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Abstract: The global greenhouse effect caused by excessive energy CO₂ emissions has seriously affected the sustainable development of the society, and energy consumption and production mainly come from industrial system and energy system. This paper used the structural decomposition analysis (SDA) and the input-output analysis to study the structural emission reduction of China's industrial and energy systems in 2007-2015. The results showed that: (1) From the analysis of structural factors, the final demand effect was the main factor to promote the growth of energy CO₂ emissions, and the energy intensity effect played a weak role in promoting the growth of energy CO₂ emissions. (2) From the perspective of energy systems, the emission reduction effect of blast furnace gas, raw coal, refinery dry gas and natural gas is obvious, while that of crude oil, gasoline, fuel oil and kerosene is not obvious. (3) From the perspective of China's industrial systems, the tertiary industry played a major role in the final demand effect, followed by secondary industries and the primary industry in turn. Finally, this paper provided a theoretical basis and realistic guiding route for the accurate and efficient emissions reduction of energy system and China's industrial system.

Keywords: Emission reduction; Energy system; Industrial system; SDA; Input-output

1 Introduction

At present, the negative environmental problem caused by human production activities has aroused widespread concern, especially for global warming caused by excessive CO₂ emissions (Henson et al., 2017). In 2019, the international energy agency (IEA) conducted a preliminary estimate of global carbon emissions for 2018, and pointed out that the increase in global carbon emissions was about 1.7% in 2018. This is a further growth followed by a slight increase (1.4%) for 2017 in global carbon emissions. Among them, carbon emissions from China accounted for 28.61% of global CO₂ emissions, and increased by about 2.5%. At the same time, carbon emissions from the United States accounted for 14.75% of global CO₂ emissions, and increased by 3.1% (Jiang et al., 2019). It can be concluded that controlling excessive carbon dioxide emissions is a good way to mitigate the greenhouse effect and protect the ecological environment.

In China, the sources of CO₂ emissions could be energy consumption (Liu et al., 2020), cement production processes (Liu et al., 2015) and biomass decomposition (Duan et al., 2017). According to statistics, China's carbon dioxide emissions were mainly derived from energy-related carbon emissions (Xu et al., 2014; Li and Sun,

2018). Naturally, the emphasis of controlling China's excessive CO₂ falls on CO₂ emissions from energy combustion. In order to control CO₂ emissions, the China's government actively participated in international activities (Zhang et al., 2017; Sundblad et al., 2014; Jiang and Green, 2017). For example, the China's government officially announced that the carbon emissions intensity of GDP by 2020 will be 40%-45% lower than that of 2005 at the Copenhagen Climate Conference in 2009 (Risinger, 2009). In 2014, China's government made a commitment at the APEC Conference that CO₂ emissions peaked around 2030 and would strive to reach an early peak; The CO₂ emission per unit GDP in 2030 decreased by 60%-65% compared with 2005; Non-fossil energy accounted for about 20% of primary energy consumption (Xie et al., 2017).

If the China's government wants to implement carbon emission reduction more effectively, it needs to start with the following two aspects. On the one hand, we must clarify the actual situation of energy CO₂ emissions reduction in China. On the other hand, we should learn from the past experience and shortcomings in energy CO₂ emissions reduction by quantitative analysis from historical data. For the first issue, on the supply-side, CO₂ emissions are mainly derived from energy combustion in energy systems; on the demand-side, CO₂ emissions are mainly derived from energy consumption of the production process in China's industries. Therefore, the China's industry and energy system are the key points for energy-related CO₂ emissions reduction. For the second issue, it is necessary to carry out a study on the evolution of CO₂ emissions in China's industrial and energy systems in the past, and to analyze the positive and negative factors that affect energy CO₂ emissions reduction. Therefore, solving these two problems in theory will help to reduce energy CO₂ emissions more effectively and accurately in practice.

There are two main decomposition methods. One is the index decomposition analysis (IDA) and the other is the SDA. The biggest difference between SDA and IDA is that the former is based on the input-output table, while the latter only needs to use the departmental aggregate data. Hoekstra et al. (2003) compared SDA and IDA in terms of applicable conditions. They believed that compared to IDA, SDA had higher requirements for data, which is its main disadvantage. However, the main advantage of SDA is that it can comprehensively analyze various direct or indirect influence factors through the input-output model, especially the indirect impact of changes in demand of one department on other departments, which IDA does not have. Therefore, SDA has become an common tool in the economic, social, resource and environmental fields.

Taking the study of China as an example, many scholars have adopted this method to study the issue of emission reduction in 2019. Wang et al. (2019) applied this method to study the issue on emission reduction in China's power industry. Wu et al. (2020) used a new spatial-temporal structure decomposition analysis (ST-SDA) method to identify the driving factors of CO₂ emissions at provinces level in China. By analyzing the existing literature about China's emission reduction, we found that most of the studies only give the impact of total energy structure effects and final demand effects on carbon emissions. There is no relevant literature to study the effects of various energy changes in the energy system and the impact of changes in various industrial systems on the growth of energy CO₂ emissions.

Based on the above analysis, this paper was devoted to the actual settlement of energy carbon emission reduction in energy system on the supply-side and China's industrial system on the demand-side, and then used the SDA and the input-output method to structurally decompose energy CO₂ emissions from 2007 to 2015. And the factors affecting carbon emissions reduction, the effects of various energy changes in the energy system to reduce emissions, and the impact of changes in various industrial systems on the growth of energy CO₂ emissions were derived. The research results showed that from the analysis of energy system, the emission reduction effect of blast furnace gas, raw coal, refinery dry gas and natural gas is obvious, while that of crude oil, gasoline, fuel oil and kerosene is not obvious, so the robustness of low-carbon energy emission reduction is generally better than that of high-carbon energy. From the analysis of industrial systems, the tertiary industry played a major role in the final demand effect, followed by secondary industries and the primary industry in turn. Moreover, the power sector is the only sector that did not play a role of increasing carbon emissions in the demand effect. So this paper provided a theoretical basis and realistic guiding route for the accurate and efficient emissions reduction of energy system and China's industrial system. The rest of the paper was as follows: The second part was the review and summary of the literature on energy CO₂ emission reduction. The third part introduced the SDA construction and data source. The fourth part was the result and analysis of structural carbon emissions reduction in energy systems and China's industries. The fifth part gave the conclusions and policy recommendations for energy structural emission reduction.

2 Literature

After sorting and summarizing the references on energy CO₂ emissions reduction

at home and abroad, we found that CO₂ emission reductions mainly came from the following two perspectives (Zhang, 2010; Poortinga et al., 2012; Liu and Liu, 2017). One is the energy supply-side, another is the energy demand-side.

2.1 The perspective of the supply-side

On the supply-side, many scholars have studied the issue on China's energy CO₂ emissions reduction (Shrestha and Marpaung, 2005; Wang et al., 2017; Ko et al., 2013), which can be divided into two categories. The first category for carbon emissions reduction research concluded that the optimization of energy structure, such as reducing the proportion of high-carbon energy use (Lei et al., 2013) and increasing the proportion of clean energy use, was conducive to realizing carbon emissions reduction (Lee, 2013). In order to control CO₂ emissions and achieve sustainable development in China, we need to learn from developed country experience in energy use, structural adjustment and energy conservation (Lang et al., 2004). With the largest rural population, carbon emissions from rural energy consumption are a serious problem in China, Li et al. (2014) analyzed the impact of adjusting the structure of energy consumption on the reduction of CO₂ emissions in rural areas through the development of renewable energy. Using the nonlinear dynamics theory, Fang et al. (2017) studied the impact of energy consumption adjustment on the dynamic evolution of emission-reduction and energy-saving. The results showed that the structure of energy consumption adjustment could effectively reduce the energy intensity.

The second category for carbon emissions reduction research also draw a conclusion that improving energy efficiency or carbon emission efficiency through energy technology updates (Wang et al., 2017) and energy management innovations (Jaccard et al., 1997) can help reducing carbon emissions. In the US, Koomey et al. (1997) found that the use of more energy-efficient technologies could significantly reduce greenhouse gas emissions while netting down the total energy services costs. Osgood et al. (2011) had conducted the research on water and wastewater treatment facilities, and found that improving the energy efficiency of existing systems through technology upgrades could effectively reduce energy costs, dependence on carbon-based energy and greenhouse gas emissions. As steel manufacturing was one of the most energy intensive industries, Hasanbeigi et al. (2014) consolidated 12 alternative emerging iron manufacturing technologies, which aimed at providing information on energy savings, environmental and other benefits.

According to the analysis of literature about carbon emission reduction from the

perspective of the supply-side, we can conclude that many literature have studied the impact of energy intensity changes and energy structure changes on carbon emissions. However, there are few literature to analyze the impact of specific energy changes on CO₂ emissions reduction in energy systems.

2.2 The perspective of the demand-side

On the energy demand-side, many scholars have also studied the issue on China's emissions reduction (Zhang and, Da, 2015; Wu and Wang, 2020), which could be divided into two kinds. One kind of research on carbon emissions reduction was from the view of intermediate use, which was based on energy consumption for the enterprise (Gao et al., 2009; Shi et al., 2012). As the power industry was a key energy consumption industry, Liu et al.(2012) studied the impact of industrial structure, power structure, energy conservation policies and technological advances on CO₂ emissions in power industries in Chongqing. The research results showed that energy-saving technology and the power industry industrial structure optimization had a greater impact on carbon emissions, and the potential of power structure optimization to reduce carbon emissions was limited by water and heat resources. For CO₂ emissions from food industries, Lin and Lei(2015) used a Logarithmic Mean Divisia Index to study the drivers of carbon emissions growth in food industries. Their results indicated that energy intensity reduction was the major driving factor for reducing carbon emissions growth. Since the metallurgical industry needs to use a large amount of energy, it is meaningful to analyze CO₂ emissions reduction in metallurgical industries. Wu et al.(2019) estimated the CO₂ emissions in China's industrial sector during 2010-2016 to uncover the reasons for the emissions stagnancy. The research results showed iron & steel and nonmetal sectors accounted for most reduced emissions in China's industrial sectors during 2014-2016. An et al.(2018) found that in China's steel industry, the elimination of outdated production capacity, adjustment of production structure, shifting to clean combustion and promotion of low-carbon emission technology were beneficial to reduce CO₂ emissions and to save energy in steel industry.

The other kind of research on CO₂ emissions reduction was from the perspective of final use, which was based on energy consumption for the residents and government (Krey et al., 2012; Fan et al., 2013). On the basis of the life cycle analysis, Zhi and Gao(2009) analyzed the impact of China's residents on carbon emissions from food consumption between 1990 and 2006. Their research showed that the China's carbon footprint was increasing due to food consumption, and the direct impact of China food

consumption on CO₂ emission was just a small share of the total carbon emissions from the perspective of the life cycle of food consumption, and food transportation contributed about 30% CO₂ emissions. Taking Guangzhou as an example, Zeng (2011) used contingent valuation method to analyze the Chinese urban resident's willingness to pay for CO₂ emission reductions, and found that the education level of urban residents, the annual per capital income of the family, the type of work, the city location, the awareness level of climate change and the environmental awareness were closely related to the original intentional emission reduction. Based on the data of Guizhou Province from 2001 to 2014, Zheng (2017) used the CO₂ emission coefficient analysis to measure the dynamic changes of indirect and direct CO₂ emissions from the energy consumption in Guizhou Province. The results showed that the CO₂ emissions from residential energy consumption were generally on the rise, while the growth rate of carbon emissions from direct energy consumption was higher than that from indirect energy consumption.

According to the analysis of literature about carbon emissions reduction from the perspective of the demand-side, we can conclude that many literature have studied the impact of final demand effects on carbon emissions. However, there are few literature to analyze the impact of changes in demand of various industries on carbon emissions growth in the industrial system.

2.3 Academic contributions

Compared with the existing literature, the contributions of this paper were reflected in the following three points. First, it compensated for the incompleteness of research on energy CO₂ emissions reduction from a single perspective of the supply-side or the demand-side, and set the actual foothold of CO₂ emissions reduction on China's industries and energy systems. Second, for the energy system on the supply-side, based on the analysis of the energy structure effect, we further made qualitative and quantitative analysis for the impact of specific energy changes on CO₂ emissions reduction in energy systems, which was not covered by previous research literature. Third, for the China's industrial system on the demand-side, on the basis of analyzing the final demand effect, we further qualitatively and quantitatively analyzed the impact of changes in demand of various industries on carbon emissions growth in the industrial system, which was not covered in previous research literature.

3 Data and model

3.1 Data sources

The main data used in the paper mainly included China's input-output tables for 2015, 2012, 2010 and 2007 and China's energy balance tables for 2015, 2012, 2010 and 2007. The latest input-output table was updated to 2015. The input-output table was updated every five years or three years, which led to input-output tables selected in the paper were not continuous. In addition, since the input-output table contains 42 sectors, we merged 42 sectors into 9 sectors to facilitate the expression of follow-up research results (Yu et al., 2020). The detailed information of merging was shown in Fig.1 (Jiang et al., 2019).

Fig. 1 The sector classification

3.2 Model construction and calculation

It should be noted that in the process of SDA construction, we extended the standard SDA in this paper. The expanded SDA model can analyze the effects of various energy changes in the energy system and the impact of changes in various industrial systems on the growth of energy CO₂ emissions. This is also an important contribution of this paper.

3.2.1 Input-output model

Input-output analysis depicts the complex interdependence between economic sectors, which links commodity production with commodity exchange between economic sectors. In terms of carbon emissions, input-output analysis has also been widely used to measure indirect and direct CO₂ emissions from various sectors. In input-output tables, the direct consumption coefficient matrix can be set as follows.

$$A = [A_{ij}], A_{ij} = \frac{X_{ij}}{X_j} \quad (1)$$

where A is the direct consumption coefficient matrix, A_{ij} is the amount of input required by the sector i for marginal output value of the sector j . If vector $X = [X_j]$ is the total output of the sector j , $X = [X_{ij}]$ is the intermediate input matrix of sector i to sector j , $Y = [Y_j]$ is final demand of sector j , the total output vector can be expressed as the following equation.

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

$$AX + Y = X \quad (3)$$

$$X = (I - A)^{-1} Y \quad (4)$$

where I is the unit matrix, $L = (I - A)^{-1}$ is the Leontief inverse matrix.

3.2.2 SDA of energy system and China's industry carbon emission structure

In the input-output model, fossil energy generates carbon emissions by investing in national production. According to China's Energy Statistics Yearbook, the energy sources that generate carbon emissions mainly include energy combustion for thermal

power generation, energy combustion for heating supply and energy consumption for final demand. However, it should be noted that not all energy sources are used for combustion in the final energy consumption sector, some of which are used as industrial raw materials to participate in production. This part does not produce carbon emissions, so it needs to be eliminated. The calculating formula for the combustion of energy k is as follows.

$$E_k = E_k^T + E_k^P + E_k^H - E_k^M \quad (5)$$

where the final energy consumption of energy k for combustion is E_k^T , energy k combustion for thermal power generation is E_k^P , energy k combustion for heating supply is E_k^H , energy consumption of energy k for industrial raw materials is E_k^M . Next, the consumption of each energy source needs to be converted into standard coal consumption. The conversion formula is as follows.

$$C_k = E_k \times e_k \quad (6)$$

where e_k the conversion coefficient of energy k converted into standard coal, C_k is the equivalent amount of standard coal obtained from the conversion coefficient of standard coal for energy k . If the carbon emission coefficient per unit heat of energy k is P_k , and the low calorific value of energy k for combustion is Q_k , the CO₂ emission coefficient f_k of per unit energy k for combustion can be calculate according the following formula.

$$f_k = P_k \times Q_k \quad (7)$$

Let $F=[f_k]$ be the carbon dioxide emission coefficient matrix, $S=[s_{ik}]$ be the energy consumption structure matrix (The energy consumption proportion of energy k in the total energy consumption in sector i), $I=[i_i]$ be the energy consumption intensity matrix (the ratio of the total output to the total energy consumption in sector i). The energy consumption structure matrix $S=[s_{ik}]$ and the energy consumption intensity matrix $I=[i_i]$ can be obtained as follows.

$$S = \begin{pmatrix} \frac{C_{11}}{\sum_{k=1}^m C_{1k}} & \frac{C_{12}}{\sum_{k=1}^m C_{1k}} & \dots & \frac{C_{1n}}{\sum_{k=1}^m C_{1k}} \\ \frac{C_{21}}{\sum_{k=1}^m C_{2k}} & \frac{C_{22}}{\sum_{k=1}^m C_{2k}} & \dots & \frac{C_{2n}}{\sum_{k=1}^m C_{2k}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{C_{i1}}{\sum_{k=1}^m C_{ik}} & \frac{C_{i2}}{\sum_{k=1}^m C_{ik}} & \dots & \frac{C_{in}}{\sum_{k=1}^m C_{ik}} \end{pmatrix}, \quad I_{n \times n} = \begin{pmatrix} \frac{\sum_{k=1}^m C_{1k}}{Y_1} & 0 & \dots & 0 \\ 0 & \frac{\sum_{k=1}^m C_{2k}}{Y_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \frac{\sum_{k=1}^m C_{nk}}{Y_n} \end{pmatrix} \quad (8)$$

where C_{ik} is energy consumption of energy k in sector i . The calculation formulas of carbon emissions from k energy consumption and the total carbon emissions from energy consumption of m types of energy resources in sector i can be expressed as follows.

$$E_{ik} = f_k \times C_{ik} = \frac{E_{ik}}{C_{ik}} \times C_{ik}, i = 1, 2, \dots, n; k = 1, 2, \dots, m. \quad (9)$$

$$E_{ik} = \frac{E_{ik}}{C_{ik}} \times \frac{C_{ik}}{C_i} \times \frac{C_i}{X_i} \times X_i, i = 1, 2, \dots, n, j = 1, 2, \dots, m \quad (10)$$

$$E_{ik} = \frac{E_{ik}}{C_{ik}} \times \frac{C_{ik}}{C_i} \times \frac{C_i}{X_i} \times (I - A)^{-1} Y_i, i = 1, 2, \dots, n, j = 1, 2, \dots, m \quad (11)$$

$$E_i = \sum_{k=1}^m E_{ik} \quad (12)$$

where E_{ik} is the CO₂ emissions from consumption of energy k in sector i , E_i is the total carbon emissions from energy consumption of m types of energy resources in sector i . The IO-SDA of CO₂ emissions from China's industries and energy systems and the formula for the change of total CO₂ emissions are as follows.

$$E_h = \sum_{k=1}^m \frac{E_{hk}}{C_{hk}} \times \frac{C_{hk}}{C_h} \times \frac{C_h}{X_h} \times (I - A)^{-1} Y_h = FSILY \quad (13)$$

$$\Delta E_h = FS_t I_t L_t Y_t - FS_{t-1} I_{t-1} L_{t-1} Y_{t-1} \quad (14)$$

$$\begin{aligned} \Delta E_h = & \underbrace{\frac{1}{2}(F_t I_t L_t Y_t - F_{t-1} I_{t-1} L_{t-1} Y_{t-1}) \Delta S}_{\text{energy structure effect}} + \underbrace{\frac{1}{2}(F_t S_t L_t Y_t - F_{t-1} S_{t-1} L_{t-1} Y_{t-1}) \Delta I}_{\text{energy intensity effect}} \\ & + \underbrace{\frac{1}{2}(F_t S_t I_t Y_t - F_{t-1} S_{t-1} I_{t-1} Y_{t-1}) \Delta L}_{\text{input structure effect}} + \underbrace{\frac{1}{2}(F_t S_t I_t L_t - F_{t-1} S_{t-1} I_{t-1} L_{t-1}) \Delta Y}_{\text{final demand effect}} \end{aligned} \quad (15)$$

$$\Delta E_h = \Delta E_s + \Delta E_l + \Delta E_L + \Delta E_Y \quad (16)$$

$$\Delta E_s = \frac{1}{2}(FI_t L_t Y_t + FI_{t-1} L_{t-1} Y_{t-1}) \Delta S \quad (17)$$

$$\Delta E_l = \frac{1}{2}(FS_t L_t Y_t + FS_{t-1} L_{t-1} Y_{t-1}) \Delta I \quad (18)$$

$$\Delta E_L = \frac{1}{2}(FS_t I_t Y_t + FS_{t-1} I_{t-1} Y_{t-1}) \Delta L \quad (19)$$

$$\Delta E_U = \frac{1}{2}(FS_t I_t L_t + FS_{t-1} I_{t-1} L_{t-1}) \Delta Y \quad (20)$$

where ΔE_s reflects the change of total carbon emissions caused by the change of energy consumption structure, ΔE_l reflects the change of total carbon emissions caused by the change of direct energy consumption intensity, ΔE_L reflects the change of total carbon dioxide emission caused by the change of input structure effect, ΔE_Y reflects the change of total carbon emissions caused by the change of final product demand. Finally, the impact of each energy change in the energy system and various industries changes in the industrial system on carbon emission are analyzed. The formulas are as follows.

$$EP_k = \frac{\Delta C_k}{\sum_{k=1}^m \Delta C_k} \times \Delta E_s \quad (21)$$

$$FDP_j = \frac{\Delta Y_j}{\sum_{j=1}^m \Delta Y_j} \times \Delta E_Y \quad (22)$$

$$\Delta C_k = C_{t,k} - C_{t-1,k}, \Delta Y_j = Y_{t,j} - Y_{t-1,j} \quad (23)$$

where EP_k is carbon emissions reduction of each energy in energy system based on energy structural effects, FDP_j is carbon emissions growth of various industries' demand change in China's industrial system based on the final demand effect. ΔC_k is consumption changes for energy k , $C_{t-1,k}$ is the consumption of energy k in $t-1$ period, $C_{t,k}$ is the consumption of energy k in t period; ΔY_j is the demand change of sector j , $Y_{t-1,j}$ is the demand change of sector j in $t-1$ period, $Y_{t,k}$ is the demand change of sector j in t period.

4 Result and analysis

4.1 Carbon emission result and analysis based on SDA

The results of four factors affecting the growth of energy CO₂ emissions were shown in Table 1 (10,000 tons), Fig.2, Fig.3, Fig.4 and Fig.5.

Table 1

The impact of four effects on the growth of energy CO₂ emissions in 2007-2015

Effects	The effects on the growth of energy CO ₂ emissions			
	2007-2010	2010-2012	2012-2015	2007-2015
Energy structure effect	-23721.46	2175.64	-122172.87	-145751.20
Energy intensity effect	-153059.16	-37482.61	266425.62	9300.03
Input structure effect	73547.23	-155338.82	-580830.23	-612899.63
Final demand effect	291292.54	325889.93	658060.78	1274340.97
Error	-752.53	248.56	-5242.08	14050.38
Total effect	187306.62	135492.70	216241.23	539040.56

339

340

341 **Fig. 2** The share of four effects to carbon emission growth in 2007-2015

342

343 Table 1 showed the impact of four effects on the growth of energy CO₂ emissions
344 in each period of 2007-2015. It could be seen that the positive and negative effects and
345 strengths of the four effects on the growth of energy CO₂ emissions are different at
346 different stages. As shown in Fig.2, overall, the final demand effect was the main factor
347 driving China's energy CO₂ emissions growth from 2007 to 2015, which increased
348 energy CO₂ emissions by 12.743 billion tons, accounting for 236.41% of the total effect.
349 Secondly, the energy intensity effect had a slight stimulating effect on energy CO₂
350 emission growth, which increased energy CO₂ emissions by 93 million tons, accounting
351 for 1.73% of the total effect. Energy structure effect and input structure effect had
352 restraints on China's energy carbon emission growth. These two effects showed an
353 increasing trend over time for China's energy carbon emission reduction. For these two

emission reduction factors, input structure effect was the main determinant of China's energy emission reduction, which increased energy CO₂ emissions by -6.128 billion tons, accounting for -113.70% of the total effect, while energy structure effect had a limited effect on energy carbon emission reduction, resulting in an increase in CO₂ emissions by -1.457 billion tons (accounting for -27.04% of the total effect). Next, we made a detailed analysis of the impact of four effects on the growth of China's energy CO₂ emissions at different time stages in 2007-2015.

Fig. 3 The share of four effects to carbon emission growth in 2007-2010

As shown in Fig.3, from 2007 to 2010, energy structure effect and energy intensity effect restrained China's energy CO₂ emission growth. Specifically, the energy intensity effect increased energy CO₂ emissions by -1.530 billion tons, reaching -81.72% of the total effect; the energy structure effect increased energy CO₂ emissions by -237 million tons, reaching - 12.66% of the total effect; the final demand effect and input structure effect promoted the growth of energy CO₂ emissions. The final demand effect increased energy CO₂ emissions by 2.912 billion tons, reaching 155.52% of the total effect; the input structure effect increased energy CO₂ emissions by 735 million tons, reaching 39.27% of the total effect. We could concluded that from 2007 to 2010, among these four factors, the energy intensity effect was the main emission reduction factor of energy CO₂ emissions growth, and the final demand effect was the main driving factor

to promote energy CO₂ emissions growth.

Fig.4 The share of four effects to carbon emission growth in 2010-2012

As was shown in Fig.4, in 2010-2012, input structure effect and energy intensity effect restrained energy CO₂ emission growth. The input structure effect had increased energy CO₂ emissions by -1.553 billion tons, reaching -114.65% of the total effect; the energy intensity effect had increased China's energy CO₂ emissions by -374 million tons, reaching -27.66% of the total effect. Final demand effect and energy structure effect promoted China's energy carbon emission growth. The final demand effect increased China's energy CO₂ emissions by 3.258 billion tons, reaching 240.52% of the total effect; the energy structure effect increased China's energy CO₂ emissions by 21.75 million tons, reaching 1.61% of the total effect. From 2010 to 2012, among these four factors, the input structure effect was the main emission reduction factor of energy CO₂ emissions growth, and the final demand effect was the main driving factor to promote energy CO₂ emissions growth.

Fig.5 The share of four effects to carbon emission growth in 2012-2015

As shown in Fig.5, in 2012-2015, energy structure effect and input structure effect restrained China's energy CO₂ emission growth. Among them, the input structure effect increased energy CO₂ emissions by -5.80 billion tons, reaching -268.60% of the total effect; the energy structure effect increased energy CO₂ emissions by -1.221 billion tons, reaching -56.50% of the total effect. The final demand effect and energy intensity effect could promote the growth of energy CO₂ emissions. The final demand effect increased energy CO₂ emissions by 6.580 billion tons, reaching 304.32% of the total effect; the input structure effect increased energy CO₂ emissions by 2.664 billion tons, reaching 123.21% of the total effect. Thus, from 2012 to 2015, among the four factors, input effect was the main emission reduction factor of China's energy CO₂ emissions growth, while ultimate demand effect was the main driving factor to promote energy CO₂ emissions growth.

On the whole, from 2007 to 2015, the input structure effect and energy structure effect had significant effects on China's energy carbon emission reduction, and the degree of carbon emission reduction effect was on the rise; while the final demand effect played a decisive leading role in energy CO₂ emissions increase, and the driving role of CO₂ emissions growth was getting stronger and stronger. At the same time, the energy intensity effect had a slight stimulating effect on the increase of China's energy CO₂ emissions. It should be noted that from the perspective of emission reduction

means, energy intensity effect and input structure effect were important means of achieving emission reductions in long-term, while final demand and energy structure adjustment could mitigate carbon emissions growth in the short term.

4.2 Analysis of emission reduction mechanism based on energy intensity effect

The energy intensity coefficient (unit: ton/10000 yuan) and the change of energy intensity coefficient of China's industry in 2007-2015 were shown in Tables 2 and Fig.6.

Table2

Energy Consumption Intensity Coefficient of China's Industry in 2007-2015

Year	2007	2010	2012	2015
Energy intensity Coefficient	6.28	5.36	5.19	6.32

Fig.6 Change of Energy Consumption Intensity Coefficient in 2007-2015

Table 2 presented the energy intensity coefficient of China's industries from 2007 to 2015. Fig.6 showed the change of energy intensity coefficient from 2007 to 2015. It could be seen that except for 2012-2015, the energy intensity effect coefficient had been showing a downward trend. In 2007-2010, the energy intensity coefficient declined the most, and in 2010-2012, the decline coefficient was smaller. This explains that the energy intensity effect had been reducing energy CO₂ emissions in other time ranges except 2012-2015. Among them, the energy intensity effect in 2007-2010 had the

greatest emission reduction effect, while the energy intensity effect in 2010-2012 had a smaller emission reduction effect, and the energy intensity effect in 2012-2015 had a positive role in promoting the growth of energy CO₂ emissions. The above analysis showed that the reduction of energy intensity coefficient was the cause of energy intensity effect on emission reduction, and the greater decline in energy intensity coefficient was, the greater the emissions reduction effect appeared.

4.3 Analysis of emission reduction mechanism based on energy structure effect

The consumption increment of each type of energy for combustion (converting standard coal)) on the energy supply-side in 2007-2015 was calculated as shown in Table 3 (unit: 10,000 tons). The proportion of each energy consumption structure on the energy supply-side in 2007-2015 was shown in Table 4.

Table 3

Energy consumption increments in 2007-2015

Kinds of energy	2007-2010	2010-2012	2012-2015
Raw Coal	30167.60	22182.65	13436.03
Cleaned Coal	293.05	219.83	2346.50
Other Washed Coal	374.40	102.16	868.00
Briquettes	-56.64	4.05	515.80
Coke	3249.38	5370.72	4430.67
Coke Oven Gas	954.43	418.36	71.65
Blast Furnace Gas	29093.56	2171.15	66580.98
Converter Gas	437.70	248.61	190.49
Other Gas	-13367.38	-451.24	243.61
Other Coking Products	273.42	147.84	-132.81
Crude Oil	-234.07	-302.96	246.22
Gasoline	2006.07	1851.25	4762.32
Kerosene	740.07	316.63	1037.59
Diesel Oil	3160.39	3358.44	499.55
Fuel Oil	-1754.60	-607.35	-163.76
LPG	-257.95	250.70	1848.43
Refinery Gas	5203.38	1929.05	3912.00
Other Petroleum Products	-1589.08	-618.19	-316.62
Natural Gas	2964.28	3319.08	4528.15
LNG	1394.72	810.77	1814.08

Table 4

Proportion of energy consumption structure in 2007-2015

Kinds of energy	2007	2010	2012	2015
Raw Coal	53.27%	52.21%	52.46%	43.41%
Cleaned Coal	0.73%	0.68%	0.66%	1.01%
Other Washed Coal	1.31%	1.17%	1.07%	1.01%
Briquettes	0.26%	0.19%	0.17%	0.24%
Coke	10.81%	9.70%	10.09%	8.74%
Coke Oven Gas	1.35%	1.38%	1.34%	1.05%
Blast Furnace Gas	0.00%	9.02%	8.60%	20.81%
Converter Gas	0.00%	0.14%	0.19%	0.19%
Other Gas	6.25%	0.89%	0.66%	0.57%
Other Coking Products	0.23%	0.27%	0.28%	0.19%
Crude Oil	0.48%	0.31%	0.19%	0.20%
Gasoline	3.12%	3.13%	3.29%	3.56%
Kerosene	0.70%	0.79%	0.79%	0.83%
Diesel Oil	7.00%	6.61%	6.79%	5.36%
Fuel Oil	2.18%	1.21%	0.91%	0.67%
LPG	1.50%	1.13%	1.07%	1.22%
Refinery Gas	6.18%	6.59%	6.38%	5.76%
Other Petroleum Products	1.92%	1.05%	0.76%	0.52%
Natural Gas	2.72%	3.11%	3.68%	3.80%
LNG	0.00%	0.43%	0.61%	0.86%

Analysis of Table 3 showed that consumption of high-carbon energy represented by raw coal exhibited a decrease or negative growth, while the consumption of low-carbon energy represented by natural gas and blast furnace gas was increasing continuously. This also explained well that in Table 4, the proportion of high-carbon energy structures represented by fuel oil, crude oil, raw coal and diesel showed a downward trend, while the proportion of low-carbon energy structure represented by natural gas, blast furnace gas and converter gas showed an upward trend. We could conclude that the energy structure effect exerted the emission reduction effect due to the continuous optimization of energy consumption structure on the supply-side.

Next, we analyzed the impact of energy structure changes on carbon emission growth in different time periods from 2007 to 2015. The results of the changes in energy structure on carbon emission growth were shown in Table 5 (10,000 tons). The share of each type of energy in the energy structure effect was shown in Fig.7.

Table 5

469 Energy emission reductions in 2007-2015

Kinds of energy	2007-2010	2010-2012	2012-2015	2007-2015
Raw Coal	-11350.72	1185.07	-15381.56	-45547.25
Cleaned Coal	-109.12	11.75	-2687.80	-1982.22
Other Washed Coal	-139.96	5.44	-989.60	-932.81
Briquettes	21.35	0.22	-586.43	-320.65
Coke	-1221.66	286.97	-5070.17	-9036.57
Coke Oven Gas	-358.19	22.41	-85.52	-1005.68
Blast Furnace Gas	-10945.08	115.96	-76223.65	-67745.16
Converter Gas	-163.68	13.27	-219.91	-612.16
Other Gas	5028.95	-24.15	-281.00	9400.95
Other Coking Products	-102.00	7.83	146.61	-204.05
Crude Oil	87.77	-16.10	-281.00	204.05
Gasoline	-754.34	98.99	-5448.91	-5961.22
Kerosene	-277.54	16.97	-1185.08	-1442.94
Diesel Oil	-1188.45	179.49	-574.21	-4853.51
Fuel Oil	659.46	-32.42	183.26	1749.01
LPG	97.26	13.49	-2113.59	-1268.04
Refinery Gas	-1957.02	103.13	-4483.74	-7651.94
Other Petroleum Products	597.78	-33.07	366.52	1749.01
Natural Gas	-1114.91	177.32	-5180.13	-7491.61
LNG	-524.24	43.30	-2076.94	-2783.85

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Fig.7 Share of each energy in energy structure effect

From the perspective of energy structure and time, the analysis from Table 5 and Fig.7 showed that the positive and negative effects of different energy sources on fossil energy CO₂ emissions growth were different in different stages of 2007-2015. In 2007-2010, the energy structure changes such as raw coal, blast furnace gas, refinery dry gas, coke, diesel and natural gas had emissions reduction effects on the growth of fossil energy CO₂ emissions, while the energy structure changes such as briquette, crude oil and other gas had no emission reduction effect on the growth of fossil energy CO₂ emissions. From 2010 to 2012, changes in energy structure such as other petroleum products, fuel oil and crude oil had no emission reduction effect on the growth of fossil energy CO₂ emissions, while changes in energy structure such as coke, natural gas, diesel, raw coal, refinery dry gas and gasoline had emission reduction effect on the growth of fossil energy CO₂ emissions. In 2012-2015, the energy structure changes such as blast furnace gas, raw coal, coke, refinery dry gas, natural gas and gasoline had emissions reduction effects on the growth of fossil energy CO₂ emissions, while the energy structure changes of other petroleum products, fuel oil and other coking products had no carbon emission reduction effects on the growth of fossil energy CO₂ emissions.

From the above analysis, we drew the following conclusions. First, from 2007 to 2015, 2012-2015 was the optimal interval for energy structure effect to reduce

emissions, followed by 2007-2010, and 2010-2012 with no emission reduction effects. Second, the energy structure changes of blast furnace gas, raw coal, coke, refinery dry gas and natural gas played a greater role in reducing emissions, while the energy structure changes of crude oil, kerosene and diesel oil played a weaker role in reducing emissions. Third, the soundness of low-carbon energy (other gas and natural gas, etc.) to reduce emissions was generally stronger than that of high-carbon energy reduction (gasoline, kerosene and diesel).

4.4 Analysis of emission reduction mechanism based on final demand effect

The demand increment of various industries in China from 2007 to 2015 (adjusted as the price benchmark in 2007) was shown in Table 6 (unit: 10,000 yuan). The share of the changes in demand effects of various industries to carbon emission growth were shown in Table 7 (unit: 10,000 tons) and Fig.8. The direct consumption coefficients of fossil energy for various industries in 2007-2015 were shown in Fig.9 (tons/10,000 yuan). The degree of optimization of direct fossil energy consumption coefficients for various industries in 2007-2015 was shown in Figure 10.

Table 6

The demand increment of various industries in 2007-2015

Sector	2007-2010	2010-2012	2012-2015	2007-2015
Service Sector	448683491	421485678	807796977	1677966146
Heavy Industry	284380585.8	114992250.8	173004998.4	572377835
Light Industry	135518914.9	97356525.4	186602864.9	419478305.2
Construction Sector	319580235	242163959	697385457	1259129651
Chemical Industry	2729610.464	24942968.72	6081053	33753632.18
Agriculture Sector	-1081493.2	73023654.3	-25516222.4	46425938.7
Transportation Sector	-25387904.54	70904464.74	-11619157.7	33897402.5
Fossil Energy Sector	-41284707.6	-13559360.1	61652827.54	6808759.84
Power Sector	-174287	14006615.16	-16863554.16	-3031226.001

Table 6 showed the changes in the demand increment of various industries in different time periods from 2007 to 2015. We could see that the demand increment of various industries generally showed an increasing trend, which was a good explanation for the final demand effect generally promoting the energy CO₂ emission growth. This was because the scale of output of various industries was expanding, leading to an increase in demand for production factors (labor, capital, energy, etc.). So further there was an increasing trend in fossil energy consumption in various industries. At the same

time, from the perspective of industry, the demand increment of various industries was different, among which the demand increment of service industry was the fastest, followed by industries such as heavy industry, light industry and construction industry. However, the demand increment of power sector was negative. Next, we specifically analyzed the contribution of each industry demand increment to the growth of fossil energy CO₂ emissions from 2007 to 2015.

Table 7

The impact of industrial demand changes on carbon emissions growth

Sector	2007-2010	2010-2012	2012-2015	2007-2015
Agriculture Sector	-280.54	22765.99	-8938.51	14619.55
Fossil Energy Sector	-10709.09	-4227.29	21597.42	2144.08
Light Industry	35153.07	30352.05	65368.31	132093.89
Power Sector	-45.21	4366.73	-5907.42	-954.53
Heavy Industry	73767.20	35850.20	60604.88	180242.01
Chemical Industry	708.05	7776.27	2130.24	10629.03
Construction Sector	82897.85	75497.49	244299.09	396500.43
Transportation Sector	-6585.52	22105.31	-4070.27	10674.31
Service Sector	116386.72	131403.17	282977.04	528392.21
Total	291292.54	325889.93	658060.78	1274340.97

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Fig.8 Share of each industry to the final demand effect

Table 7 and Figure 8 showed the impact of China's industrial demand changes on carbon emissions growth in 2007-2015. It could be concluded that the positive and negative effects and strength levels of industrial demand changes on fossil energy CO₂ emissions growth were different at different time stages. Among them, in 2007-2010, service industry, construction industry, heavy industry and light industry played a major role in promoting carbon emission growth, while fossil energy, transportation, agriculture and power sectors did not promote carbon emissions growth. From 2010 to 2012, service industry, construction industry, heavy industry, light industry and agriculture played a major role in promoting carbon emission growth, while the fossil energy sector did not promote carbon emissions growth. In 2012-2015, service industry, construction industry, light industry and heavy industry played a major role in promoting CO₂ emissions growth, while agriculture, power sector and transportation industry did not play a role in carbon emissions growth.

Overall, from 2007 to 2015, the tertiary industry played a major role in the final demand effect, followed by the secondary industry, and the last was primary industry. At the same time, the power sector was the only sector that did not play a role in increasing CO₂ emissions in the demand effect. Next, we analyzed the direct

consumption coefficients of fossil energy for various industries from 2007 to 2015.

Fig.9 Direct consumption coefficient of fossil energy by various industries

Fig.9 showed the direct consumption coefficient of fossil energy in various industries from 2007 to 2015. It could be concluded that the direct consumption coefficients of fossil energy in various industries were different. From 2007 to 2010, the direct consumption coefficient of fossil energy was higher in fossil energy, transportation, power sector and chemical industry, while the direct consumption coefficient of fossil energy in agriculture, light industry and service industry was lower. In 2010-2012, the direct consumption coefficient of fossil energy was higher in fossil energy, transportation, chemical industry and transportation industry, while the direct consumption coefficient of fossil energy in agriculture, construction industry and light industry was lower. From 2012 to 2015, the direct consumption coefficient of fossil energy was higher in fossil energy, power sector, transportation industry and chemical industry, while the direct consumption coefficient of fossil energy in light industry, service industry and construction industry was lower.

In general, from 2007 to 2015, the direct consumption coefficient of fossil energy in the secondary industries such as fossil energy, transportation, power sector, chemical industry and heavy industry was generally higher, while the direct consumption

coefficient of fossil energy in services and agriculture was lower. This also showed that expanding the tertiary industry or the primary industry promoted the growth of CO₂ emissions less than expanding the secondary industry on the same scale. It further proved that optimizing the industrial structure was conducive to slowing down the growth of CO₂ emissions. Next, we further analyzed the optimization degree of the direct consumption coefficient of fossil energy in various industries from 2007 to 2015.

Fig.10 Optimization of direct consumption coefficient of fossil energy by various industries

Fig. 10 showed the optimum degree of direct consumption coefficient of fossil energy for each industry in 2007-2015. We could conclude that from 2007-2015, the optimum direct consumption coefficient of fossil energy for light industry, construction industry, transportation industry and service industry was very obvious; the optimum direct consumption coefficient of fossil energy for chemical industry, heavy industry and fossil energy sector was obvious; the optimum direct consumption coefficient of fossil energy for agriculture and power sector was not obvious.

5 Conclusion and Implication

We employed the input-output analysis and SDA to study structural carbon

emissions reduction of China's industries and energy systems from 2007 to 2015. Under the background of the four structural factors which affected CO₂ emissions, we studied the effects of various energy changes in the energy system and the impact of changes in various industrial systems on the growth of energy CO₂ emissions. The results showed that on the one hand, the final demand effect was the main factor driving the growth of energy CO₂ emissions from 2007 to 2015. On the one hand, the energy intensity effect had a slight stimulating effect on energy CO₂ emissions growth. However, energy structure effect and input structure effect had significant emissions reduction effects on energy CO₂ emissions growth. These two effects exhibited an increasing trend over time for energy CO₂ emissions reduction. For these two emission reduction factors, input structure effect was the main determinant of energy emission reduction, while energy structure effect has limited effect on energy emissions reduction. At the same time, for specific effects of various energy sources on carbon emissions reduction in the energy system, blast furnace gas, raw coal, refinery gas and natural gas etc. played a significant role in reducing CO₂ emissions, while crude oil, gasoline, fuel oil and kerosene etc. did not exert carbon emissions reduction effects. For specific effects of the various industries on CO₂ emissions reduction from the demand effect, the tertiary industry played a major role in the final demand effect, followed by the secondary industry and the primary industry. However, since the direct consumption coefficient of fossil energy in the tertiary industry and the primary industry was lower than that in the secondary industry, the optimization of industrial structure was conducive to mitigating the carbon emission growth caused by the demand effect.

Through the analysis of the above research results, we gave the following policy recommendations. (1) The input structure effect had the greatest effect on CO₂ emissions reduction, followed by the energy structure effect. This showed that China's long-term policy of encouraging production technology innovation had received significant positive effects. At the same time, the government's active carried out the optimization of energy consumption structure, which also had a positive impact on energy reduction. However, the optimization of energy consumption structure was still slow Therefore, it was recommended that in the short-term, the Chinese government should continue to reduce emissions by optimizing the energy consumption structure, especially for oils, gasoline and diesel that did not exert significant emissions reduction effects; in the long run, the Chinese government could mainly promote emissions reduction by encouraging technological innovation. (2) The energy intensity effect was

not obvious for carbon emissions reduction, which was mainly due to the significant slowdown of output in various sectors from 2012 to 2015. This indicated that the space for reducing emissions through optimizing energy intensity was still large in China in the future. Therefore, it was suggested that the Chinese government actively carry out the optimization and upgrading of energy technologies, especially to promote the development of low-carbon industries, and to achieve carbon emissions reduction by optimizing energy intensity in the long-term. (3) The final demand effect was the main driving factor for the increase of carbon dioxide, but the direct consumption coefficient of fossil energy in the secondary industry was generally higher than that of the primary industry and the tertiary industry. Therefore, actively carrying out industrial structure optimization and increasing the proportion of the tertiary industry structure were conducive to slowing down the growth of carbon emissions. (4) For the industrial structure, the optimization of direct consumption coefficient of fossil energy was obvious in service industry, light industry, construction industry and transportation industry, while the optimization of direct consumption coefficient of fossil energy in the fossil energy sector and power sector was not obvious, even accompanied by negative optimization phenomenon. Therefore, in the process of carrying out the emissions reduction, we needed to pay special attention to the energy-related carbon emissions reduction in these two industries, and to guide carbon emissions reduction by formulating separate policies.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

JY proposed the idea, gave the method guidance for the paper, and wrote the research background. HHD collects data and writes manuscripts. TYJ uses software to process the data and calibrate the paper. Everyone's contribution is equal. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

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

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Figures

Figure 1

The sector classification

Figure 2

The share of four effects to carbon emission growth in 2007-2015

Figure 3

The share of four effects to carbon emission growth in 2007-2010

Figure 4

The share of four effects to carbon emission growth in 2010-2012

Figure 5

The share of four effects to carbon emission growth in 2012-2015

Figure 6

Change of Energy Consumption Intensity Coefficient in 2007-2015

Figure 7

Share of each energy in energy structure effect

Figure 8

Share of each industry to the final demand effect

Figure 9

Direct consumption coefficient of fossil energy by various industries

Figure 10

Optimization of direct consumption coefficient of fossil energy by various industries