Factor analysis of energy-related carbon dioxide emissions in China from 1984 to 2006

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Abstract

On the basis of Kaya Identity, a decomposition model is built to analyze how much contribution each of eight relevant pre-defined factors makes to carbon dioxide emissions over the period 1984 to 2006 in China in the method of LMDI. The results indicate that the economic development and the decline of energy intensity are the two most important factors of the change of carbon dioxide emissions. The effect of industrial structures and that of sectoral structures are different: the former increases the carbon dioxide emissions while the latter decreases them, and the added effect of the two factors is -4.9%. In the short run the room of the decline of energy intensity caused by technology progress is smaller and smaller. The reduction of carbon dioxide emissions needs to be driven by the adjustment of industrial structure and sectoral structure, especially the adjustment toward the tertiary industry. The change of energy structure reduces the carbon dioxide emissions and the contribution is only -2.9% because the change of energy structure is small itself. Strategically, the change of energy structure is very important, especially the substitution of natural gas for coal and the change towards non-fossil energy including nuclear energy, water energy, wind energy, solar energy and so on.

Key words: carbon dioxide emission, energy consumption, decomposition model

1. Introduction

Global climate change has already become the most serious environment problem, and the scientific community has reached a consensus that it is partly caused by human activities, especially carbon dioxide emissions from combustion of fossil energy.

The proportions of energy-related carbon dioxide emissions of main countries from 1980 to 2005 are described in Fig.1. In 2005 China’s energy-related carbon dioxide emission accounts for 19% of the global amount, next to 21% of that of America.
Since 2001 the energy consumption in China has increased quickly, as shown in Fig.2, from 1.35 billion tce in 2001 to 2.65 billion tce in 2007, and the energy-related carbon dioxide emissions have also mounted up.

In recent several years, electricity, coal and oil are frequently in short supply. Chinese government proposed to decrease energy consumption per unit of GDP by 20% during the period of the 11th five-plan from 2006 to 2010. However, the decline only reached 1.33% in 2006, and 3.27%[1] in 2007.

In this paper, on the basis of Kaya Identity (1990), the current studies are first extended to quantify the contributions of more factors of changes in total energy-related carbon dioxide emissions, and then an empirical study is made on how the contributing effects have evolved over the period from 1984 to 2006 in China.

The decomposition model can be traced back to 1970s. In the debate between Ehrlich, Holdren[2] and
Commoner about the impact of human activities on environment, the IPAT Equation was put forward: \( I = PAT \), where \( I \) denotes the impact of human’s activities on environment, \( P \) denotes population, \( A \) denotes the output per capita and \( T \) represents the impact of unit output on environment, which depends on the technology.

On the basis of IPAT Equation, Kaya(1990) put forward Kaya Identity on the seminar of IPCC(Intergovernmental Panel on Climate Change): \( C = \frac{C}{E} \cdot \frac{E}{GDP} \cdot \frac{GDP}{P} \cdot P \), in which \( \frac{C}{E} \) describes the intensity of carbon dioxide emission, \( \frac{E}{GDP} \) denotes the energy intensity of GDP, \( \frac{GDP}{P} \) denotes GDP per capita, and \( P \) represents population. This equation links the factors of population, GDP per capita, energy intensity to carbon dioxide emissions caused by human’s activities.

Since then, Kaya Identity and its extended forms have been widely used to make empirical analyses on the factors of carbon dioxide emissions in many researches. Ang(1997) took sector structures and energy structures into consideration, and analyzed the impact of factors on carbon dioxide emissions of manufacturing sectors in Singapore. Schipper et al.(2001) presented a similar decomposition model and performed an empirical analysis of factors that had long-term impacts on carbon dioxide emissions of manufacturing sectors in 13 countries.

Many empirical researches have also focused on factors of carbon dioxide emissions in China. Can Wang(2005) executed a decomposition research on carbon dioxide emissions over the period of 1957-2000 and the factors included population, GDP per capita, energy intensity, proportion of fossil energy and intensity of carbon dioxide emission. Lan-Cui Liu(2007) considered five factors including GDP, sector structures, energy intensity, proportion of fossil energy and intensity of carbon dioxide emission while analyzing the carbon dioxide emissions over the period of 1998-2005.

In conclusion, sectoral structure factors and energy structure factors are not considered simultaneously in current decomposition models; and this might be caused by difficulties in obtaining reasonable data. Since the empirical results of decomposition models are greatly affected by the distinct variables included, explanatory power of various factors will be miscalculated if important factors are ignored. Therefore, in this paper the current models are first extended to include eight important and related factors, and then with credible data an empirical study is made based on the model to quantify the contributions of the pre-defined factors to changes in total energy-related carbon dioxide emissions over the period 1984-2006 in China. The eight related factors taken into account in this paper are namely: population, economic development (GDP per capita), industrial structures, sectoral structures, energy intensity, proportion of fossil energy in total energy, structures of fossil energy and the carbon dioxide emission intensity of each type of fossil energy.

\[\text{1 In china statistics yearbooks, the economic system is divided into three industries: the primary industry, the secondary industry, and the tertiary industry. The primary industry includes farming, forestry, animal husbandry, fishery and water conservancy, the secondary industry includes mining and quarrying, manufacturing, electric power, gas and water production and supply, and construction, and the tertiary industry includes all service sectors. Each industry can be divided into many sectors. Industrial structures refer to the output proportions of each industry in total output and sectoral structures denotes the output proportions of each sector in the output of a certain industry.}\]
2. Methodology and data

The model is expressed as follows:

\[ C = \sum_{jki} C_{jki} = \sum_{jki} P \cdot \frac{Q_j}{P} \cdot \frac{Q_j}{Q_j} \cdot \frac{E_{jk}}{E_{jk}} \cdot \frac{E_{jk}}{E_{jk}} \cdot \frac{C_{jki}}{C_{jki}} \]  

(1)

where \( C_{jki} \) denotes the consumption of energy type \( i \) in sector \( k \) of industry \( j \), and the other variables are defined in Table 1.

However, due to the availability of respective data, we made some modifications to improve the model structure. Firstly, two separate models are constructed: the carbon dioxide emission model, represented by Eq. (2), and the energy consumption model, as shown in Eq. (3). The first of these describes the relationship between carbon dioxide emissions and four factors: total energy consumption, proportion of fossil energy in total energy, structures of fossil energy and the carbon dioxide emission intensity of each type of fossil energy. While the second one explains the relationship between total energy consumption and five different factors: population, economic development, industrial structures, sectoral structures, energy intensity. In the end, Eq. (2) and Eq. (3) are combined to translate the impact of the latter five factors on energy consumption in terms of the impact on carbon dioxide emissions.

\[ C = \sum_{i} C_i = \sum_{i} E \cdot \frac{E_f}{E} \cdot \frac{E_i}{E_i} \cdot \frac{C_i}{C_i} = \sum_{i} E \cdot fe \cdot es_i \cdot ec_i \]  

(2)

\[ E = \sum_{jk} E_{jk} = \sum_{jk} P \cdot \frac{Q_j}{P} \cdot \frac{Q_j}{Q_j} \cdot \frac{E_{jk}}{E_{jk}} = \sum_{jk} P \cdot q \cdot is_j \cdot ss_j \cdot ei_{jk} \]  

(3)

Table 1 Definition of variables

| \( i=1,2,3 \) | Three kinds of fossil energy: coal and its derivatives, oil and its derivatives, gas |
| \( j=1,2,3 \) | Three industries: primary industry, secondary industry, tertiary industry |
| \( k=1,2,… \) | Various sectors in industry \( j \) |
| \( C \) | Total energy-related carbon dioxide emissions |
| \( C_i \) | Energy-related carbon dioxide emissions from the use of energy type \( i \) |
| \( E \) | Total energy consumption |
| \( E_f \) | Total fossil energy consumption |
| \( E_i \) | Consumption of energy type \( i \) |
| \( fe \) | Proportion of fossil energy consumption in total energy consumption |
| \( es_i \) | Proportion of fossil energy type \( i \) |
Among many decomposition methods, LMDI (Log-Mean Divisia Index) is chosen in this paper. Ang (2004) compared various index decomposition analyses, and concluded that the LMDI method was the preferred method, due to its theoretical foundation, adaptability, ease of use and result interpretation, along with some other desirable properties in the context of decomposition analysis. According to LMDI decomposition model, Eq. (5)–(8) are deduced.

\[
\Delta C = C^t - C^0 = \sum_i C^t_i - \sum_i C^0_i = \Delta C_e + \Delta C_{fe} + \Delta C_{es} + \Delta C_{ec} \tag{4}
\]

where \( t \) denotes the current year, \( 0 \) denotes the base year, \( \Delta C \) denotes the change of carbon dioxide emissions over the period from the base year to the current year, \( \Delta C_e \) denotes the change of carbon dioxide emissions caused by energy consumption, which is called the effect of energy consumption, and similarly \( \Delta C_{fe}, \Delta C_{es}, \Delta C_{ec} \) denotes respectively the effect of fossil energy proportion in total energy, the effect of energy structure, the effect of carbon dioxide emission intensity.
\[
\begin{aligned}
\Delta C_E &= \sum_i w_i \ln \frac{E_i^t}{E_i^0} \\
\Delta C_{fc} &= \sum_i w_i \ln \frac{f_{c_i}^t}{f_{c_i}^0} \\
\Delta C_{es} &= \sum_i w_i \ln \frac{e_{s_i}^t}{e_{s_i}^0} \\
\Delta C_{ec} &= \sum_i w_i \ln \frac{e_{c_i}^t}{e_{c_i}^0} \\
\Delta E &= E^t - E^0 = \sum_{j,k} E_{j,k}^t - \sum_{j,k} E_{j,k}^0 = \Delta E_P + \Delta E_q + \Delta E_{is} + \Delta E_{ss} + \Delta E_{ei}
\end{aligned}
\]

where \( \Delta E \) denotes the change of energy consumption from the base year to the current year, and \( \Delta E_P, \Delta E_q, \Delta E_{is}, \Delta E_{ss}, \Delta E_{ei} \) denotes respectively the effect of population, the effect of economic development, the effect of industrial structure, the effect of sectoral structure, and the effect of energy intensity.

\[
\begin{aligned}
\Delta E_P &= \sum_{j,k} w_{j,k} \ln \frac{P_{j,k}^t}{P_{j,k}^0} \\
\Delta E_q &= \sum_{j,k} w_{j,k} \ln \frac{q_{j,k}^t}{q_{j,k}^0} \\
\Delta E_{is} &= \sum_{j,k} w_{j,k} \ln \frac{i_{s_i}^t}{i_{s_i}^0} \\
\Delta E_{ss} &= \sum_{j,k} w_{j,k} \ln \frac{s_{s_i}^t}{s_{s_i}^0} \\
\Delta E_{ei} &= \sum_{j,k} w_{j,k} \ln \frac{e_{i_i}^t}{e_{i_i}^0} \\
w_{j,k} &= \frac{E_{j,k}^t - E_{j,k}^0}{\ln(E_{j,k}^{t} / E_{j,k}^{0})}
\end{aligned}
\]

Through the variable \( E \) in both Eq. (2) and Eq. (3), the change of carbon dioxide emission is linked to the impacts of population, economic development, industrial structures, sectoral structures and energy intensity on the energy, in the following way:

\[
\Delta C_E = \frac{\Delta E_P}{\Delta E} \cdot \Delta C_E + \frac{\Delta E_q}{\Delta E} \cdot \Delta C_E + \frac{\Delta E_{is}}{\Delta E} \cdot \Delta C_E + \frac{\Delta E_{ss}}{\Delta E} \cdot \Delta C_E + \frac{\Delta E_{ei}}{\Delta E} \cdot \Delta C_E
\]  

According to (4) and (8),...
\[
\Delta C = \frac{\Delta E_p}{\Delta E} \cdot \Delta C_E + \frac{\Delta E_q}{\Delta E} \cdot \Delta C_{E} + \frac{\Delta E_{sl}}{\Delta E} \cdot \Delta C_{E} + \frac{\Delta E_{st}}{\Delta E} \cdot \Delta C_{E} + \Delta C_{ge} + \Delta C_{ge} + \Delta C_{ec}
\]

(9)

The data regarding energy consumption, population and GDP, spanning from 1984 to 2006 used in this study, are obtained from China statistics yearbooks. The data of the output in each sector of the industry are from China statistics yearbooks of industrial economy. The carbon dioxide emissions are calculated in terms of the final energy consumption and the carbon emission intensity. According to Energy Institution of National Development and Reform Commission, the carbon emission intensities of coal, oil and natural gas are respectively 0.7476, 0.5825, 0.4435\(^{(9)}\). Because the carbon emission intensity of a certain type of fossil energy depends on energy chemical composition theoretically, it is deemed as constant in this paper and thus the effect of carbon emission intensity is 0.

3. Empirical results and discussions

Empirical results comprise three parts: (1) the results of the carbon dioxide emission model Eq.(2); (2) the results of the energy consumption model Eq.(3); (3) the added results from Eq.(9).

(1) Results of the carbon dioxide emission model

According to Eq. (2), with 1984 as the base year, the decomposition results are described in Fig.3.

The results show that the increase of carbon dioxide emissions from 1984 to 2006 can be mainly explained by the change of energy consumption. And the change of the fossil energy proportion and that of the structure of fossil energy have a much smaller impact on carbon dioxide emissions. Over the period of 1984~2006, the effect of energy consumption is positive, that is to say, the effect of energy consumption increases the carbon dioxide emissions, while the effect of fossil energy proportion and that of the structure of fossil energy are negative.

The fossil energy proportion in total energy has decreased gradually from 95.1\% in 1984 to 92.8\% in 2006. After the middle of 1990s, the proportion of coal in fossil energy has declined while the proportions of oil and gas have ascended as shown in Fig.4. In three kinds of energy, the carbon emission intensity of coal is the highest, and that of oil is the second, and that of gas is the lowest. According to Development and Reform Commission of China, the carbon emission intensities of the three kinds of energy are 0.7476,
0.5825, and 0.4435 respectively. Therefore, the change of energy structure over the period helps to decrease carbon dioxide emissions.

![Energy structures from 1984 to 2006 in China](image)

**Fig.4. Energy structures from 1984 to 2006 in China**

With 1984 as the base year and 2006 as the current year, according to Eq. (2) the decomposition results are as follows:

![Decomposition results between 1984 and 2006 in China in Eq. (2)](image)

**Fig.5. Decomposition results between 1984 and 2006 in China in Eq. (2)**

As shown in Fig.5, the change of energy consumption contributes 102.9% to the increase of carbon dioxide emissions between 1984 and 2006, while the decline of fossil energy proportion contributes -2.02% and the change of the structure of fossil energy contributes -0.89%.

(2) **Results of the energy consumption model**

According to Eq. (3), with 1984 as the base year, the results are described in Fig.6.
As mentioned in the introduction, the energy consumption increases quickly from 1984 to 2006, which is described in Fig. 6 by the curve of change of energy consumption. The results show that the economy development increases energy consumption, while the decline of energy intensity decreases it. The economy development and the change of energy intensity are the most important factors.

Fig. 7 describes the change of energy intensities in GDP and three industries. As shown, the energy intensities decrease sharply over the period. Especially, the intensity of the secondary industry has a great decline, which contributes to the carbon reduction significantly.

And Fig. 8 shows the change of energy intensities in the level of sectors in the secondary industry. In this paper the secondary industry is divided into 11 sectors, namely mining and quarrying, food, clothing, papermaking, building materials, Chemical industry, energy industry, metallurgy industry, mechanical industry, building industry and other industry. The energy intensities of all sectors decrease greatly over the period. The sectors with high energy intensities, such as building materials industry, metallurgy industry, chemical industry and energy industry, have respectively a great decline before the middle of 1990s.
In addition, the effect of the population on energy consumption is positive, which is obvious, for that the population in China increases continually.

The change of industrial structures increases energy consumption. During the period of 1984 to 2006, the output proportions of the primary and tertiary industry in total output make a great change: the output proportion of the primary industry has declined greatly while that of the tertiary industry has ascended greatly. But the output proportion of the secondary industry has little change, even a small ascent. The energy intensities of the primary and tertiary industry are close to each other, but are much lower than that of the secondary industry. Therefore, the change of industrial structures from 1984 to 2006 increases the energy consumption.

The change of sectoral structures decreases the energy consumption, and the decrement is larger than the increment caused by the change of industrial structures. Fig. 10 shows the change of output proportions in each sector of the secondary industry. For example, in energy-intensive sectors, the building materials sector has a decrement in the output proportion while the metallurgy sector expands in recent years.
According to Eq. (3), with 1984 as the base year and 2006 as the current year, the decomposition results are as follows:

The increase of the population contributes 14.2% to the increase of energy consumption from 1984 to 2006; the economy development contributes 210.0%; the change of industrial structures contributes 8.6%; the change of sectoral structures contributes -13.4%, and the decline of the energy intensity contributes -119.4%.

(3) The added results
According to Eq. (9), on the basis of Eq. (2) and Eq. (3) the decomposition results are as follows:

![Graph showing decomposition results from 1984 to 2006 in China in Eq. (9)](image)

With 1984 as the base year and 2006 as the current year, the results are shown in Fig. 13.

![Graph showing decomposition results between 1984 and 2006 in China in Eq. (9)](image)

Fig. 13 shows thoroughly how much each pre-defined factor makes contributions to the change of carbon dioxide emissions over the period 1984-2006.
4. Conclusions

From the study above, some important conclusions can be drawn:

① The economic development and the decline of energy intensity are the two most important factors that have impact on the carbon dioxide emissions over the period 1984-2006 in China. The decline of energy intensity reduced the carbon dioxide emissions greatly while the increase of the carbon dioxide emissions caused by the economic development is greater. The effect of economic development is twice as much as that of energy intensity decline.

② The economic development is dependent on energy supply, so in some degree there are conflicts between reduction of carbon dioxide emissions and economic development. In order to reduce carbon dioxide emissions and not to restrain economic development, other factors need to be considered more carefully, such as the decline of energy intensity, the adjustments of industrial structure and the energy structure.

③ Without doubt, the decline of energy intensity is the most contributive factor to reduce the carbon dioxide emissions. But after the middle of 1990s the decline of the energy intensity began to slow down, and since 2000 it was slower. The energy thermal efficiency was 34-41% in the ECE district (including West Europe, East Europe and the former Soviet Union) in the middle of 1990s and it was 33.4% in 2000 in China, which is close to the former. It can be concluded that in the short run the room of carbon dioxide reduction caused by technology progress is smaller and smaller.

④ The adjustment of industrial structure increased the carbon dioxide emissions with a contribution of 8.9%. It is related to the course of industrialization, especially the development of the heavy industry. Over the period of 1984-2006, the decline of energy intensity decreases sharply the carbon dioxide emissions, but it seems to be at the bottleneck now. Therefore, the reduction of carbon dioxide emissions will be driven by the adjustment of industrial structure. In 2006 the energy intensity of the tertiary industry was 0.41tce per ten thousand Yuan while that of the secondary industry was 1.73tce per ten thousand Yuan, which was 4.22 times as much as the former. The adjustment toward the tertiary industry is a great help to reduce carbon dioxide emissions.

⑤ The effect of industrial structure is different from that of sectoral structure and that’s why the two factors are separated in this paper. If the economic structure is divided into only three industries and each industry is not divided further, the results will be rough because the effect of sectoral structure will be calculated into the effect of energy intensity. As shown in this paper, each industry is divided into some sectors and the results are different: the effect of industrial structure is plus while that of sectoral structure is minus, and the added effect of the two is -4.9%, which reduces the carbon dioxide emissions. In fact, if each sector is divided further, the results will be more accurate, but it is a pity that the data in such details can not be obtained.

⑥ The change of energy structure reduces the carbon dioxide emissions and the contribution is only -2.9% because the change of energy structure which has decreased from 95.1% in 1984 to 92.8% in 2006 is small itself. This structure causes that economic development depend terribly on the fossil energy and that the carbon dioxide emissions must increase with the economic development. This is decided by the energy endowment which is abundant in coal. But in the view of strategic policies in the reduction of carbon dioxide emissions, the change of energy structure is very important, especially the substitution of natural gas for coal and the change towards non-fossil energy including nuclear energy, water energy, wind energy, solar energy and so on.
Further researches on this problem should be more interesting and attractive, and will concentrate on the two points: (1) why the energy intensity declines over the period of 1984–2006; (2) what can drive the change of energy structures; (3) what factors drive the change of sectoral structures for the carbon reduction.

References