed among these data. To harmonize the caliber of different industries in the product sector and facilitate the processing of data, the product sector is divided into 28 industries, among them, number 1 is the sector in the first industry, numbers 2–25 are the sectors in the second industry, and numbers 26–28 are the sectors in the third industry (Table 2).

Table 2. Industrial classification and codes.

Codes	Product Industry Classification	Codes	Product Industry Classification
1	Agriculture	15	Metal Product Industry
2	Coal Mining and Washing Industry	16	General and Special Equipment Manufacturing Industry
3	Petroleum and Natural Gas Mining Industry	17	Transportation Equipment Manufacturing Industry
4	Metal Mining and Dressing Industry	18	Electrical, Machinery, and Equipment Manufacturing Industry
5	Non-metallic Minerals and Other Mining Industries	19	Communication Equipment, Computer, and Other Electronic Equipment Manufacturing Industry
6	Food Manufacturing and Tobacco Processing Industry	20	Instruments, Meters, Cultural, and Office Machinery Manufacturing Industry
7	Textile Industry	21	Other Manufacturing Industries
8	Garment Down Leather Clothing and Other Manufacturing	22	Electricity, Heat Production, and Supply Industry
9	Timber Processing and Furniture Manufacturing	23	Fuel Gas Production and Supply Industry
10	Paper Printing and Cultural, Educational and Sports Goods Manufacturing Industry	24	Water Production and Supply Industry
11	Petroleum Processing, Coking, and Nuclear Fuel Processing Industry	25	Construction Industry
12	Chemical Industry	26	Transportation, Storage, and Postal Services
13	Non-metallic Mineral Products Industry	27	Wholesale, Retail, and Catering Industry
14	Metal Smelting and Rolling Processing Industry	28	Other Service Industry

4.2. CO_2 Emission Estimates from Energy Sources

According to the2006IPCC Guidelines for National GHG Inventories (chapter six of the second volume) for the UNFCCC and the Kyoto Protocol, CO_2 emissions can be calculated by summing CO_2 emissions estimation from the consumption of various fossil fuels. The CO_2 emission coefficient from fossil energy is

$$\phi_k = NCV_k \times CEF_k \times COF_k \times (\frac{44}{12}) \quad (k = 1, 2, 3, \cdots, 8) \tag{10}$$

where ϕ_k represents the coefficient of CO_2 emissions from k_{th} energy consumption; NCV_k represents the average low calorific value (referred to as net calorific value by IPCC); CEF_k represents carbon emission factors; COF_k represents carbon oxidation factor; 44 and 12 represent the molecular weights of CO_2 and C, respectively; k is one of the selected eight kinds of fossil fuel consumption. The data in the formula are mainly from the 2015 "China Energy Statistical Yearbook," 2006 IPCC Guidelines for National GHG Inventories, and collecting. The values of NCV are derived from various reference coefficients of energy conversion of standard coal in Appendix 4 of 2015 China Energy Statistical Yearbook. The values of CEF and COF are from the 2006 IPCC. The specific data and calculated results are shown in Table 3. By substituting Equation (10) into Equation (2), the specific direct carbon emission coefficient can be obtained. The equation is

$$E_i = \sum_{k=1}^{n} \left[\theta_{ik} \times NCV_k \times CEF_k \times COF_k \times (\frac{44}{12}) \right] \bigg/ X_i \ (i = 1, 2, \cdots, 28;\ k = 1, 2, 3, \cdots, 8) \tag{11}$$

Table 3. *NCV*, *CEF*, *COF*, and CO_2 Emission Coefficient of Various Energy Sources.

Correlation Coefficient	Coal	Coke	Crude	Petrol	Kerosene	Diesel Fuel	Fuel Oil	Natural Gas
NCV Value	0.020908 GJ/kg	0.028435 GJ/kg	0.041816 GJ/kg	0.043070 GJ/kg	0.043070 GJ/kg	0.042652 GJ/kg	0.041816 GJ/kg	0.038931 GJ/m^3
CEF Value	26.0 kg/GJ	29.2 kg/GJ	20.0 kg/GJ	19.0 kg/GJ	19.6 kg/GJ	20.2 kg/GJ	21.1 kg/GJ	15.3 kg/GJ
COF Value	1	1	1	1	1	1	1	1
CO_2 Emission Coefficient	1.993 kg/kg	3.045 kg/kg	3.070 kg/kg	3.001 kg/kg	3.095 kg/kg	3.159 kg/kg	3.235 kg/kg	2.184 kg/m^3

Notes: 1 GJ (Ji Jiao) = 1000 MJ (Megajoule) = 1,000,000,000 J (Joule); m^3 (Stere); kg (Kilogram).

5. Empirical Results and Discussion Analysis

According to the pretreatment of data, the corresponding calculation equation, and the corresponding estimation model and data, the decoupling relationship between the output of the product sector in China and its embodied carbon emissions can be obtained.

5.1. Overall Perspective

During the study period, the total output of the product sector in China showed a rapid growth. Among them, the growth rate of 73.17% from 2002 to 2005 was particularly large. In the rest of the study period, the growth rates of output from 2005 to 2007, from 2007 to 2010, and from 2010 to 2012 were 50.87%, 52.97%, and 27.86%, respectively. The rapid growth of output in the product sector and the large consumption of energy and resources accelerated the growth of embodied carbon emissions. Specifically, the carbon emissions increased by 182.90%, from 13.647 billion tonsin 2002 to 38.607 billion tons in 2012. However, the growth rate of embodied carbon emissions gradually decreased. In particular, the growth rates from 2002 to 2005, from 2005 to 2007, from 2007 to 2010, and from 2010 to 2012 were 65.92%, 29.99%, 21.91%, and 7.59%, respectively. Therefore, China's policies for energy saving and emission reduction are effective. Under the influence of the growths in output and embodied carbon emissions, the decoupling elasticity between output and embodied carbon emissions decreased (Table 4). Specifically, the decoupling elasticity from 2002 to 2005, from 2005 to 2007, 2007 to 2010 and from 2010 to 2012 were 0.90, 0.59, 0.41 and 0.27, respectively. The decoupling elasticity in the entire study period, from 2002 to 2012, was 0.45. The embodied carbon emissions in

China have been weakly decoupled with the output of the product sector besides 2002 to 2005, which have been in growth link, thereby indicating that the increase in output also results in an increased embodied carbon emissions. However, the growth rate of embodied carbon emissions was less than that of output. This finding indicates that the output growth of the product sector in China tends to be rationalized, which is conducive to low-carbon development.

Table 4. Decoupling Relationship Evaluation of the Total Output of the Product Sector in China and Its Embodied Carbon Emissions from 2002 to 2012.

Period	Decoupling Elasticity	Decoupling Relationship
2002–2005	0.90	Growth Link
2005–2007	0.59	Weak Decoupling
2007–2010	0.41	Weak Decoupling
2010–2012	0.27	Weak Decoupling
2002–2012	0.45	Weak Decoupling

Notes: Data sources: According to the correlation equation mentioned earlier and the data collation calculation.

5.2. Perspective from Each Industry in the Product Sector

With the development of China's economy, economic growth of product sectors is no longer accompanied by much CO_2 emission, and the sectors with strong decoupling relationships are increasing (Table 5).

The empirical results show that, from 2002 to 2005, 14 product sectors presented a growth link between the output of the product sector and its embodied carbon emissions. These product sectors are the coal mining and washing industry, metal mining and dressing industry, and non-metallic minerals and other mining industry. This finding shows that the total output of the 14 sectors increased while their embodied carbon emissions also increased. In other words, output and embodied carbon emissions presented a linear growth relationship in this period. All 14 growth-linked sectors belong to the industrial sector, except other service industry. In the present study, weak decoupling between the output of the product sector and its embodied carbon emissions from 2002 to 2005 was observed in 12 sectors. The growth rates of the embodied carbon emissions and total output of these sectors were higher than zero. However, the growth rate of embodied carbon emissions was much smaller than that of output. The decoupling elasticity between the two elements was between 0 and 0.8. Besides the growth link and weak decoupling relationship observed in 28 sectors from 2002 to 2005, there was strong decoupling relationship in the petroleum and natural gas mining industry and wholesale, retail, and catering industry with decoupling elasticity of −0.22 and −0.11, respectively. The rapid growth of the total output of the two sectors contributes to the continuous reduction in carbon emissions. The economic growth way of the two industries must therefore be promoted.

From 2005 to 2007, a growth link between output and embodied carbon emissions was observed in the petroleum and natural gas mining industry, garment leather down and other manufacturing industry, and construction industry. Compared with the previous period, the number of industries with growth link between output and embodied carbon emissions decreased from 2005 to 2007. In this period, 22 sectors presented weak decoupling between output and embodied carbon emissions. Compared with the previous period, the number of sectors with weak decoupling between output and embodied carbon emissions increased by 10 from 2005 to 2007.Except for the growth link and weak decoupling relationship was observed between the output of 28 sectors and their embodied carbon emissions from 2005 to 2007, there was strong decoupling relationship in the agriculture, Instruments, meters, cultural and office machinery manufacturing industry, and fuel gas production and supply industry. The decoupling elasticities of the three sectors were −0.08, −0.33, and −0.17, respectively.

Table 5. Decoupling Relationship Evaluation of the Product Sector Output of China and Its Embodied Carbon Emissions from 2002 to 2012.

Product Sector	2002–2005		2005–2007		2007–2010		2010–2012		2002–2012	
	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship
Agriculture	0.53	Weak Decoupling	−0.08	Strong Decoupling	0.34	Weak Decoupling	0.63	Weak Decoupling	0.28	Weak Decoupling
Coal Mining and Washing Industry	1.10	Growth Link	0.38	Weak Decoupling	0.36	Weak Decoupling	0.44	Weak Decoupling	0.46	Weak Decoupling
Petroleum and Natural Gas Mining Industry	−0.22	Strong Decoupling	0.88	Growth Link	0.11	Weak Decoupling	−3.58	Strong Decoupling	0.04	Weak Decoupling
Metal Mining and Dressing Industry	0.81	Growth Link	0.68	Weak Decoupling	0.58	Weak Decoupling	−1.82	Strong Decoupling	0.39	Weak Decoupling
Non-metallic Minerals and Other Mining Industry	1.02	Growth Link	0.44	Weak Decoupling	0.73	Weak Decoupling	−0.60	Strong Decoupling	0.39	Weak Decoupling
Food Manufacturing and Tobacco Processing Industry	0.58	Weak Decoupling	0.54	Weak Decoupling	0.48	Weak Decoupling	0.11	Weak Decoupling	0.31	Weak Decoupling
Textile Industry	0.82	Growth Link	0.68	Weak Decoupling	−0.19	Strong Decoupling	−0.25	Strong Decoupling	0.35	Weak Decoupling
Garment Leather Down and Other Manufacturing Industries	0.77	Weak Decoupling	0.81	Growth Link	0.24	Weak Decoupling	0.03	Weak Decoupling	0.43	Weak Decoupling
Timber Processing and Furniture Manufacturing	0.87	Growth Link	0.55	Weak Decoupling	0.68	Weak Decoupling	−0.27	Strong Decoupling	0.39	Weak Decoupling
Paper Printing and Cultural, Educational and Sporting Goods Manufacturing Industry	1.13	Weak Decoupling	0.38	Weak Decoupling	0.44	Weak Decoupling	0.50	Weak Decoupling	0.51	Weak Decoupling
Petroleum Processing, Coking, and Nuclear Fuel Processing Industry	0.60	Weak Decoupling	0.30	Weak Decoupling	0.48	Weak Decoupling	0.40	Weak Decoupling	0.30	Weak Decoupling
Chemical Industry	0.68	Weak Decoupling	0.55	Weak Decoupling	0.31	Weak Decoupling	0.54	Weak Decoupling	0.39	Weak Decoupling
Non-metallic Mineral Products Industry	0.70	Weak Decoupling	0.28	Weak Decoupling	0.52	Weak Decoupling	0.08	Weak Decoupling	0.36	Weak Decoupling
Metal Smelting and Rolling Processing Industry	0.88	Growth Link	0.36	Weak Decoupling	0.44	Weak Decoupling	0.50	Weak Decoupling	0.40	Weak Decoupling
Metal Product Industry	0.85	Growth Link	0.47	Weak Decoupling	0.57	Weak Decoupling	0.31	Weak Decoupling	0.44	Weak Decoupling
General and Special Equipment Manufacturing Industry	1.09	Growth Link	0.32	Weak Decoupling	0.65	Weak Decoupling	−1.24	Strong Decoupling	0.42	Weak Decoupling
Transportation Equipment Manufacturing Industry	1.07	Growth Link	0.41	Weak Decoupling	0.60	Weak Decoupling	−0.70	Strong Decoupling	0.43	Weak Decoupling
Electrical, Mechanical and Equipment Manufacturing Industry	0.95	Growth Link	0.55	Weak Decoupling	0.62	Weak Decoupling	−0.52	Strong Decoupling	0.52	Weak Decoupling
Communications Equipment, Computer and Other Electronic Equipment Manufacturing Industry	0.98	Growth Link	0.16	Weak Decoupling	0.77	Weak Decoupling	−0.90	Strong Decoupling	0.39	Weak Decoupling

Table 5. *Cont*.

Product Sector	2002–2005		2005–2007		2007–2010		2010–2012		2002–2012	
	Decoupling Elasticity	**Decoupling Relationship**	**Decoupling Elasticity**	**Decoupling Relationship**	**Decoupling Elasticity**	**Decoupling Relationship**	**Decoupling Elasticity**	**Decoupling Relationship**	**Decoupling Elasticity**	**Decoupling Relationship**
Instruments, Meters, Cultural and Office Machinery Manufacturing Industry	0.92	Growth Link	−0.33	Strong Decoupling	0.66	Weak Decoupling	1.50	Recessive Decoupling	0.28	Weak Decoupling
Other Manufacturing Industries	0.93	Growth Link	0.50	Weak Decoupling	0.30	Weak Decoupling	1.08	Recessive Link	0.30	Weak Decoupling
Electricity, Heat Production and Supply Industry	0.51	Weak Decoupling	1.12	Weak Decoupling	0.29	Weak Decoupling	0.97	Growth Link	0.50	Weak Decoupling
Fuel Gas Production and Supply Industry	0.46	Weak Decoupling	−0.17	Strong Decoupling	0.14	Weak Decoupling	−0.02	Strong Decoupling	0.06	Weak Decoupling
Water Production and Supply Industry	0.71	Weak Decoupling	0.36	Weak Decoupling	0.74	Weak Decoupling	12.73	Recessive Decoupling	0.27	Weak Decoupling
Construction Industry	0.61	Weak Decoupling	0.88	Growth Link	0.40	Weak Decoupling	0.47	Weak Decoupling	0.45	Weak Decoupling
Transportation, Storage, and Postal Services	0.72	Weak Decoupling	0.42	Weak Decoupling	0.56	Weak Decoupling	0.25	Weak Decoupling	0.41	Weak Decoupling
Wholesale, Retail and Catering Industry	−0.11	Strong Decoupling	0.74	Weak Decoupling	−0.04	Strong Decoupling	0.06	Weak Decoupling	0.10	Weak Decoupling
Other Services Industry	1.00	Growth Link	0.00	Weak Decoupling	0.43	Weak Decoupling	0.39	Weak Decoupling	0.35	Weak Decoupling

Notes: Data sources: According to the correlation equation mentioned earlier and the data collation calculation.

From 2007 to 2010, no sector showed a growth link between the output of the product sector and its embodied carbon emissions. In this period, only strong and weak decoupling relationships was observed. This result shows that, with the increase in the output of the product sector, China provide importance to improving the efficiency of production and energy utilization and promoting the sound and rapid development of the economy. Among the studied sectors, 26 sectors showed a weak decoupling, a strong decoupling was found in the textile industry and wholesale, retail, and catering industry; the decoupling elasticity of the two industries were −0.19 and −0.04.

From 2010 to 2012, five different decoupling relationships between output and embodied carbon emissions were found. Specifically, electricity and heat production and supply showed a growth link; other manufacturing industries showed a recession link; and instruments, meters, cultural, and office machinery manufacturing industry and water production and supply showed a recessive decoupling. Except these three relationships, weak decoupling was observed in 14 sectors, and a strong decoupling was found in 10 sectors. Compared with the previous period, the number of sectors with strong decoupling became more from 2010 to 2012. Therefore, China's measures for energy saving and emission reduction have achieved considerable success.

During the entire period of the study, the decoupling relationship of output and embodied carbon emissions from 2002 to 2012 was weak decoupling. This observation indicates that China's production methods tend to rationalize in recent years. To achieve the emission reduction targets of China as soon as possible, under the premise of ensuring the increase in the total output of each sector, energy consumption must be continuously reduced. Accordingly, the increase in embodied carbon emissions can be mitigated, and the strong decoupling relationship between output and embodied carbon emissions should be promoted.

5.3. Perspective of Three Industries

In the entire study period, a growth link between output and embodied carbon emissions in three industries was only observed from 2002 to 2005. The rest of the stages presented weak decoupling or strong decoupling; therefore, the continuous adjustment of industrial structure causes the output of various product industries to continuously move toward the direction of low-carbon development (Table 6).

The obtained empirical results are as follows: From 2002 to 2005, the primary industry showed a decoupling elasticity of 0.53 and a weak decoupling. Thus, the growth mode of this industry is low-carbon development. Without excessive consumption of energy, the secondary and tertiary industries presented decoupling elasticity of 0.82 and 0.83, respectively, and a growth link. In the past production, excessive pursuit of the increase in output without considering the environmental carrying capacity, excessive consumption of energy and resources to stimulate the increase in output, and the secondary industry also promotes the improvement of the total output. Accordingly, energy consumption continues to rise, thereby producing embodied carbon emissions. The tertiary industry is in the bottom of the industrial chain and is the final consumption terminal of most intermediate input products. The embodied carbon emissions in the tertiary industry include the amount of CO_2 from the initial production of raw materials to the manufacture of finished products. Therefore, without the adjustment in industrial structure, the increase in the output of the tertiary industry is accompanied by a large amount of embodied carbon emissions.

Table 6. Decoupling Relationship Evaluation of the Three Industrial Output and Its Embodied Carbon Emissions in China from 2002 to 2012.

Three Industries	2002–2005		2005–2007		2007–2010		2010–2012		2002–2012	
	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship	Decoupling Elasticity	Decoupling Relationship
First Industry	0.53	Weak Decoupling	−0.08	Strong Decoupling	0.34	Weak Decoupling	0.63	Weak Decoupling	0.28	Weak Decoupling
Second Industry	0.82	Growth Link	0.56	Weak Decoupling	0.42	Weak Decoupling	0.32	Weak Decoupling	0.44	Weak Decoupling
Third Industry	0.83	Growth Link	0.28	Weak Decoupling	0.40	Weak Decoupling	0.26	Weak Decoupling	0.32	Weak Decoupling

Data Sources: According to the correlation equation mentioned earlier and the data collation calculation.

From 2005 to 2007, the decoupling elasticity between the output of the primary industry and its embodied carbon was −0.08. This value implies a strong decoupling relationship, which indicates that the primary industry increases its output while reducing the embodied carbon emissions. This kind of economic growth mode is ideal. In this period, the secondary and tertiary industries exhibited decoupling elasticity of 0.56 and 0.28 respectively, and a weak decoupling. The decoupling elasticity of the two industries were lower than those in the previous period. The decoupling relationship changes from the growth link to the weak decoupling. Indicating that the two industries in the time of the output increased, paid attention to the use of the resources and energy, avoided the consumption of unnecessary energy. As a result, the embodied carbon emissions decreased. The decoupling elasticity of the tertiary industry was significantly lesser than that of the secondary industry. This finding indicates that the tertiary industry plays a significant role in reducing carbon emissions. The direction for future emission reduction can thus focus on the tertiary industry.

From 2007 to 2010, the three industries exhibited weak decoupling relationship. The decoupling elasticity were 0.42, 0.40, and 0.34 for the secondary, tertiary, and primary industries, respectively. For this period, the primary industry showed the greatest reduction effect, followed by the tertiary industry, and the secondary industry.

From 2010 to 2012, the three industries presented a weak decoupling. The decoupling elasticity of the secondary and tertiary industries were smaller than those in the previous period. This finding indicates that the development mode of the secondary and tertiary industries is tending to low carbonization.

In the entire study period, from 2002 to 2012, the decoupling elasticity of the three industries were 0.28, 0.44, and 0.32; they also exhibited a weak decoupling. The emission reduction effect from large to small industries is arranged as follows: the primary industry, tertiary industry, and secondary industry. In the future work of emission reduction, the practice of the primary and tertiary industries must be considered. Adjusting the industrial structure, eliminating high-carbon industries, vigorously developing low-carbon industries, optimizing the secondary industry, and transforming it to the tertiary industry.

6. Conclusions and Policy Implications

This study uses the Tapio decoupling model to measure the decoupling relationship between the output of the product sector in China and its embodied carbon emissions from the overall perspective, product sector perspective, and three-industries perspective. For this purpose, the I-O model and the non-competitive I-O data of 2002, 2005, 2007, 2010, and 2012 are used. The obtained empirical results are as follows: (1) Under the influence of the growth in the total output and embodied carbon emissions, the decoupling elasticity between the output of the product sector and its embodied carbon emissions decreased. The total output and embodied carbon emissions presented a growth link between 2002 and 2005, and a weak decoupling for the rest of the studied period. (2) From the perspective of each product sector, the development of China's economy has increased the growth rate of output in each product sector. However, more and more products sector are no longer accompanied by large CO_2 production. The product sector of the strong decoupling relationships between the total output and embodied carbon emissions gradually increased. Among these sectors, two sectors showed strong decoupling from 2002 to 2005, three sectors from 2005 to 2007, two sectors from 2007 to 2010, and 10 sectors from 2010 to 2012. (3) From the perspective of three industries, in the entire study period, a growth link between output and embodied carbon emissions in the secondary and tertiary industries was observed only from 2002 to 2005. Three industries exhibited weak decoupling or strong decoupling for the rest of the stages. Therefore, the continuous adjustment of industrial structure causes the production of various product industries to continuously move toward the direction of low-carbon development. However, because of the limitations of data availability, this paper calculates the carbon emissions of the product sector through the value of I-O table mainly. The advantage is that it can unify the differences between the values of different products. It is easy to make a comparative analysis in the framework of unified unit but this kind of discussion is also influenced by price easily. In the future research and analysis to fully consider the impact of price.

On the basis of the empirical results, the following recommendations are made:

(1) Construct ecological and environmental protection of low carbon agriculture. Firstly, governments at all levels should gradually integrate the concept of low-carbon agriculture into management and decision-making, formulate and implement the relevant standards of agricultural production and products, and actively guide agricultural production and management bodies at all levels to establish a low-carbon concept. Secondly, in agricultural production, continue to promote the use of low-carbon standards of agricultural machinery, and at the same time increase the intensity of fiscal policy to promote the government's special subsidies for agriculture funds priority for water-saving irrigation, precision fertilization and straw spraying and other green production activities. Thirdly, we should also reduce the use of chemical fertilizers and pesticides, improve the utilization level of low carbon straw, promote solar energy and biogas and other renewable energy technologies.
(2) Build a low carbon cycle industrial system. Firstly, supervise the approval of new projects effectively, to ensure that the source of high energy consumption and high pollution projects strictly controlled. Secondly, eliminate backward production capacity gradually, establish and improve the backward production capacity exit mechanism, and cultivate low consumption and high efficiency industries. According to the principle of agglomeration and green, cultivate and develop electronic information industry led by big data, health care industry with the goal of great health, a new type of building material industry with energy saving, environmental protection and low carbon and other emerging industries vigorously. Thirdly, build "ecological +" industrial park actively and implement "Internet +" industrial cluster construction action, in order to promote the transformation and upgrading of traditional industries to green low-carbon industry.
(3) Build intensive and efficient service industry. Firstly, nurture and gather low-carbon service enterprises. Foster and gather a group of new energy, energy saving and environmental protection industries that are engaged in R&D, design, technology integration, consulting, sales, installation and service of customer service, logistics management and other aspects with good market prospects, high technology content, high rate of return on investment. Secondly, vigorously develop green finance. Encourage regional banks, insurance, securities, security and other institutions to develop green financial products, improving financial support for low-carbon service enterprises. Cooperate with professional organizations to explore the trading mechanism with greenhouse gas emissions, construct the trading center of green products, technology and property rights. Thirdly, encourage low-carbon services technology innovation and application. Encourage low-carbon service enterprises to strengthen technical cooperation with relevant professional institutions, research institutes and universities, accelerating the development of low-carbon technology to improve the level of scientific and technological innovation and application.

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Abbreviations

The following abbreviations are used in this manuscript:

I-O	Input–output
LMDI	Logarithmic Mean Divisia Index Decomposition Method
VAR	Vector Auto Regression
DEA	Data Envelopment Analysis
STIRPAT	Stochastic Impacts by Regression on Population, Affluence and Technology
OECD	Organization for Economic Cooperation and Development
IPCC	Intergovernmental Panel on Climate Change
GDP	Gross Domestic Product
UNEP	United Nations Environment Programme
UNFCCC	The United Nations Framework Convention on Climate Change
GHG	Greenhouse Gas

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