

RESEARCH ARTICLE

Dynamic evolution analysis of the factors driving the growth of energy-related CO₂ emissions in China: An input-output analysis

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Citation: Ma Y, Song Z, Li S, Jiang T (2020) Dynamic evolution analysis of the factors driving the growth of energy-related CO₂ emissions in China: An input-output analysis. PLoS ONE 15(12): e0243557. <https://doi.org/10.1371/journal.pone.0243557>

Editor: Bing Xue, Institute for Advanced Sustainability Studies, GERMANY

Received: March 3, 2020

Accepted: November 23, 2020

Published: December 16, 2020

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Data Availability Statement: The data underlying the results presented in the study are available from China's input-output table that published in China Statistical Yearbook. The data selected in this paper included China's energy balance tables for 2007, 2010, 2012 and 2015, and China's input-output tables for 2007, 2010, 2012 and 2015. The data are from the official websites of the China Statistical Bureau, and the websites are as follows. <http://www.stats.gov.cn/tjsj/nds/2010/indexch.htm> (The energy balance table and input-output table for 2007) <http://www.stats.gov.cn/tjsj/nds/2013/>

Abstract

In recent years, the global greenhouse effect caused by excessive energy-related carbon emissions has attracted more and more attention. In this paper, we studied the dynamic evolution of factors driving China's energy-related CO₂ emissions growth from 2007 to 2015 by using energy consumption method and input-output analysis and used the IO-SDA model to decompose the energy carbon emissions. Within the research interval, the results showed that (1) on the energy supply-side, the high carbon energy represented by raw coal was still the main factor to promote the growth of energy-related CO₂ emissions. However, the optimization of energy consumption structure is conducive to reducing emissions. Specifically, the high carbon energy represented by raw coal exhibited a downward trend in promoting the increment of energy-related CO₂ emissions, while the clean energy represented by natural gas showed an upward trend in promoting the increment of CO₂ emissions. It is worth noting that there is still a lot of room for optimization of China's energy consumption structure to reduce emissions. (2) On the energy demand-side, the final demand effect is the main driving force of the growth of carbon emissions from fossil energy. Among them, the secondary industry plays a major role in the final demand effect. The "high carbonization" of the final product reflects the characteristics of China's high energy input in the process of industrialization. At the same time, since the carbon emission efficiency of the tertiary industry and the primary industry is better than that of the secondary industry, actively optimizing the industrial structure is conducive to slowing down the growth of carbon emission brought by the demand effect. (3) The input structure effect is the main restraining factor for the growth of energy carbon emissions, while the energy intensity effect has a slight driving effect on the growth of energy carbon emissions. The results show that China's "extensive" economic growth model has been effectively reversed, but the optimization of fossil energy utilization efficiency is still not obvious, and there is still a large space to curb carbon emissions by improving fossil energy utilization efficiency in the future.

[indexch.htm](http://www.stats.gov.cn/tjsj/ndsj/2015/indexch.htm) (The energy balance table and input-output table for 2010) <http://www.stats.gov.cn/tjsj/ndsj/2015/indexch.htm> (The energy balance table and input-output table for 2012) <http://www.stats.gov.cn/tjsj/ndsj/2018/indexch.htm> (The energy balance table and input-output table for 2015).

Funding: The authors are grateful to the financial support provided by China Postdoctoral Science Foundation (2020M672459) and by the Fundamental Research Funds for the Central Universities of China (Grant No. 2722020PY056).

Competing interests: NO authors have competing interests.

Introduction

At present, global warming caused by excessive carbon dioxide emissions has become a significant factor threatening the sustainable development of society [1]. In 2019, the statistics of Global Carbon Program suggested that global carbon emissions increased by about 2% in 2018 compared with 2017. This is another increase and a record high in global carbon emissions following a small increase in carbon emissions in 2017 (up 1.4%). Among them, carbon emissions from China accounted for 27% of global emissions and increased by about 4.5%. Meanwhile, after several consecutive years of decline, carbon emissions from the United States have also rebounded, with carbon emissions accounting for 15% of global emissions and increasing by 2.5%. It could be concluded that controlling the excessive carbon emissions has become a good way to protect the ecological environment and mitigate the greenhouse effect [2].

To reduce CO₂ emissions and protect the ecological environment, the Chinese government has actively cooperated with other countries and international environmental protection organizations [3]. In 2009, China's government officially announced that the intensity of carbon emissions per unit GDP by 2020 would be 40% to 45%, which was lower than that in 2005, at the Copenhagen Climate Conference [4]. In 2014, the Chinese government made a commitment at the Asia-Pacific Economic Cooperation (APEC) meeting that CO₂ emissions would peak around 2030 and strive for a peak earlier; carbon dioxide emissions per unit GDP would decrease by 60% - 65% compared with 2005; non-fossil energy accounted for about 20% in primary energy consumption [5]. The above international commitments of the Chinese government illustrated China's determination to reduce carbon emissions and the inevitable choice for low-carbon economic development in the future.

In terms of sources, CO₂ emissions were mainly from energy consumption [6], cement production [7], and biomass decomposition [8]. However, the main source of carbon dioxide emissions in China was energy-related carbon emissions according to statistics [9, 10]. Therefore, the focus of controlling China's excessive carbon dioxide emissions naturally fell on controlling energy-related carbon emissions. Existing literature on energy carbon emissions can be divided into energy supply-side carbon emissions [11, 12] and energy demand-side carbon emissions [13, 14]. For the supply-side, energy carbon emissions mainly come from the energy system [2]. For the demand-side, energy carbon emissions mainly come from the industrial system [2]. Therefore, the control of China's industrial and energy system carbon emissions has become a key area for China to control energy carbon emissions.

With regard to the calculation of energy-related carbon emissions and analysis of factors driving the growth of energy-related carbon emissions, there are many mature methods at home and abroad that have conducted relevant research, such as the energy consumption method [15], the input-output method [16], the DEA model [17], the SDA model [18], and LMDI model [19]. Most of them focused on DEA model, SDA model or LMDI model to analyze the impact of various internal factors such as energy structure, energy intensity, input structure, final demand and industrial scale on carbon emissions. However, there are few literatures that quantitatively analyze the effects of various energy sources in the supply side energy system and industries in the demand side industry system on the growth of energy carbon emissions. Even if few scholars have done similar research, the scope of the research object is not comprehensive. For example, Jiang et al. (2019) used the energy consumption method and the input-output method to analyze the carbon emission structure of China's industries and energy systems from 2002 to 2015, but did not analyze the impact of various energy sources and industries on carbon emission growth [2]. Jiang et al. (2020) uses the energy consumption method and the input-output method to analyze the evolution of the driving factors for the

growth of electric energy-related carbon emissions from the energy supply-side and the energy demand-side in 2007–2015, but did not analyze the corresponding situation of fossil energy [20]. At the same time, since the energy system and industrial system are more practical for the implementation of emission reductions, the analysis of the effects of various energy sources and industries on the growth of energy carbon emissions in the past, which will provide realistic guidance and direction for subsequent focused emission reductions. Based on the above analysis, this paper used the energy consumption method and the input-output method to quantitatively analyze the evolution of the driving factors for the growth of energy-related carbon emissions from the fossil energy supply-side in China's energy system and the fossil energy demand-side in China's industrial system from 2007 to 2015, and applied the SDA model to decompose the carbon emission growth. Through the input-output framework, this study unifies the supply-side energy system carbon emission and the demand-side carbon emission, and quantitatively analyzes the effects of the various energy sources and industries in the energy system on the growth of energy carbon emissions. The framework provides a theoretical basis and practical direction for the follow-up energy system and industrial system to focus on emission reduction.

The rest of this paper is organized as follows. Section 2 reviewed and commented literatures about energy-related carbon emissions from the perspectives of the energy supply-side and demand-side. Section 3 described the data and model. Section 4 was the results and analysis. Section 5 was the conclusions and policy recommendations.

Literature

The extant literature mainly focuses on energy-related carbon emissions from the perspective of the energy supply-side [12, 21] or the energy demand-side [22, 23]. Carbon emission analysis on the energy supply-side emphasizes the impact of energy supply on carbon emission growth in the energy system, while carbon emission analysis on energy demand-side emphasizes the impact of energy supply on carbon emission growth in the industrial system. Therefore, we summarized literatures on energy-related carbon emissions from the perspectives of the energy supply-side and the energy demand-side, and comprehensively analyzed the driving factors of energy consumption and carbon dioxide emissions. These works provide theoretical and practical significance for accounting carbon emission reduction.

From the perspective of the supply-side

Many scholars studied energy-related CO₂ emissions from the perspective of the energy supply-side, which was mainly based on CO₂ emissions from various energy sources in the energy system. The non-renewable energy consumption had a positive impact on environmental degradation, while renewable energy consumption had a negative impact on environmental degradation, which helped to reduce environmental pollution [24]. Naturally, in the context of environmentally friendly development, fossil energy consumption and CO₂ emissions have become a research topic that scholars cannot ignore and urgently need to solve. For example, Xu et al. (2014) studied the factors that influence carbon emissions due to fossil energy consumption in China, and found that the main driving force of CO₂ emissions was economic output effect, followed by population scale and energy structure effects. The energy intensity effect was a major inhibitory factor [9]. Long et al. (2015) analyzed the relationship between CO₂ emissions and energy consumption. The results indicated that that coal consumption played a leading role in economic growth and carbon emissions; the GDP had a two-way relationship with carbon emissions, coal, natural gas and power consumption; it was imperative to change the structure of energy consumption [25]. Yu et al. (2018) proposed a new economic-

carbon emission-costs (ECC) multi-objective optimization model to measure the peak of CO₂ emissions. The results showed that optimizing the coal-dominated structure of energy consumption would effectively contribute toward ensuring that China's carbon emissions peak by 2030. Meanwhile, the study found that the volume and time of the CO₂ emission peak are not sensitive to renewable electricity price, but are sensitive to both the minimum average annual growth rates of GDP and the average annual reduction rate of energy intensity [26]. Zhao and Luo (2018) predicted the energy consumption structure of China by estimating the long-term and short-term relationship between carbon emission intensity, economic growth and consumption of natural gas, crude oil and coal. The results demonstrated that in the long run, the consumption of natural gas, crude oil and coal had a positive elasticity to GDP and carbon emission intensity, which implied that China should consider reducing the negative impact of CO₂ emission intensity on economic growth and adjusting the optimal energy consumption structure [27]. By analyzing the relationship between energy consumption, CO₂ emissions and economic growth in 68 emerging and developed countries from North Africa and Middle East, Muhammad (2019) found the increase in energy consumption led to the growth of CO₂ emissions [28]. Meanwhile, the renewable energy consumption and CO₂ emissions have also gradually attracted wide attention of scholars. However, the conclusions of these scholars are not unanimous. Although some scholars believed that renewable energy consumption could improve the growth of CO₂ emissions [29, 30], Pata (2018) found total renewable energy consumption play no role in CO₂ emissions reduction [31]. Nguyen and Kakinaka (2019) studied the relationship between CO₂ emissions and renewable energy consumption at different development stages, which indicated the difference between high-income countries and low-income countries [32]. For high-income countries, the relationship between the consumption of renewable energy and output or CO₂ emissions was just the opposite; For low-income countries, the relationship between the consumption of renewable energy was negatively and positively correlated with output and CO₂ emissions, respectively. Moreover, some scholars made a comparative analysis for the relationship between renewable or non-renewable energy consumption and CO₂ emissions [33–35], but its conclusion is based on data at the level of total energy consumption.

By summarizing the above literatures about carbon emissions from the supply-side perspective, it could be concluded that most of the literatures focused on the impact of energy intensity, population size, energy structure, and renewable energy on carbon emissions. The analysis of carbon emissions was also concentrated on the types with a large consumption structure such as coal and oil. Few literatures analyzed the evolution of the contribution of 17 different energy sources to the growth of energy-related carbon emissions in the entire energy system, which will provide scientific basis and theoretical basis for China's energy system to focus on the optimization of energy structure and carbon emissions reduction.

From the perspective of the demand-side

A number of studies focus on energy-related carbon emissions from the perspective of the energy demand-side [36, 37], which was mainly based on the perspective industrial system. Due to the large proportion of construction, electricity, cement and heavy industry in China's industrial structure, these industries had attracted more attention [38–40]. However, some scholars studied the carbon emissions from other industries. For example, Wang et al. (2015) analyzed CO₂ emissions of transportation infrastructure industry, and estimated CO₂ emissions from four expressway projects in southwestern regions. The results showed that more than 80% of the carbon emissions from expressway projects came from raw material production, while material transportation and on-site construction accounted for only 3% and 10% of

the total carbon dioxide emissions, respectively [41]. Tang et al. (2017) proposed a factor decomposition model to study the CO₂ emissions of tourism. Their results manifested that the expansion of tourism scale and the growth of tourism output were the main reasons for the growth of CO₂ emissions of tourism, and the decrease of energy intensity was beneficial to the reduction of tourism emissions [42]. Furthermore, some scholars decomposed the CO₂ emissions in different industries. For example, Lin and Lei (2015) evaluated CO₂ emissions of China's food industries, and found that energy intensity and industry activities were main factors affecting the increase and decrease of CO₂ emissions in China's food industry, and optimizing the scale of industry and improving energy efficiency could effectively reduce carbon emissions [43]. Yang and Lin (2016) analyzed CO₂ emissions in China's power industries, and pointed out that power intensity and economic activities were the main driving factors to promote the growth of carbon dioxide emissions; energy efficiency optimization had a significant effect on the CO₂ emission reduction. In addition, other scholars have studied carbon emissions in other non-high energy-consuming industries [38]. Feng et al. (2018) decomposed CO₂ emissions from China's metal industry, and drew a conclusion that the industrial output effect and the energy intensity effect were major factors for CO₂ emissions growth and CO₂ emissions reduction, respectively [44]. Du et al. (2018) analyzed CO₂ emissions in six high-energy intensive industries of China. Their results demonstrated that the energy intensity effect was the prominent contributor for CO₂ emissions reduction, while the industrial structure effect and the energy structure effect made small contribution to CO₂ emissions change [45]. Gao et al. (2018) studied CO₂ emissions in China's pharmaceutical industry, and found the production scale effect and the investment intensity effect were responsible for CO₂ emission growth, while the energy intensity effect and the R&D efficiency effect were decisive for CO₂ emissions reduction [46].

By summarizing the above literatures about energy-related carbon emission from the demand-side perspective, it could be concluded that most of the literatures focused on the carbon emissions of a certain industry and the impact of factors such as industrial growth, scale expansion and economic activities on the growth of carbon emissions. Few literatures analyzed the evolution of the contribution share of energy demand of various industries in the entire China's industrial system to the growth of energy-related carbon emissions. This study can accurately and objectively reflect the impact of energy demand of various industries in the industrial system on the growth of carbon emissions, which provides scientific basis and theoretical basis for the China's industrial system to focus on the optimization of industrial structure and carbon emissions reduction.

The academic contribution of this paper

Compared with previous research literatures about energy-related carbon emissions and driving factors, the contribution points of this paper are mainly reflected in the following three aspects. First, the fossil energy supply-side in energy system and the demand-side in industrial system have been unified to make up for the shortcomings of conducting research on energy-related carbon emissions from a single perspective in the past, and analyzed the impact of four effects on the growth of energy carbon emissions. Second, from the perspective of the supply-side, the driving factors and evolution of each specific fossil energy supply on the growth of energy-related carbon emissions were analyzed. Third, from the perspective of the demand-side, the driving factors and evolution of energy demand from various industries on the growth of energy-related carbon emissions were analyzed. The above three contribution points in this paper provide theoretical basis and data analysis for more efficient energy carbon emission control from the energy supply-side in the energy system and the energy demand-side in the industrial system.

Data and model

Data

Because the core data used in this paper is China's input-output table, which is updated every five years and extended every two or three years. As of the time when this paper is finished, we can get the latest input-output table is China's input-output table for 2015 that published in the 2019 China Statistical Yearbook. Therefore, the deadline of related data from input-output table in this paper is 2015. Meanwhile, because the input-output table before 2007 is relatively old, the research period of this paper is 2007–2015. Based on this, according to the research objectives of this paper, the data selected in this paper included China's energy balance tables for 2007, 2010, 2012 and 2015, and China's input-output tables for 2007, 2010, 2012 and 2015.

Method and calculation

Based on the above analysis in introduction, this paper adopts the energy consumption method and the input-output method to analyze the impact of the energy system on the supply-side and the industry system on the demand-side on the growth of energy-related carbon emissions. We refer to the analytical model [44], and make corresponding modifications according to the research needs of this paper.

First, we use the energy consumption method to measure the CO₂ emissions generated by the energy system on the supply-side. Carbon emissions from energy system are measured by the following calculation formula.

$$M = E \times W \quad (1)$$

where M is the carbon emissions generated by all energy sources combustion; E is the amount of each energy combustion; W is the carbon dioxide emission coefficient.

It is noteworthy that the energy system on the supply-side is composed of many energy sources. Due to differences of energy sources in the CO₂ emission coefficients, the above-mentioned formula of carbon emission from energy system needs to be revised. The formula for calculating the CO₂ emissions from the energy i for combustion is as follows.

$$M_i = E_i \times W_i \quad (2)$$

where M_i is the CO₂ emissions from energy i for combustion; E_i is the amount of energy i for combustion; W_i is the carbon emission coefficient of energy i .

By summing up the CO₂ emissions from all energy sources, the total CO₂ emissions from energy system combustion on the supply-side can be derived. The summation formula is as follows.

$$M = \sum_i M_i = \sum_i E_i \times W_i \quad (3)$$

From the above analysis, we can draw that one of the key points of using energy consumption method to calculate carbon emissions of energy system was how to determine the total amount of energy combustion in energy system. By analyzing the China Energy Statistics Yearbook from 2003 to 2016, we find that 17 types of energy sources are listed in 2008 and 2011, while 20 types of energy sources are listed in 2013 and 2016. We summarize 17 types of energy sources for facilitating the research. From the perspective of energy consumption, energy consumption is divided into heat supply, thermal power generation, final consumption and the industrial raw materials. Among them, heat supply, thermal power generation and the final consumption belong to energy resource consumption for combustion, while the

industrial raw materials does not involve energy combustion, so it needs to be eliminated. The total consumption of the energy i for combustion can be calculated by the following formula.

$$E_i = E_i^T + E_i^P + E_i^H - E_i^M \quad (4)$$

where E_i is the energy i consumption for combustion; E_i^T , E_i^P , E_i^H , E_i^M are the consumption of the energy i for final consumption, thermal power generation, heat supply and industrial raw materials, respectively.

At the same time, when using the energy consumption method to measure carbon emissions, we also need to measure the CO₂ emission coefficient of each type of energy. In the paper, the CO₂ emission coefficient of each energy is calculated by multiplying the CO₂ emission coefficient of each type of energy per unit heat and the average low calorific value of each energy. The calculation formula is as follows.

$$W_i = R_i \times Q_i \quad (5)$$

where W_i is the CO₂ emission coefficient of energy i ; R_i is carbon emission coefficient of energy i per unit heat; Q_i is the average low calorific value of energy i for combustion.

We have measured the carbon emission of energy system on the supply-side. Then we measure the carbon emissions of industries on the demand-side. The CO₂ emissions include two parts, namely, CO₂ emissions from intermediate demand (enterprises) and CO₂ emissions from final demand (residents and governments).

Next, we utilize the input-output analysis to calculate CO₂ emissions of China's industry on the demand-side. When using input-output analysis to measure CO₂ emissions on the demand-side, we need to pay attention to energy capital deposits and loans and energy export which will lead to CO₂ emissions measurement errors on the demand-side besides excluding some energy sources used as industrial raw materials. Energy capital deposits and loans are saved in kind, so they will not generate carbon emissions; Energy exports will generate carbon emissions, but the place where carbon emissions occur is off-site. Therefore, it cannot be counted as China's carbon emissions. Firstly, we estimated the total energy investment of each energy industry j for combustion in the input-output table without excluding these two factors. The calculation formula is as follows.

$$K_j = KI_j + KF_j \quad (6)$$

where K_j is the total energy investment of each energy industry j for energy combustion; KI_j is the intermediate demand investment of energy industry j for energy combustion; KF_j is the final demand investment of energy industry j for energy combustion. In theory, we need to eliminate the two factors (energy capital deposits and loans, energy export). When these two factors are excluded, the formula for calculating the total investment of each energy industry for energy combustion is as follows.

$$K_j = KI_j + KF_j - KC_j - KE_j \quad (7)$$

where KC_j is the energy capital deposits and loans of energy industry j for energy combustion; KE_j is the energy export of energy industry j for energy combustion. Then, based on the previously calculated CO₂ emissions from the energy combustion produced by the 4 energy industries and the amount of input of 4 energy industries in the input-output table to 42 other sectors, we measured CO₂ emissions per unit input in 4 energy industries. The calculation

formula is as follows.

$$T_j = \sum_i^n M_i \tag{8}$$

$$e_j = \frac{T_j}{K_j} \tag{9}$$

where e_j is CO₂ emissions coefficient of energy industry j for energy combustion; T_j is total CO₂ emissions from energy industry j for energy combustion. The CO₂ emission coefficient of each energy industry j multiplied by the investment of the energy industry to each sector gets the carbon emissions from the sector consuming energy sources that are produced by energy industry on the demand-side. Due to 4 energy industries in input-output tables, the CO₂ emissions of each sector are the sum of CO₂ emissions from the sector consuming energy sources that are produced by 4 energy industries. The calculation formula is as follows.

$$E^k = \sum_j E_j^k = \sum_j C_j^k \times e_j \tag{10}$$

where E^k is CO₂ emissions from industry k on the demand-side; E_j^k is carbon emissions from energy industry k for energy combustion provided by energy industry j on the demand-side; C_j^k is energy investment of the industry k in energy industry j for energy combustion part. We can measure the CO₂ emissions of energy system on the supply-side and CO₂ emissions of industries on the demand-side based on all the above formulas.

Next, we analyze the growth of CO₂ emissions on the demand-side and supply-side, and calculate the contribution share of various factors to the growth of CO₂ emissions on the demand-side and supply-side, so as to provide direction suggestions on how to carry out specific emission reduction.

From the perspective of carbon emissions on the supply-side, the calculation formulas for the contribution share of each type of energy to the carbon emissions increment of energy system on the supply-side is as follows.

$$W_i^{(k-n)k} = \frac{M_i^k - M_i^{k-n}}{\sum_{k=1}^{17} M_i^k - \sum_{k=1}^{17} M_i^{k-n}} \tag{11}$$

where $W_i^{(k-n)k}$ is the structure proportion of carbon emission increment of energy i in whole energy system from the year of $k-n$ to the year of k ; M_i^k is CO₂ emissions from energy i in the year of k ; M_i^{k-n} is CO₂ emissions from energy i in the year of $k-n$; $\sum_{i=1}^{17} M_i^k$ is total carbon emissions from all 17 types of energy sources in the year of k ; $\sum_{i=1}^{17} M_i^{k-n}$ is total carbon emissions from all 17 types of energy sources in the year of $k-n$.

From the perspective of CO₂ emissions on the demand-side, on the one hand, the calculation formulas for the contribution share of final demand (residents and governments) to the

carbon emissions increment on the demand-side is as follows.

$$P^{(k-n)k} = \frac{L^k - L^{k-n}}{\sum_{k=1}^{17} M_i^k - \sum_{k=1}^{17} M_i^{k-n}} \tag{12}$$

where $P^{(k-n)k}$ is the contribution share of final demand to the carbon emissions increment on the demand-side from the year of $k-n$ to the year of k ; L^k is carbon emissions from final demand in the year of k ; L^{k-n} is carbon emissions from final demand in the year of $k-n$. On the other hand, the calculation formulas for the contribution share of intermediate demand (enterprises) to the carbon emissions increment on the demand-side is as follows.

$$S^{(k-n)k} = \frac{R^k - R^{k-n}}{\sum_{k=1}^{17} M_i^k - \sum_{k=1}^{17} M_i^{k-n}} \tag{13}$$

where $S^{(k-n)k}$ is the contribution share of intermediate demand to the carbon emissions increment on the demand-side from the year of $k-n$ to the year of k ; R^k is carbon emissions from intermediate demand in the year of k ; R^{k-n} is carbon emissions from intermediate demand in the year of $k-n$. Moreover, we analyzed the impact of various industries with energy demand on carbon emission increment in China. The formula for calculating the contribution of each sector to the growth of energy-related CO₂ emission in China's industry is as follows.

$$P_{(i-n)i}^k = \frac{E_i^k - E_{i-n}^k}{\sum_{k=1}^9 E_i^k - \sum_{k=1}^9 E_{i-n}^k} \tag{14}$$

where $P_{(i-n)i}^k$ is the contribution share of sector k to the CO₂ emissions increment on the demand-side from the year of $i-n$ to the year of i ; E_i^k is carbon emissions from sector k the year of i ; E_{i-n}^k is carbon emissions from sector k in the year of $i-n$; $\sum_{k=1}^9 E_i^k$ is the total carbon emissions from all 9 sectors in the year of i . $\sum_{k=1}^9 E_{i-n}^k$ is carbon emissions from all 9 sectors in the year of $i-n$.

$$SE_i = \frac{W_i}{P_i} \tag{15}$$

Where SE_i is the carbon emission sensitivity coefficient of energy i ; W_i is the standard coal conversion coefficient of energy i ; P_i is the coefficient of carbon emission of energy i .

Next, we build an IO-SDA model to decompose the structural factors of energy carbon emission growth [47], which can be decomposed into four factors: final demand effect, input structure effect, energy intensity effect, and energy structure effect [48].

$$AX + Y = X \tag{16}$$

$$\begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_i \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1j} \\ A_{21} & A_{22} & \cdots & A_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ A_{i1} & A_{i2} & \cdots & A_{ij} \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_i \end{pmatrix} + \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_i \end{pmatrix} \tag{17}$$

Where, $X = [X_j]$ is the total output matrix, $Y = [Y_j]$ is the final demand matrix, and A is the direct consumption matrix.

In the input-output model, fossil energy participates in national economic production as an intermediate input in the fossil energy sector. It can be concluded that China's fossil energy carbon emissions E_h can be expressed as:

$$E_h = FSILY \tag{18}$$

$$\begin{aligned} \Delta E_h = & \underbrace{\frac{1}{2}(F_t I_t L_t Y_t - F_{t-1} I_{t-1} L_{t-1} Y_{t-1}) \Delta S}_{\text{energy structure effect}} + \underbrace{\frac{1}{2}(F_t S_t L_t Y_t - F_{t-1} S_{t-1} L_{t-1} Y_{t-1}) \Delta I}_{\text{energy intensity effect}} \\ & + \underbrace{\frac{1}{2}(F_t S_t I_t Y_t - F_{t-1} S_{t-1} I_{t-1} Y_{t-1}) \Delta L}_{\text{input structure effect}} + \underbrace{\frac{1}{2}(F_t S_t I_t L_t - F_{t-1} S_{t-1} I_{t-1} L_{t-1}) \Delta Y}_{\text{final demand effect}} \end{aligned} \tag{19}$$

Where, S is the energy structure matrix, F is the carbon emission coefficient matrix of each fossil energy, I is the energy consumption intensity matrix, and L is the Leontief inverse matrix. Then the growth of fossil energy carbon dioxide emissions is ΔE_h .

Results and analysis

Calculation of energy-related CO₂ emissions from 2007 to 2015

We could calculate China's energy-related carbon emissions in 2007, 2010, 2012 and 2015 according to the above energy consumption method. The growth rate of energy-related CO₂ emissions was shown in Fig 1.

According to the Fig 1, China's energy-related CO₂ emissions increased by 1510.132 million tons in 2010, 1135.492 million tons in 2012, and 1681.177 million tons in 2015 compared

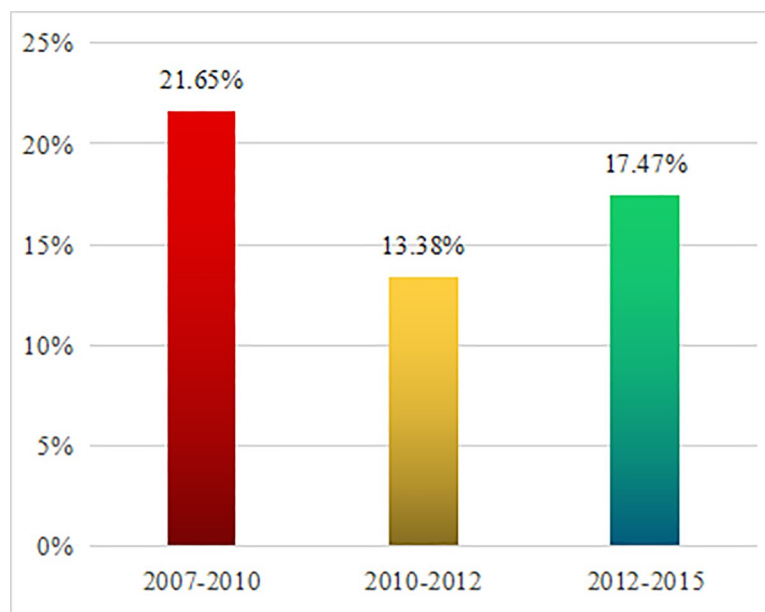


Fig 1. The growth rate of energy-related CO₂ emissions.

<https://doi.org/10.1371/journal.pone.0243557.g001>

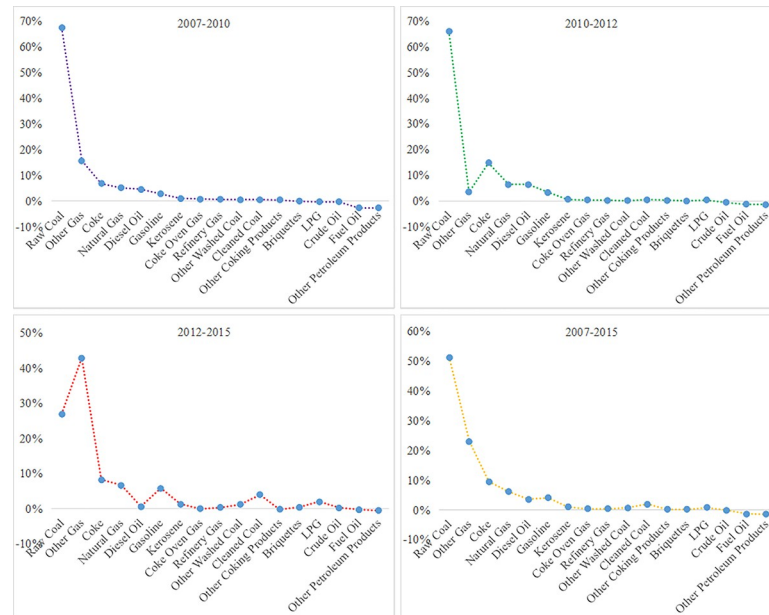


Fig 2. Contribution of various energy sources to CO₂ emissions growth from 2007 to 2015.

<https://doi.org/10.1371/journal.pone.0243557.g002>

with 2007, 2010, 2012, respectively. It could be concluded that the increase rate of energy-related CO₂ emissions showed a downward trend from 2007 to 2015. Specially, the growth rate of energy-related CO₂ emissions was 21.65% from 2007 to 2010, 13.38% from 2007 to 2012, and 17.47% from 2012 to 2015.

Analysis of the contribution of various energy sources to the CO₂ emissions growth of energy system on supply-side

The share of each type of energy to the CO₂ emissions increment in energy system was shown in Fig 2. The carbon emission sensitivity of each energy consumption was shown in Fig 3.

As shown in Fig 2, in the view of time evolution, the contribution share of high-carbon energy sources, such as other coking products, raw coal and diesel oil, to China's energy carbon emission growth showed a downward trend from 2007 to 2015. Specifically, contribution of raw coal to China's carbon emission growth was 67.35%, 65.86%, 26.94% during 3 sub-periods (2007–2010, 2010–2012, 2012–2015), respectively; other coking products contributed 0.45%, 0.32%, -0.19% to China's energy-related carbon emissions increment during above 3 sub-periods; diesel oil contributed 4.53%, 6.41%, 0.64% to China's energy carbon emission increment during the same 3 sub-periods. This change benefited from the Chinese government actively carrying out the optimization of energy consumption structure, controlling the excessive growth of high-carbon energy consumption proportion (especially the proportion of high-carbon energy such as coal and diesel oil), vigorously promoting technological progress, and improving energy efficiency. These initiatives led to the contribution share of raw coal, other coking products and diesel oil to China's energy-related carbon emissions growth showing a fluctuating downward trend.

In addition, the contribution share of other gas and natural gas, as clean energy sources, to energy carbon emission increment showed a rising trend. Concretely, natural gas contributed 5.10%, 6.46%, 6.68% to China's energy carbon emission increment during the same 3 sub-periods, and the other gas contributed 15.60%, 3.45%, 42.87% to China's energy-related carbon

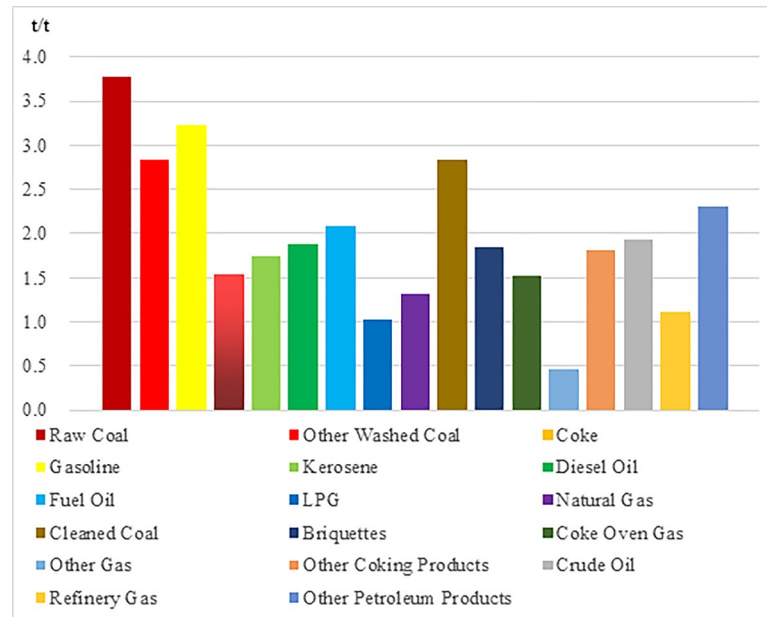


Fig 3. The carbon emission sensitivity of each energy consumption.

<https://doi.org/10.1371/journal.pone.0243557.g003>

emissions increment. This was because the Chinese government not only controlled the rapid increment of high-carbon energies such as raw coal, but also actively promoted the diversification of energy sources, and deepened the processing of extensive energy sources, and focused on the development of clean low-carbon energies such as natural gas. As a result, the contribution of clean energy sources to energy-related carbon emissions was increasing.

From the above analysis, we concluded that, from 2007 to 2015, although the structure of China's energy consumption has been optimized, the high-carbon energy sources were still the main factor to promote the growth of CO₂ emissions.

As shown, Fig 3 presented the carbon emission sensitivity of each energy consumption. We concluded that the carbon emission coefficients of each energy source are significantly different. Among them, raw coal, other washed coal, coke, cleaned coal and other energy sources have higher carbon emission sensitivity coefficient, which means that the carbon emission generated by burning these energy sources per unit standard coal is large. However, the carbon emission sensitivity coefficient of natural gas, other gas, liquefied petroleum gas and refinery dry gas is relatively low, which means that the carbon emission generated by burning these energy sources per unit standard coal is relatively small. Through the above analysis, it can be concluded that reducing the proportion of high carbon energy consumption structure, such as raw coal, other washed coal, coke and cleaned coal, while increasing the proportion of energy consumption structure, such as natural gas, other gas, liquefied petroleum gas and refinery dry gas, which is conducive to slowing down the growth of carbon emission caused by the growth of energy consumption.

Analysis of the contribution of various industries to the CO₂ emission growth of industrial system on demand-side

The energy-related carbon emissions on the demand-side were not entirely accomplished by enterprises, but included two parts: intermediate demand (enterprises) and final demand

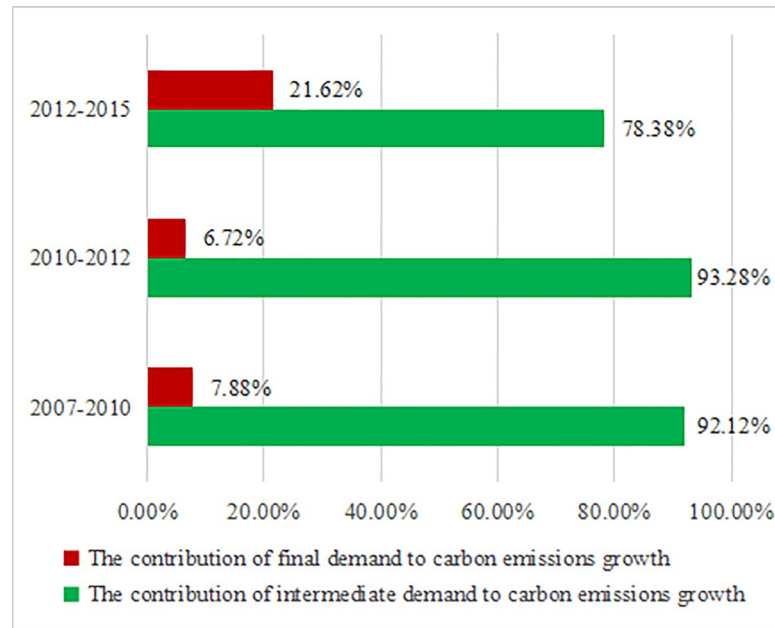


Fig 4. The contributions of intermediate demand and final demand to carbon emissions growth from 2007 to 2015.

<https://doi.org/10.1371/journal.pone.0243557.g004>

(residents and governments). The contribution share of intermediate demand and final demand to the increment of total CO₂ emissions was shown in Fig 4.

The analysis of Fig 4 led to the fact that the growth of energy-related CO₂ emissions from 2007 to 2015 was still mainly driven by intermediate demand, while the final demand played a smaller role. In 2007–2010, the contribution share of intermediate demand to carbon emission growth was 92.12%, while the contribution share of final demand to carbon emission growth was 7.88%. In 2010–2012, the contribution share of intermediate demand to carbon emission growth was 93.28%, while the contribution share of final demand to carbon emission growth was 6.72%. In 2012–2015, the contribution share of intermediate demand to carbon emission growth was 78.38%, while final demand contributed 21.61% to the growth of carbon emissions. Therefore, it could be concluded that the contribution share of intermediate demand to carbon emissions growth exhibited a slow downward trend, while the contribution share of final demand to carbon emissions growth showed a slow upward trend.

In China's input-output table, the industrial structure was divided into 42 sectors, but we merged them into 9 sectors [2]. The trend chart of contribution share of each industry to carbon emission growth along with time evolution was shown in Fig 5.

As shown in Fig 5, from the perspective of industrial structure, from 2007 to 2010, fossil energy, heavy industry, electric power, transportation and chemical industry contributed larger share to China's industrial carbon emission growth on the demand-side, while agriculture and construction had negative effects on China's industrial carbon emission growth on the demand-side. From 2010 to 2012, contribution share of the electric power, fossil energy, chemical industry and service sector to the growth of industrial CO₂ emissions on the demand-side were larger, while contribution share of light industry and heavy industry to the growth of industrial CO₂ emissions on the demand-side were negative. From 2012 to 2015, the electric power, agriculture and light industry had negative effects on the growth of industrial CO₂ emissions on the demand-side, while the fossil energy, chemical industry, transportation

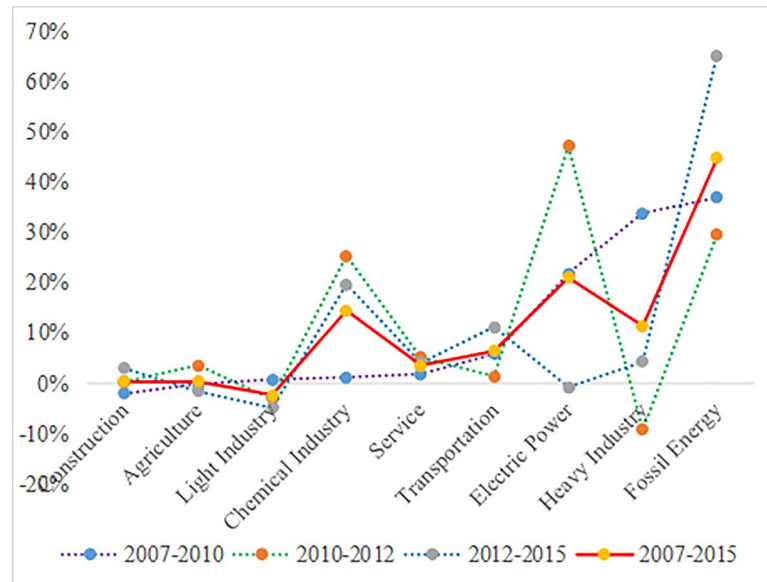


Fig 5. Contribution shares of various sectors to carbon emission growth from 2007 to 2015.

<https://doi.org/10.1371/journal.pone.0243557.g005>

and heavy industry contributed a larger share to the growth of industrial CO₂ emissions on the demand-side.

According to the above analysis, we concluded that the main sectors to promote the growth of industrial CO₂ emissions on the demand-side were fossil energy sector, electric power, heavy industry, chemical industry and transportation, while the service industry, construction and agriculture played a smaller role in promoting the growth of industrial CO₂ emissions on the demand-side. At the same time, light industry had a negative effect on the increment of CO₂ emissions.

Next, we analyzed the impact of industrial structure changes on CO₂ emission growth. The direct consumption coefficient of fossil energy by various industries were shown in Fig 6 (Ton/10,000 RMB).

According to the above Fig 6, we concluded that the direct consumption coefficient of fossil energy from the primary and tertiary industries was prior to that of the secondary industries (heavy industry, chemical industry, fossil energy sector, etc.), which indicated that expansion in the secondary industry on the same scale could produce more carbon emissions than that of the tertiary industry or the primary industry. Therefore, industrial structure optimization could make contribution to the carbon emissions reduction.

Table 1 shows the four-factor decomposition results obtained by using the IO-SDA model.

From the analysis of results in Table 1, it can be concluded that the positive and negative effects of the four-factors on the growth of China's energy carbon emissions from 2007 to 2015 and the intensity of the effects are significantly different. To be specific, first, the final demand effect is the main driving force of the growth of carbon emissions from fossil energy, which is consistent with the research results of Liao and Xu (2017). The "high carbonization" of the final product reflects China's high energy input in the process of industrialization. Second, energy intensity has a weak driving effect on the growth of carbon emissions from fossil fuels. The result indicates that the optimization of fossil energy utilization efficiency in China is still not obvious during the study period, and there is still a large space to curb carbon emissions by improving fossil energy utilization efficiency in the future. Third, the input structure effect

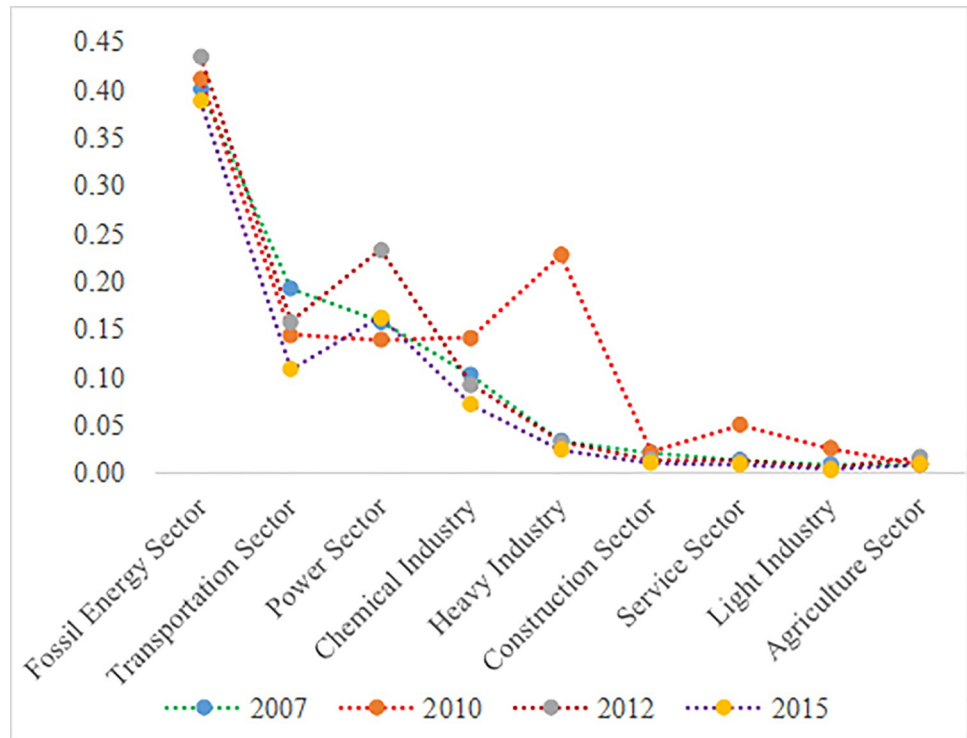


Fig 6. Direct consumption coefficient of fossil energy by various industries.

<https://doi.org/10.1371/journal.pone.0243557.g006>

is the main restraining factor for the growth of fossil energy carbon emissions. The results show that China’s extensive pattern of economic growth has been effectively reversed from 2007 to 2015. Fourth, the energy structure effect has an inhibitory effect on the growth of carbon emissions. This reflects that the national "Eleventh Five-Year Plan" and "Twelfth Five-Year Plan" proposed to reduce the proportion of raw coal consumption and increase the proportion of low-carbon consumption such as natural gas have been well implemented.

Conclusions and policy recommendations

By using the energy consumption method and input-output method, we calculated and analyzed the contribution share of energy sources and industries to energy-related carbon emissions growth from 2007 to 2015 on the supply-side and demand-side. At the same time, we used the IO-SDA model to decompose the energy carbon emissions. Within the research interval, the research results show that (1) on the energy supply-side, the high carbon energy represented by raw coal was still the main factor to promote the growth of energy-related CO₂ emissions. However, the optimization of energy consumption structure is conducive to reducing emissions. Specifically, the high carbon energy represented by raw coal exhibited a

Table 1. Decomposition results of the four-factors from 2007 to 2015.

Effect of name	Energy structure effect	Energy intensity effect	Input structure effect	Final demand effect
Impacts of various effects on the growth of energy carbon Emissions (unit: TONS)	-145751.2	9300.03	-612899.63	1274340.97
The contribution share of each effect in the total effect	-27.04%	1.73%	-113.70%	236.41%

<https://doi.org/10.1371/journal.pone.0243557.t001>

downward trend in promoting the increment of energy-related CO₂ emissions, while the clean energy represented by natural gas showed an upward trend in promoting the increment of CO₂ emissions. It is worth noting that there is still a lot of room for optimization of China's energy consumption structure to reduce emissions. (2) On the energy demand-side, the final demand effect is the main driving force of the growth of carbon emissions from fossil energy. Among them, the secondary industry plays a major role in the final demand effect. The "high carbonization" of the final product reflects the characteristics of China's high energy input in the process of industrialization. At the same time, since the carbon emission efficiency of the tertiary industry and the primary industry is better than that of the secondary industry, actively optimizing the industrial structure is conducive to slowing down the growth of carbon emission brought by the demand effect. (3) The input structure effect is the main restraining factor for the growth of energy carbon emissions, while the energy intensity effect has a slight driving effect on the growth of energy carbon emissions. The results show that China's "extensive" economic growth model has been effectively reversed, but the optimization of fossil energy utilization efficiency is still not obvious, and there is still a large space to curb carbon emissions by improving fossil energy utilization efficiency in the future.

According to the conclusions, we put forward the following policy recommendations on CO₂ emissions reduction. (1) The growth of CO₂ emissions mainly came from the combustion of high-carbon energy represented by raw coal and washed coal on the supply-side; On the contrary, natural gas, as a clean energy, played a less promotive role. Therefore, it was suggested to further decrease (increase) the supply of high-carbon (low-carbon) energy so as to optimize the energy structure (2) The power sector, heavy industry, fossil energy sector, chemical industry and transportation industry belonged to the industry with larger carbon emissions, while agriculture, construction, service industry and light industry belonged to the industry with smaller carbon emissions. Naturally, the Chinese government should focus on emissions reduction in enterprises with large carbon emissions such as the power sector, heavy industry, fossil energy and other sectors. Especial for the fossil energy sector and the chemical industry, their growth of energy-related CO₂ emissions had not decreased but had increased. Therefore, the follow-up emission reduction work needed to guide the two industries to increase the intensity of emission reduction through policies. (3) Because the efficiency of carbon emission from the primary and tertiary industries was prior to that of the secondary industries. It was necessary to further increase the structural proportion of services and agriculture sectors, and reduce the structural proportion of fossil energy sector and heavy industry in the secondary industry in industrial structure. (4) Since energy intensity effect and input structure effect are the main ways for China to reduce emissions in the long-term, it is the main entry point for future industrial emission reduction to actively upgrade and innovate energy use technologies and improve energy utilization efficiency.

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Investigation: Shuangqi Li.

Methodology: Yan Ma.

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Resources: Tangyang Jiang.

Software: Zhe Song.

Supervision: Yan Ma, Zhe Song, Shuangqi Li, Tangyang Jiang.

Validation: Shuangqi Li, Tangyang Jiang.

Visualization: Zhe Song.

Writing – original draft: Shuangqi Li, Tangyang Jiang.

Writing – review & editing: Yan Ma.

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