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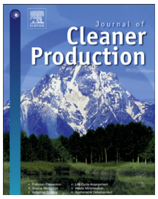

Factor analysis of energy-related carbon emissions: a case study of Beijing

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ABSTRACT

Carbon emissions in China have attracted increasing world attention with rapid urbanization of this country. It is critical for the government to identify the key factors causing these emissions and take controlling measures. Consistent results have not been achieved yet although some research has been conducted on the factors leading to emissions. Meanwhile, there is still considerable room to improve the methods of previous research. Index decomposition analysis (IDA) is the main method for quantifying the impact of different factors on carbon emissions. At present, the widely used forms of IDA are primarily the Laspeyres and the Divisia index methods. Compared with the Laspeyres and the majority of the Divisia index methods, the generalized Fisher index (GFI) decomposition method can eliminate the residuals and has better factor decomposition characteristics. This paper chooses Beijing as a typical example and analyzes the factors causing carbon emissions. Based on the extended Kaya identity, we built a multivariate generalized Fisher index decomposition model to measure the impacts of economic growth, population size, energy intensity and energy structure on energy-related carbon emissions from 1995 to 2012 in Beijing. The results show that the sustained growth of economic output in Beijing was the leading factor in carbon emissions. Population size had a stimulating effect on the growth of carbon emissions during this period; the pulling effect increased after 2003 and then decreased slightly after 2011 with a cumulative effect of 165.4%. Energy intensity was the primary factor restraining carbon emissions, and the inhibition effect increased yearly. The continuous optimization of the energy structure had no obvious inhibitory effect on carbon emissions. To control carbon emissions, Beijing should continue to adjust the mode of economic development and appropriately control the population size while improving energy efficiency.

1. Introduction

With the rapid development of China's economy, energy consumption based on fossil fuel continues to increase. Air pollution, greenhouse effect and other environmental problems have become increasingly prominent, seriously restricting the sustainable development of China's economy. As China's capital and its political and cultural center, Beijing should play a leading role in mitigating and adapting to climate change. Since entering the 21st century, Beijing's economy has maintained rapid growth, with an average gross domestic product (GDP) annual growth rate of 11.17%; energy intensity has fallen sharply, whereas the energy consumption structure and consumption pattern have improved. However, although Beijing has made remarkable achievements, economic growth continues to depend on energy. Energy consumption grew at an average annual rate of 4.16% from 1995 to 2012. Correspondingly, carbon emissions also increased significantly. Faced with a lack of resources, energy restrictions have gradually become a bottleneck in restricting the Beijing's economic and social development and remain a challenge for energy conservation. For better implementation of emission reduction targets, the contribution of factors influencing carbon emissions from energy consumption in Beijing should be explored and relevant policies and effective measures must be formulated to control and reduce carbon emissions according to the influencing factors. These tasks are urgently needed to achieve the goal of building a “green Beijing”, which has positive practical significance for the successful operation of the Chinese low-carbon economy at the provincial level.

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2. Literature review

Accurate analysis of the reasons for the increase in carbon emissions is critical to finding a path to carbon reduction. Index decomposition analysis (IDA) as an analytical framework to study the characteristics and mechanisms of change first expanded from the field of energy consumption to energy-related carbon dioxide (CO_2) emissions in 1991, and has gradually become the main research method for analyzing changes to carbon emissions (Xu and Ang, 2013). At present, the most commonly used IDA are the Laspeyres and the Divisia index methods. Complete decomposition analysis was used by Das and Paul (2014) to identify the causes of changes in CO_2 emissions from household consumption between 1993–94 and 2006–07 in India. The results indicate that activity, structure and population effects are the main causes of the increase in CO_2 emissions from household fuel consumption. Diakoulaki et al. (2006) split the period 1990–2002 into two equal intervals and relied on the refined Laspeyres model starting from the major energy consuming sectors and aggregating the obtained effects for estimating their relative impacts on CO_2 emissions in Greece. Ang and Pandiyan (1997) and Lee et al. (2001) used the Divisia decomposition method and adaptive weighting Divisia decomposition method, respectively, to analyze the factors affecting carbon emissions in the manufacturing sectors of different countries.

The Laspeyres and the majority of the Divisia index methods cannot handle the residuals existing in the decomposition process, which renders the model unable to explain all of the changes in carbon emissions. Ang and Choi (1997) put forward an improved method called logarithmic mean Divisia index (LMDI), which has been widely applied in practical research. Fernández et al. (2014) applied the LMDI method to quantify the driving forces behind changes in CO_2 emissions in the EU-27 in 2001–2008 and noted in general terms that the increased efficiency in CO_2 emissions by European countries had been sufficient to override the joint pressure of population and economic growth on CO_2 emissions. Liu et al. (2007) and Deng et al. (2014) also used the LMDI decomposition method to explore the reasons and regulations of the Chinese industrial sector and the changes in carbon emissions in different regions of China.

As observed in the above literature, the Laspeyres and the Divisia index methods are chosen more often in the decomposition of carbon emissions. As noted above, these methods have their defects; although LMDI can eliminate the residuals, its formulae contain logarithmic terms that cannot accommodate negative values (Ang et al., 2004). The generalized Fisher index (GFI) has better decomposition characteristics because it can overcome the shortcomings of the Laspeyres index and the Divisia index and the traditional two-factor analysis of the Fisher index well. Ang et al. (2004) compared the GFI method with five widely known IDA methods. In the comparison, factor-reversal, time-reversal, proportionality, aggregation, zero-value robust and negative-value robust tests had been done. The GFI method failed only the aggregate test and passed the remaining tests, achieving complete factor decomposition, which provide a powerful basis for reasonable selection of the GFI for factor decomposition.

Some scholars have analyzed the factors in carbon emissions from energy consumption in Beijing. Wang et al. (2012) and Zhu and Zhang (2012) adopted STIRPAT to examine the relationship between carbon emissions produced in the process of economic development in Beijing and different driving factors, with different results. Wang et al. (2012) noted that CO_2 emissions were positively influenced by urbanization level, economic level and industry proportion and negatively influenced by the proportion of tertiary industry, energy intensity and R&D output. Zhu and Zhang (2012) confirmed the contribution of the level of urbanization and population to carbon emissions but noted that per capita GDP and energy intensity had less effect than urbanization and population. The proportion of secondary industry was negatively correlated with CO_2. Based on input–output structural decomposition analysis, Wang et al. (2013) analyzed the driving forces of the increase in CO_2 emissions in Beijing from both production and final demand perspectives during 1997–2010. According to the results, the growth in CO_2 emissions in Beijing was driven mainly by changes in production structure and population growth, partly offset by a reduction in the intensity of CO_2 emissions and a decline in per capita final demand volume during the study period. Change in final demand structure had a limited effect on the change in CO_2 emissions in Beijing. From the final demand perspective, urban trade, urban residential consumption, government consumption and fixed capital formation were mainly responsible for the boom in emissions. Tian et al. (2013) conducted a structural decomposition analysis to quantify the contributions of technological and socio-economic factors to Beijing's rapid growth in CO_2 emissions from 1995 to 2007. The results showed that the final demand for export and investment led to variations in CO_2 emissions in Beijing for the same period by 56% and 21%, respectively; the change in production structure jointly contributed 455% of the total increase in CO_2 emissions; and improved energy intensity was Beijing's primary source of decarbonizing its economic development in 1995–2007. Zhang and Xie (2013) introduced the same method and analyzed the driving factors of carbon emissions in Beijing at the levels of the overall situation, different industries and different industrial sectors in 1997–2007. The results proved the pulling effect of economic growth and the inhibitory effect of energy intensity on carbon emissions and noted that domestic exports and consumption override exports and investment were major contributors to the increased emissions in the size expansion effect. In the studies using the LMDI decomposition technique to decompose the changes in Beijing's carbon emissions in different periods, Liu et al. (2010), Liu and Chen (2013), Li (2011), and Wu et al. (2014) produced results consistent with those of previous research on the role of economic growth and energy intensity in carbon emissions. As for the impact of energy structure and industrial structure, the researchers' opinions differ. Wu et al. (2014) expressed the view that energy structure and industry structure have greatly contributed to carbon emission reduction. Liu et al. (2010) and Liu and Chen (2013) noted that energy structure has played a positive role in reducing carbon emissions but that the effect is small. Li (2011) further noted that the contribution of energy structure to carbon emission reduction in Beijing is not large, showing a further weakening trend after 2006.

As observed, the factors influencing carbon emissions have been analyzed with different methods by current scholars; however, the GFI model is used by few scholars, and the conclusions have not been the same. The GFI model, as the best choice for factor decomposition, is seldom used in the empirical analysis of carbon emissions in China and is used even less at the regional level. Tian and Zhang (2011) and Li and Wang (2008) respectively constructed decomposition models of per capita carbon emissions and regional energy-related carbon emissions in China. However, when calculating the contributions of the influencing factors, they violated the multiplication form of the GFI and adopted the proportion form for calculation and analysis; thus, the conclusions are not accurate. From the above analysis, this paper selects the GFI method to explore the driving forces of carbon emissions in Beijing.

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3. Methodology and data

As noted above, the GFI method can overcome the shortcomings of the Laspeyres and the Divisia index methods and the limitations of traditional Fisher index analysis with only two factors; therefore, it has better decomposition characteristics. In this paper, we extended the Kaya identity and analyzed various factors on carbon emissions using the GFI method.

3.1. The extended Kaya identity

The Kaya identity was first proposed by the Japanese scholar Yoichi Kaya (Kaya, 1990) at an IPCC workshop; it is a useful tool for analyzing the factors in carbon emissions (Albrecht et al., 2002). Its expression is as follows:

$$C = (C/E)(E/GDP)(GDP/P)P \tag{1}$$

The Kaya identity relates energy-related carbon emissions with energy (E), economic development level (GDP) and population (P). Its structure is relatively simple and explores only the quantitative relationship among carbon emissions, energy intensity, economic development and population at a national level without considering the influence of structural factors. Consequently, we added energy structure as a factor to the Kaya identity, considering data availability, and decomposed carbon emissions into energy structure, energy intensity, economic output and population. The expansion of the equation is as follows:

$$C = \sum_i C_i = \sum_i \frac{C_i}{E_i}\frac{E_i}{E}\frac{E}{Y}\frac{Y}{P}P \tag{2}$$

where C is carbon emissions; C_i is the carbon emissions of the ith fuel type; E_i and E represent the ith fuel consumption and the total primary energy consumption, respectively; Y is gross domestic product (GDP); and P is population. C_i/E_i is the carbon emissions of the ith fuel type, namely the carbon emission coefficient; E_i/E represents the total energy consumption share of the ith fuel type; E/Y is energy consumption per unit GDP, namely energy intensity; and Y/P represents the per capita GDP, namely economic output. Thus, the change in carbon emissions is decomposed into the following factors: carbon emission efficiency, energy structure, energy intensity, economic output and population.

3.2. Generalized Fisher index decomposition

The Fisher index decomposition method was first proposed by Fisher in 1922. The model is expressed as follows:

$$V = \sum_i V_i = \sum_i X_{1i}X_{2i} \tag{3}$$

where V represents an aggregate indicator, i denotes the subcategory of the aggregate, and X_{1i} and X_{2i} indicate the decomposed variables. The effect associated with changes in X_1 and X_2 from year 0 to year T is given in equation (4):

$$D = \frac{V^T}{V^0} = \frac{\sum_i X_{1i}^T X_{2i}^T}{\sum_i X_{1i}^0 X_{2i}^0} = D_{X_1} \cdot D_{X_2} \tag{4}$$

According to the Fisher index formula, we have the following:

$$D_{X_1} = \left[\frac{\sum_i X_{1i}^T X_{2i}^0}{\sum_i X_{1i}^0 X_{2i}^0} \cdot \frac{\sum_i X_{1i}^T X_{2i}^T}{\sum_i X_{1i}^0 X_{2i}^T}\right]^{\frac{1}{2}} \tag{5}$$

$$D_{X_2} = \left[\frac{\sum_i X_{1i}^0 X_{2i}^T}{\sum_i X_{1i}^0 X_{2i}^0} \cdot \frac{\sum_i X_{1i}^T X_{2i}^T}{\sum_i X_{1i}^T X_{2i}^0}\right]^{\frac{1}{2}} \tag{6}$$

The traditional Fisher model with factors is used to study energy and relative gas emissions by some scholars (Liu and Ang, 2003; Boyd and Roop, 2004); however, in empirical studies, two factors are insufficient to solve this problem. Ang et al. (2004) extended the two factors into multiple factors and proposed the GFI method. The specific steps are as follows:

V, the total index, is composed of n elements; therefore:

$$V = \sum_i X_1 X_2 \bullet\bullet\bullet X_n \tag{7}$$

Define the set $N = \{1,2,\cdots,n\}$ where the cardinality of N is n. S is a subset of N, for which the cardinality is s'. Define a function $V(S) = \sum(\prod_{l\in S} X_l^T \prod_{m\in N\backslash S} X_m^0)$ and $V(\Phi) = \sum(\prod_{m\in N} X_m^0)$ where Φ is a null set and superscripts denote the current year T and the base year 0. According to the “geometric average” principle, V^T/V^0 is divided into n parts, and the decomposition results of factor X_j ($j = 1, 2,\cdots, n$) are given by:

$$\begin{aligned} D_{X_j} &= \prod_{\substack{S\subset N\\ j\in S}} \left[\frac{V(S)}{V(S\backslash\{j\})}\right]^{\frac{1}{n}\cdot\frac{1}{\binom{n-1}{s'-1}}} \\ &= \prod_{\substack{S\subset N\\ j\in S}} \left[\frac{V(S)}{V(S\backslash\{j\})}\right]^{\frac{(s'-1)!(n-s')!}{n!}} \end{aligned} \tag{8}$$

$D_{X_j} (j = 1, 2, \cdots, n)$ is the decomposition factor of the GFI method.

According to the above method, formula (2) is defined as follows: the energy-related carbon emission coefficient $X_{1i} = C_i/E_i$, energy structure $X_{2i} = E_i/E$, energy intensity $X_3 = E/Y$, economic development $X_4 = Y/P$, and population size $X_5 = P$. Thus, the carbon emissions formula can be written as:

$$C = \sum_i C_i = \sum_i \frac{C_i}{E_i}\frac{E_i}{E}\frac{E}{Y}\frac{Y}{P}P = \sum_i X_{1i}X_{2i}X_3X_4X_5 \tag{9}$$

Generally speaking, the carbon emission coefficients of all types of fossil fuels X_{1i} are fixed; therefore, the factors impacting carbon emissions in Beijing are mainly energy structure, energy intensity, economic development and population size. Its change can be decomposed into:

$$C^T \big/ C^0 = D_{X_1} D_{X_2} D_{X_3} D_{X_4} \tag{10}$$

In equation (10), C^T is the carbon emissions in year T, C^0 is the carbon emissions in the base year, D_{X_1} is energy structure effect, X_1 is the product of the energy consumption structure (E_i/E) and corresponding carbon emission coefficients (C_i/E_i), D_{X_2} is energy intensity effect, D_{X_3} is economic development effect, and D_{X_4} is population size effect. Among them

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$$\begin{aligned} D_{X_1} = {} & \left[\frac{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^0}{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^0}\right]^{\frac{1}{4}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^0 X_4^0}{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^T X_2^0 X_3^T X_4^0}{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^0} \cdot \frac{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^T}{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^T}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^T X_4^0}{\sum_i X_{1i}^0 X_2^T X_3^T X_4^0} \cdot \frac{\sum_i X_{1i}^T X_2^T X_3^0 X_4^T}{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^T} \cdot \frac{\sum_i X_{1i}^T X_2^0 X_3^T X_4^T}{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^T}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^T X_4^T}{\sum_i X_{1i}^0 X_2^T X_3^T X_4^T}\right]^{\frac{1}{4}} \end{aligned} \tag{11}$$

$$\begin{aligned} D_{X_2} = {} & \left[\frac{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^0}{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^0}\right]^{\frac{1}{4}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^0 X_4^0}{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^0 X_2^T X_3^T X_4^0}{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^0} \cdot \frac{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^T}{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^T}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^T X_4^0}{\sum_i X_{1i}^T X_2^0 X_3^T X_4^0} \cdot \frac{\sum_i X_{1i}^T X_2^T X_3^0 X_4^T}{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^T} \cdot \frac{\sum_i X_{1i}^0 X_2^T X_3^T X_4^T}{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^T}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^T X_4^T}{\sum_i X_{1i}^T X_2^0 X_3^T X_4^T}\right]^{\frac{1}{4}} \end{aligned} \tag{12}$$

$$\begin{aligned} D_{X_3} = {} & \left[\frac{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^0}{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^0}\right]^{\frac{1}{4}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^0 X_3^T X_4^0}{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^0 X_2^T X_3^T X_4^0}{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^T}{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^T}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^T X_4^0}{\sum_i X_{1i}^T X_2^T X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^T X_2^0 X_3^T X_4^T}{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^T} \cdot \frac{\sum_i X_{1i}^0 X_2^T X_3^T X_4^T}{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^T}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^T X_4^T}{\sum_i X_{1i}^T X_2^T X_3^0 X_4^T}\right]^{\frac{1}{4}} \end{aligned} \tag{13}$$

$$\begin{aligned} D_{X_4} = {} & \left[\frac{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^T}{\sum_i X_{1i}^0 X_2^0 X_3^0 X_4^0}\right]^{\frac{1}{4}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^T}{\sum_i X_{1i}^T X_2^0 X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^T}{\sum_i X_{1i}^0 X_2^T X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^T}{\sum_i X_{1i}^0 X_2^0 X_3^T X_4^0}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^0 X_4^T}{\sum_i X_{1i}^T X_2^T X_3^0 X_4^0} \cdot \frac{\sum_i X_{1i}^0 X_2^T X_3^T X_4^T}{\sum_i X_{1i}^0 X_2^T X_3^T X_4^0} \cdot \frac{\sum_i X_{1i}^T X_2^0 X_3^T X_4^T}{\sum_i X_{1i}^T X_2^0 X_3^T X_4^0}\right]^{\frac{1}{12}} \\ & \cdot \left[\frac{\sum_i X_{1i}^T X_2^T X_3^T X_4^T}{\sum_i X_{1i}^T X_2^T X_3^T X_4^0}\right]^{\frac{1}{4}} \end{aligned} \tag{14}$$

3.3. Data sources

Energy consumption data in the transportation sector are from energy balance tables for Beijing in the previous China Energy Statistical Yearbook. The selection of fuel types references energy consumption in different areas according to the 2013 China Energy Statistics Yearbook. The fuel types are mainly coal, coke, kerosene, gasoline, diesel, fuel oil, and natural gas. Crude oil is a primary fuel of which the vast majority is converted into other fuels rather than used for direct consumption; to avoid repeated calculations, crude oil is excluded from the calculation process. To ensure comparability among the data, energy sources were converted into standard coal equivalent according to standard coal coefficients from appendix 4 of the 2013 China Energy Statistical Yearbook. Carbon emission coefficients upon the standard coal equivalent are obtained with reference to Zhao (2009). Other economic data are from past Beijing Statistical Yearbooks. The sample data span the period from 1995 to 2012, and the statistical data are given at current prices. To eliminate the impact of price fluctuations, the GDP was converted into the 1995 price according to the corresponding price.

4. Results and discussion

4.1. Results

From the factors influencing carbon emissions in formulas (11)–(14), we produce the decomposition results of changes in carbon emissions shown in Table 1 and Fig. 1.

As seen in Table 1 and Fig. 1, the total carbon emissions in Beijing are growing. From 1995 to 2003, the total change in emissions was relatively stable, with an average annual growth rate of 0.7%. After 2003, the growth in carbon emissions accelerated, with an average annual growth rate of 1.9%. Economic development contributed exponentially to Beijing's growth in carbon emissions. The cumulative effect of economic development on carbon emissions is 3.345, far greater than that of other factors. Economic development was the dominant factor in the growth of carbon emissions over the period 1995–2012. Population size was also a factor in the increase in carbon emissions from energy consumption in Beijing; after 2003, the trend increased annually, with effect values greater than 1 and a cumulative effect reaching 165.4%. Energy intensity and energy structure are the inhibitory factors in carbon emissions. The energy intensity index is basically less than 1, the cumulative effect is 0.266, and the contribution rate decreased annually from 0.948 in

Table 1
Decomposition effect of carbon emissions in Beijing.

Year	Energy structure D_{X_1}	Energy intensity D_{X_2}	Economic development D_{X_3}	Population size D_{X_4}	Total effect of carbon emissions V
1995–1996	0.995	0.948	1.031	1.007	0.980
1996–1997	1.000	0.859	1.106	0.985	0.935
1997–1998	0.997	0.940	1.101	1.005	1.036
1998–1999	0.990	0.897	1.101	1.009	0.987
1999–2000	0.994	0.928	1.068	1.084	1.068
2000–2001	0.984	0.926	1.065	1.016	0.986
2001–2002	0.985	0.881	1.091	1.028	0.973
2002–2003	1.006	0.948	1.083	1.023	1.056
2003–2004	0.990	0.990	1.114	1.025	1.119
2004–2005	0.989	0.934	1.091	1.030	1.039
2005–2006	0.980	0.933	1.091	1.041	1.039
2006–2007	0.987	0.912	1.097	1.047	1.034
2007–2008	0.969	0.918	1.037	1.057	0.975
2008–2009	0.986	0.938	1.046	1.050	1.016
2009–2010	0.993	0.942	1.048	1.055	1.034
2010–2011	0.976	0.864	1.038	1.029	0.901
2011–2012	0.981	0.975	1.049	1.025	1.028
1995–2012	0.819	0.266	3.345	1.654	1.203

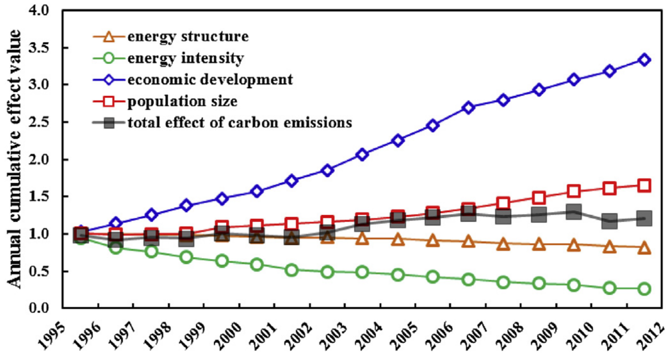

Fig. 1. Influencing factors of carbon emissions in Beijing from 1995 to 2012.

1995 to 0.266 in 2012. The annual decline in energy intensity is related to encouragement and support from the government for technological innovation in energy utilization in the “Eleventh Five-Year Plan” and “Twelfth Five-Year Plan”, and the standard system for policy formulation and other measures are constantly being improved. Consequently, energy-saving efforts have achieved remarkable results in Beijing. The inhibitory effect of the energy structure on carbon emissions is still weaker than energy intensity but is gradually increasing. This increase shows that the structure of energy consumption dominated by coal in Beijing has not changed but that oil, natural gas and clean energy consumption are growing in a benign direction. Between 1995 and 2003, the gap between the inhibitory effect of energy intensity and energy structure and the pulling effect of population size and economic development was the smallest, and the total change in carbon emissions was stable. After 2003, the gap between the effect of energy intensity and energy structure on carbon emissions and the contribution of the pulling factors expanded. The contribution of the inhibiting factors was less than the pulling effects of economic development and population size, which increased the total carbon emissions.

4.2. *Discussion*

The factors influencing carbon emissions from energy consumption in different regions or industries have been studied by many scholars. The driving factors of carbon emissions in Beijing are analyzed using the GFI model in this paper. Some of our results confirm previous conclusions, and some contain new discoveries.

4.2.1. *Economic development*

The contribution of economic development to carbon emissions in Beijing is growing exponentially. The rapid growth of the economy demands more energy; from 1995 to 2012, the per capita GDP increased by 234% (at the 1995 constant price), and energy consumption increased by 53%. As a by-product of energy consumption, carbon emissions continue to increase. This conclusion is similar to that of Wang et al. (2012), Zhang and Xie (2013) and proves that Beijing's economic growth relies too much on energy consumption. At the same time, we see in Table 1 that the pulling effect of economic development on carbon emissions in Beijing did not show sustained growth as economic development did. This finding shows that Beijing is vigorously developing its economy while constantly optimizing the industrial structure adjustment, which keeps the pulling effect of economic development on carbon emissions at a certain level. This paper further indicated that the gap between the inhibitory factors and the contribution factors from 1995 to 2003 was minimal; consequently, carbon emissions grew slowly. However, the contribution of the inhibiting factors was less than that of the pulling factors, leading to the increase in carbon emissions. Little analysis of the results has been found in existing research.

4.2.2. *Population size*

Population size is another factor that increased carbon emissions from energy consumption in Beijing. The cumulative effect is 165.4%, corresponding to the conclusion of Liu and Chen (2013) and Wang et al. (2013). As the capital, Beijing has a disproportionate share of advantageous resources, attracting a large quantity of outstanding talent. The large population with rigid demand leads to the increase in carbon emissions. Furthermore, we find that the effect of population size shows an increasing trend after 2003 but a slight decline after 2011, which is closely related to Beijing's rapid urbanization in recent years. Population size increases annually along with urbanization. Urban infrastructure and the consumption of steel and cement in housing construction need a large amount of energy, resulting in the growth in carbon emissions. However, after 2011, Beijing implemented a more stringent population policy; as a result, the population size effect declined slightly.

4.2.3. *Energy intensity*

Generally speaking, a decline in energy intensity has a positive effect on reducing carbon emissions. Analyses by Tian et al. (2013), Wang et al. (2013) and other scholars show that the contribution of

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energy intensity to the rate of carbon emissions is negative; however, Zhu and Zhang (2012) argues that the decline in energy intensity is much lower than the economic and population growth; energy intensity has almost no effect on reducing CO_2 emissions. The results of this study show that energy intensity indices are less than 1, the contribution rate of carbon emissions in Beijing exhibits a significant inhibitory effect, confirming the views of most scholars; and this inhibitory effect has been increasing annually, which is closely related to the changing trend in energy intensity. For a long time, Beijing insisted on developing high-efficiency and high-radiation industries, promoting the optimization and upgrading of industry structures and realizing the transformation from a manufacturing economy to a service economy. Due to taking the initiative to eliminate a number of heavily polluting industries does not meet the obligations of the capital city, Beijing initially formed a low-consumption, -pollution and -emission model of economic development. Amid constantly increasing energy consumption, the entire industry shows a declining trend, with energy intensity declining from 1.982 standard coal per 10^4 yuan in 1995 to 0.526 standard coal per 10^4 yuan in 2012 (in 1995 constant price) — a decline of 73.46%, showing that Beijing's energy efficiency has made great strides.

4.2.4. Energy structure

Scholars have not reached an agreement on the impact of energy structure on carbon emissions in Beijing. Liu et al. (2010) suggested that energy structure was affected by resource constraints in regions and is difficult to change in the short term. Although in the long run, energy structure has a pulling effect on CO_2 emissions, the contribution is small at 1.67%. Li (2011) argues that energy structure has an inhibitory effect on the per capita carbon emissions of Beijing; the contribution is small, similar to Liu et al. (2010), further weakening after 2006. However, Wu et al. (2014) found that due to the great effort to reduce coal-fired emissions in winter, the proportion of coal consumption decreased significantly; therefore, energy structure made great contributions to reducing emissions in Beijing. The results regarding factors influencing changes in carbon emissions in our research are partly consistent with Wu's conclusion (2014). We affirm the contribution of energy structure to carbon emissions and highlight that energy structure exerts an inhibitory effect on the growth of carbon emissions—except in 1996–1997 and 2002–2003—and that the inhibition has been increasing year by year, which differs from the conclusion of Li (2011). Since 2004, Beijing has adopted a series of measures, such as substituting oil and gas for coal to optimize energy structure and promote the stability of the energy consumption structure. The coal consumption rate decreased from 64.36% in 1995 to 35.49% in 2012; the proportion of consumption of clean energy is rising, playing a positive role in inhibiting the growth of carbon emissions; however, the energy structure dominated by coal has not fundamentally changed. Therefore, although the energy structure inhibits the growth of carbon emissions, the inhibitory effect is small, contrary to the findings of Wu et al. (2014).

5. Conclusions and suggestions

Based on the data on energy consumption and economic development during 1995–2012 in Beijing, we established a factor decomposition model of energy-related carbon emissions with the extended Kaya identity and GFI method, quantitatively analyzed the effects of energy structure, energy intensity, economic development and population size on carbon emissions from energy consumption in Beijing, We draw the following main conclusions and policy recommendations:

i) The contribution of economic development to energy-related carbon emissions in Beijing shows exponential growth. Energy consumption caused by sustained growth of economic output is still a dominant factor in the growth of carbon emissions in Beijing; the cumulative contribution is 334.5%. The growth in economic output is necessary for meeting the basic national goals of survival and development. Environmental pressure from maintaining the economic system is unavoidable. With Beijing's rapid economic development, carbon emissions have also grown since 2003, mainly because economic growth in Beijing has not eliminated the city's dependence on energy consumption. To control carbon emissions in the process of economic development, Beijing should first change its mode of economic development and divert attention from a one-sided pursuit of economic growth to the pursuit of quality economic growth and environmental protection. Furthermore, it should establish and improve related laws and regulations on carbon emissions; review these provisions' content on permits, distribution, trading and other matters; implement an access threshold for enterprises on carbon trading and carbon emissions; and achieve harmony among economic, social and environmental development.

ii) Population size is another factor promoting the growth of energy-related carbon emissions in Beijing. The pulling effect on carbon emissions is obvious; after 2003, the contribution rate shows an increasing trend year by year. However, since 2011, due to the implementation of a more stringent population control policy, its contribution rate has declined slightly. Although the contribution of population is smaller than that of economic growth, population growth also promotes the growth of carbon emissions to a certain extent. The increasing population will place greater pressure on the environment. Therefore, in the process of urbanization, the government should improve the existing household registration system, rationally distribute the population, actively guide migrant workers to and settle them in specific urban areas, pay attention to optimizing the structure and quality of population, and control the population to achieve harmony with environmental capacity.

iii) Energy intensity is a major contributor to the decline in carbon emissions. With the optimization of the energy structure and the improvements in energy efficiency, the inhibition of energy intensity on carbon emissions has increased yearly. Improving energy efficiency is a well-known method for reducing carbon emissions. In our analysis, energy intensity has an obvious inhibiting effect on carbon emissions, and the trend continues to grow. There is still room to decrease carbon emissions by increasing energy efficiency. In the future, Beijing should continue to reduce energy consumption per unit of GDP, establish a target responsibility system, and take a variety of approaches to accelerate the development of a low-carbon economy. For example, the capital could increase scientific and technological input into energy, use advanced technology to improve energy utilization efficiency in high-energy-consuming industries, and fully explore the potential for saving energy and reducing the emissions of high-energy-consuming industrial sectors. Additionally, Beijing could actively promote the transformation and application of clean energy technology achievements, realize the upgrade and transformation of energy-saving technology, and reduce the loss of energy in the processes of production, transformation, transportation and consumption.

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iv) Energy structure plays an inhibitory role in the growth of carbon emissions. Its inhibitory effect is weaker than that of energy intensity. However, with the optimization of energy structure, the inhibition effect of energy structure has enhanced yearly. Because the traditional energy is highly polluting and a dwindling stock, the optimization and adjustment of the energy consumption structure will be crucial to saving energy and reducing consumption. Constrained by energy storage and economic conditions, Beijing's economic, scientific and technology allow a new energy strategy to reduce emissions. Therefore, positively constructing a diverse, safe, clean, and efficient energy supply and consumption system; promoting the application and popularization of no- or low-carbon energy, such as solar, wind, nuclear and tidal; and achieving the substitution of traditional fossil energy will further ease Beijing's carbon emissions. Additionally, to strengthen the adjustment of the energy structure, the government should provide support in the forms of tax incentives, capital, technology, markets and other aspects of environmental protection; create a favorable environment for the development of clean energy; and reduce the emission of greenhouse gases from the sourcing and production processes.

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