RESEARCH ARTICLE

Using Kaya and LMDI models to analyze carbon emissions from the energy consumption in China

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Abstract

China has become the largest carbon-emitting country in the world since 2007. To achieve national environmental goals by 2030, the carbon emissions per unit of gross domestic product (GDP) will need to fall to 60–65% of 2005 levels. Such a dramatic decrease presents a challenge for a nation in adjusting its energy source and usage, but via monitoring of reductions, greater understanding can be gained of how carbon emitters are responding to national goals. We analyzed the change in carbon emissions from China's fossil energy consumption from population, per capita GDP, energy efficiency improvements and energy structure using a Kaya identity model and Logarithmic Mean Divisia Index (LMDI) factor decomposition method from 2006 to 2018. Results suggest that trends in carbon emissions from 2006 to 2018 can be broken down into four periods: a rapid increase period during 2006–2011, a slowdown increase period during 2011–2014, a consecutive decline period during 2014–2016 and a rebound during 2017–2018. Trends in carbon emissions were greatly affected by per capita GDP and energy efficiency. While per capita GDP increased carbon emissions, energy efficiency had a countering effect on carbon emissions. Our results suggests that China's measures in the past decade to reduce carbon emissions (i.e. carrying out carbon emissions trading on a fixed basis, readjusting the economic structure, optimizing the energy structure, improving energy efficiency and increasing forest carbon sinks) have helped to reduce carbon emissions. However, China should continue to actively respond to climate change while striving to achieve of economic sustainable development and social progress.

Keywords China's carbon emissions · Energy consumption · Kaya model · LMDI factor decomposition

Introduction

China's energy consumption and rapid economic development has resulted in it becoming the world's largest carbon emitter (Wang et al. 2014; Yang and Kong 2017; Liang et al. 2019a, b) along with developing a number of environmental problems. In response, some in China, along with the government, have strived for further development to embrace a principle known as Ecological Civilization in order to promote a circular, green, low-carbon development economy that addresses climate change and maintains ecological security (Wei et al. 2011).

The philosophy behind China's 2007 proposal (Wang et al. 2014) to build an Ecological Civilization (Tiejun et al. 2012; Pan 2016) promotes a sustainable development path and the adoption of a low-carbon economy to balance the relationship between energy consumption and economic development (Wei et al. 2011). China has become aware that many human activities can exacerbate carbon emissions via the burning of fossil fuels to support per capita consumption. However, the structure of energy development, associated use or adoption differences across geographic regions of China can hinder or help achieving an Ecological Civilization (Liu et al. 2016). For example, the movement away from coal-fired sources of energy and the embracing of vehicle electrification could promote an Ecological Civilization. Several approaches have been taken to assess how China is benefiting from changes in carbon emissions in response to human activities and energy management (Huisingh et al. 2015; Liu et al. 2016); these are in addition to other existing approaches used in China and beyond (Moss et al. 2010; O'Mahony 2013).

Kaya identity and the Logarithmic Mean Divisia Index (LMDI) approach are two methods that have become

commonly used in China and across the world for assessing changing carbon emissions due to source types. Kaya identity is a widely used method for studying large scale energy and environmental problems, which can describe the relationship between population, economy, policy, energy and carbon emissions (Kaya 1990; O'Mahony 2013; Mavromatidis et al. 2016; Mai and Cai 2018). For example, O'Mahony (2013) used a Kaya identity analysis to evaluate Ireland's carbon emissions from 1990 to 2010. Mavromatidis et al. (2016) evaluated Switzerland's future energy strategy via a Kaya identity analysis with a specific focus on the building sector and its effect on the Swiss village. Mai and Cai (2018) used a Kaya identity analysis and evaluated the Chinese commercial building sector to examine trends in commercial building carbon emissions from 2001 to 2015.

The Logarithmic Mean Divisia Index (LMDI) approach, which can analyze the importance of each factor influencing carbon emissions, has been used widely in the field of energy economics (An et al. 1998; Wang et al. 2005). Madaleno and Moutinho (2017) decomposed the energy emissions of the European Union into six drivers used the LMDI method and found that the impacts of individual drivers on carbon emissions varied with different countries and analytical periods. Carbon emissions from Italy were decomposed into two time intervals and four drivers (Andreoni and Galmarini 2012). The LMDI approach has also been used to identify the main factors, sectors and industries that influenced carbon emissions in different time periods in China (Xu et al. 2014, 2016) and to analyze the effect of industrial structural activity on industrial carbon emissions (Liu et al. 2007).

Previous research on China using the Kaya identity or LMDI approach has examined CO_2 emissions from earlier time periods (and in some case with multiple sectors) (Liu et al. 2007; Xu et al. 2014, 2016; Liang et al. 2019a, b), projected emissions into the further (Guan et al. 2008), examined specific industry effects, examined a range of CO_2-producing sectors in a time period and the interplay of economics or examined a range of CO_2-producing sectors in a time period in a single city. Our study focuses on China during the time period of 2006–2018 (most recently available data). We conducted a novel analysis that employed both a Kaya identity and LMDI approach and that examined (1) carbon emissions sources/drivers from energy consumption and (2) the form of the carbon emissions effect in terms of population, per capita GDP, energy efficiency and energy structure. Our goal is to improve understanding of recent emission trends, in relation to past and facilitate the further development of a low-carbon economy in China.

Data and methods

The carbon emitters of the combustion of fossil energy (i.e. coal, crude oil, natural gas) were focused on our study, and data were acquired from the *China Statistical Yearbook* (National Bureau of Statistics of China 2019) (Table 1). Carbon emissions were estimated from the consumption of coal, crude oil and natural gas, per the following formula:

$$C^t = \sum_{i}^{3} E_i^t \times c_i \quad (i = 1, 2, 3) \tag{1}$$

where the C^t represents the total carbon emissions in the t year, the E_i^t represents the energy consumption of energy i in the t year, and the c_i represents the carbon emission coefficient of energy i. The carbon emission coefficient (c_i) is obtained by consulting typical literature related to carbon emissions and taking its average value (Table 2).

Carbon emissions from energy consumption in China were analyzed per a Kaya model and LMDI decomposition approach using four factors (population, per capita GDP, energy efficiency and energy structure). These factors were expressed by an extended Kaya model as follows:

$$C^t = \sum_{i} P^t \times \frac{Y^t}{P^t} \times \frac{E^t}{Y^t} \times \frac{E_i^t}{E^t} \times \frac{C_i^t}{E_i^t}$$
$$= \sum_{i} P^t \times a^t \times e^t \times s_i^t \times I_i^t \tag{2}$$

where C^t represents the total carbon emissions in the t year, P^t represents the total population in the t year, Y^t represents the GDP in the t year, E^t represents the total energy consumption in the t year, E_i^t represents the energy consumption of energy i in the t year, and C_i^t represents the carbon emissions of energy i in the t year.

According to the addition and decomposition method of LMDI decomposition:

$$\Delta C^t = \Delta C_p^t + \Delta C_a^t + \Delta C_e^t + \Delta C_s^t + \Delta C_{int}^t \tag{3}$$

Energy consumption carbon emissions were defined as the comprehensive effect ΔC^t; the comprehensive effect included the effect of population (ΔC_p^t), per capita GDP (ΔC_a^t), energy efficiency (ΔC_e^t), energy structure (ΔC_s^t) and energy carbon emission intensity (ΔC_{int}^t), respectively.

Cumulative effect was calculated per the following formulas and using 2006 as the base period:

$$\Delta C_p^t = \sum_{i} L\left(C_i^t, C_i^{2006}\right) \ln \frac{P^t}{P^{2006}} \tag{4}$$

$$\Delta C_a^t = \sum_{i} L\left(C_i^t, C_i^{2006}\right) \ln \frac{a^t}{a^{2006}} \tag{5}$$

$$\Delta C_e^t = \sum_{i} L\left(C_i^t, C_i^{2006}\right) \ln \frac{e^t}{e^{2006}} \tag{6}$$

$$\Delta C_s^t = \sum_{i} L\left(C_i^t, C_i^{2006}\right) \ln \frac{s^t}{s^{2006}} \tag{7}$$

Table 1 The population, GDP and energy consumption during 2007 to 2016 in China

Year	Population (ten thousand people)	GDP (billion yuan)	Total energy consumption (ten thousand tce)	Coal (%)	Crude Oil (%)	Natural Gas (%)	Primary electricity and other energy (%)
2006	131,448	219 43.85	286,467	72.4	17.5	2.7	7.4
2007	132,129	270 23.23	311,442	72.5	17.0	3.0	7.5
2008	132,802	319 51.55	320,611	71.5	16.7	3.4	8.4
2009	133,450	349 08.14	336,126	71.6	16.4	3.5	8.5
2010	134,091	413 03.03	360,648	69.2	17.4	4.0	9.4
2011	134,735	489 30.06	387,043	70.2	16.8	4.6	8.4
2012	135,404	540 36.74	402,138	68.5	17.0	4.8	9.7
2013	136,072	595 24.44	416,913	67.4	17.1	5.3	10.2
2014	136,782	643 97.40	425,806	65.6	17.4	5.7	11.3
2015	137,462	689 05.21	429,905	63.7	18.3	5.9	12.1
2016	138,271	744 12.72	436,000	62.0	18.3	6.4	13.3

$$\Delta C_{int}^t = \sum_i L\left(C_i^t, C_i^{2006}\right) \ln \frac{I^t}{I^{2006}} \tag{8}$$

Defined as:

$$L\left(C_i^t, C_i^{2006}\right) = \begin{cases} \dfrac{C_i^t - C_i^{2006}}{\ln\left(C_i^t\right) - \ln\left(C_i^{2006}\right)}, & C_i^t \neq C_i^{2006} \\ C_i^t \text{ or } C_i^{2006}, & C_i^t = C_i^{2006} \end{cases} \tag{9}$$

According to Eq. (2), the effect of energy carbon intensity (ΔC_{int}^t) refers to the impact of changes in each energy carbon emission coefficient on carbon emission, and its value is zero, which means ΔC_{int}^t has not exerted its influence on carbon emission. Thus, our study only examines four factors: population effect (ΔC_p^t), per capita GDP effect (ΔC_a^t), energy efficiency effect (ΔC_e^t) and energy structure effect (ΔC_s^t).

In order to compare the contribution of different effects to carbon emission in the same year and the contribution of the same effect to carbon emission in different years, we defined contribution degrees for the effects of population, per capita GDP, energy efficiency and energy structure as follows:

$$\mu_p = \frac{\Delta C_p}{\Delta C}, \mu_a = \frac{\Delta C_a}{\Delta C}, \mu_e = \frac{\Delta C_e}{\Delta C}, \mu_s = \frac{\Delta C_s}{\Delta C} \tag{10}$$

Results and discussion

Cumulative effect of energy consumption emissions

China's carbon emissions increased from 18.33×10^8 in 2006 to 26.49×10^8 t in 2018, which represents a total increase of 8.16×10^8 t and average annual growth rate of 0.68×10^8 t (Fig. 1). Our results suggest that the growth of carbon emissions can be broadly divided into two phases. The first phase is a rapid growth stage (2006–2011), with an average increase of 1.19×10^8 t carbon emission per year. This time frame in China coincides with a period of rapid economic development given China had recently joined the World Trade Organization (WTO) in December of 2001 (Agarwal and Wu 2004). The second phase is a deceleration stage (2012–2018), during which the average carbon emission increase was 0.28×10^8 t per year (less than the first stage), and even declined in 2015 and 2016, while energy consumption still grew. We argue that this second phase is related to a shift in economic forces in part driven by long-term declines in the agriculture and industry sectors and that began stabilizing in 2013 to a new Normal' (Wang and Jiang 2019). However, carbon emissions rebounded from 2017 and reached a new high in 2018, a trend consistent with the global change in carbon emissions over the same period (Peters et al. 2020). Global carbon emissions

Table 2 Carbon emission coefficient of each energy

Data sources	Coal	Crude oil	Natural gas	Electricity
DOE/EIA	0.702	0.478	0.389	0.0
Japan institute of energy economics	0.756	0.586	0.449	0.0
Energy research institute of National development and reform commission	0.748	0.583	0.444	0.0
The average	0.735	0.547	0.427	0.0

from global energy consumption were roughly flat from 2014 to 2016 but rose 2% in 2018 (Fig. 1) and by 2.6% in 2019 (Peters et al. 2020). Wang and Jiang (2019) note that from 2003/2004 to 2013/2014, China's efforts in energy conservation and emission reduction were having a positive effect, but industry-associated emissions were a continual challenge for China to reduce. Xu et al. (2014) show that this effect from industry began prior to 1995. Xu et al. (2016) note the strong effect of energy intensity in the industrial sector and carbon emission production and suggest continued focus on improving energy efficiency to reduce emissions but especially in the industrial sector. Liang et al. (2019a, b) note that between 1998 and 2015, per capita output was a primary driver of emissions, and beginning around 2010, population began to become a predominant secondary driver.

Our results show that the energy consumption carbon emission effect (comprehensive effect) sustained a rapid increase from 2007 to 2011, a slower increase from 2011 to 2014 and then decreased slightly for two consecutive years from 2014 to 2016, which is consistent with the change in total carbon emissions (Peters et al. 2020). Carbon emissions from China's energy consumption have been roughly flat for 3 years (Fig. 2). China in 2014 enacted the "energy development strategic action plan (2014–2020)", which strived to move China towards a low carbon energy development strategy (more natural gas and non-fossil fuels (Wang and Jiang 2019). However, our results suggest that even with the shift in fossil fuel use (Fig. 5), China's per capita GDP still remains through 2018 a substantial contributor of carbon emissions and is perhaps countering positive governmental policies to reduce emissions.

Similar to results from Liang et al. (2019a, b) for earlier time periods, we found that the population effect and the per capita GDP effect had a positive correlation with the change of energy consumption and carbon
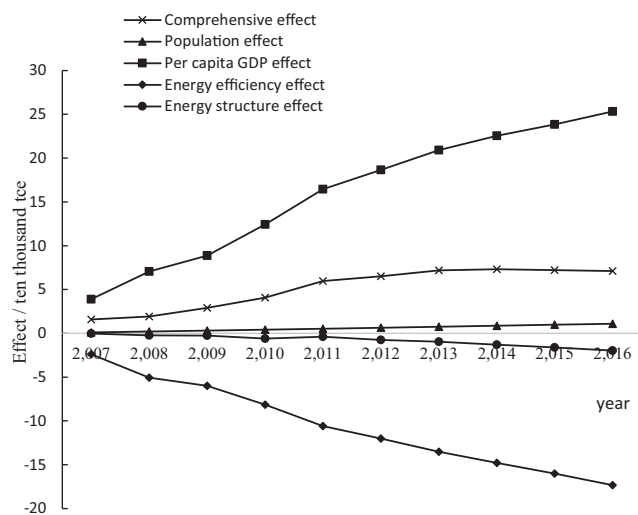
emissions. Our data show a notable increase beginning after 2008, and as of 2014, per capita GDP is a primary driver still, while the effect of population has remained relatively constant since 2011. The energy efficiency effect and the energy structure effect exhibit a negative correlation with the change in energy consumption and carbon emissions (Fig. 2). Per capita GDP and the energy efficiency effect had a strong impact on carbon emissions, while population effect and energy structure effect impact carbon emissions weakly.

Contribution of each effect to carbon emission

Carbon emission from energy consumption in China was analyzed per four factors: energy efficiency effect (37.904), per capita GDP effect (− 25.325), energy structure effect (− 1.968) and population effect (1.385) (Table 3).

Population effect was in a state of continual modest increase, and its contribution to carbon emissions remained around 0.1 over the study time period (Table 3). The natural population increase rate remained between 4.79 and 5.86%. Although China is a country with a large population, its population increase rate has dropped sharply in recent years and remained relatively stable, most likely due to China's one child policy, aging and declining fertility rate.

Our results show that the contribution of per capita GDP effect on carbon emissions was positively linear from 2007 to 2018. Our results also show that per capita GDP increased from 20,450 yuan/person in 2007 to 53,882 yuan/person in 2017, and the carbon emission effect increased over the same time from 3.879×10^4 t of standard coal in 2007 to 25.322×10^4 t of standard coal in 2017 (Fig. 3). We suggest that the increase of per capita GDP is an important factor driving the increase of total carbon emissions in China. China became the third largest economy in the world in 2007 and the second largest in 2011 (CRS 2019) but recently growth has slowed (Wang and Jiang 2019). To date, China has become the largest carbon emission country in the world (Peters et al. 2020).
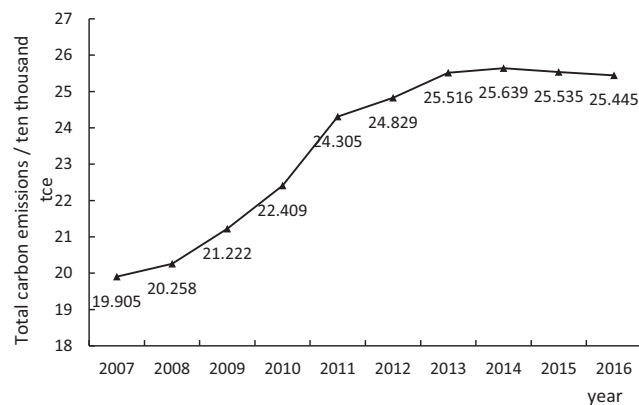

Fig. 1 The total effect of energy consumption carbon emission

Fig. 2 Change of Chinese carbon emission

Table 3 Contribution of carbon emissions from energy consumption in China from 2007 to 2016

Year	Contribution of population effect	Contribution of per capita GDP effect	Contribution of energy efficiency effect	Contribution of energy structure effect	Contribution of comprehensive effect
2007	0.063	2.462	−1.511	−0.014	1.0
2008	0.102	3.655	−2.631	−0.126	1.0
2009	0.103	3.065	−2.077	−0.091	1.0
2010	0.099	3.048	−2.001	−0.146	1.0
2011	0.087	2.753	−1.775	−0.066	1.0
2012	0.098	2.870	−1.851	−0.117	1.0
2013	0.104	2.909	−1.880	−0.133	1.0
2014	0.118	3.084	−2.024	−0.179	1.0
2015	0.135	3.310	−2.222	−0.222	1.0
2016	0.154	3.559	−2.436	−0.277	1.0

Increasing carbon emissions are in part a result of policy gaps for achieving China's climate targets in the Paris Agreement (Gallagher et al. 2019); it remains to be seen if any country will sacrifice economic growth and security for achievement of environmental goals such as carbon emission controls.

Energy consumption of unit GDP was 54.78% in 2018 lower than that of 2007 (Fig. 4). Optimizing the unit GDP from energy consumption could curb the increase in carbon emissions. The absolute value of energy efficiency effect indicated that the optimization of energy consumption per unit GDP is important to reducing carbon emissions, and a similar conclusion is noted by Xu et al. (2016). China has improved energy efficiency through improving technology for cleaner production. Even so, China's energy consumption still constitutes a large proportion of the world's total consumption. Although China's unit GDP of energy consumption has been declining year by year (Fig. 4), it has remained higher than the global average during the study period. In 2016, for example, China's unit GDP of energy consumption was 1.4 times greater than the global average and 2.1 times greater than the average for developed countries.

Energy structure

Our results show that in China, coal consumption, as of 2018, still accounts for the largest energy supply among all three energy sources, and natural gas has a relatively small share. From 2007 to 2018, the proportion of natural gas consumption in the total energy consumption of the three major primary energy sources increased by 5.1%, with a small and steady growth rate. At the same time, the proportion of coal consumption decreased from 72.5 in 2007 to 59.0% in 2018 (Fig. 5). Coal is still widely consumed by China's population, and natural gas consumption only accounts for a small proportion of energy supply. The promotion and use of natural gas still lags behind. However, while total energy consumption is large in China, the per capita share of energy is small, and the demand for energy is still high. As a result, large-scale exploitation and utilization of fossil energy will likely continue in China to meet the need of sustained and rapid growth of energy consumption. Considering the potential environmental consequences from such energy consumption should be taken
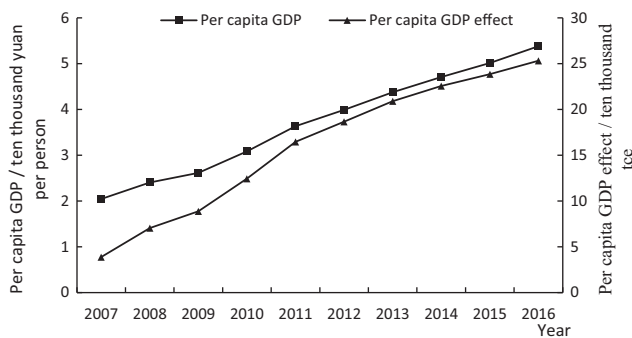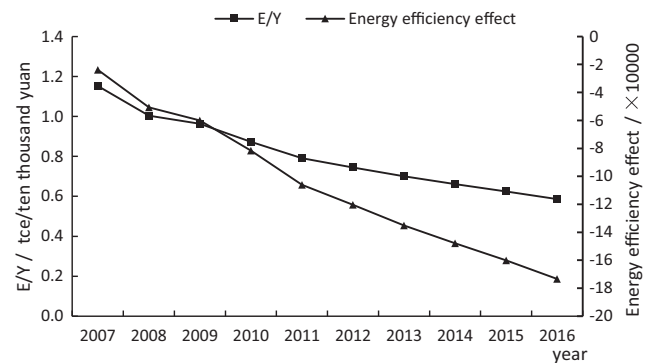

Fig. 3 The change of per capita GDP and its effect

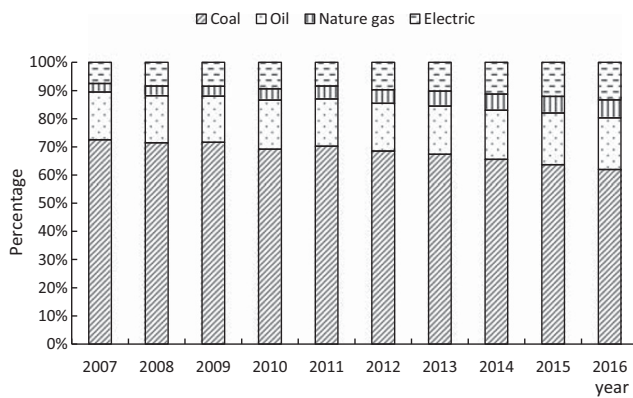**Fig. 4** The change of E/Y and energy efficiency effect

Fig. 5 The change of energy structure

to achieve a sustainable development pathway of China's economy and society.

Conclusions

Via a Kaya model and LMDI decomposition approach, we resolved carbon emissions from energy consumption in China between 2006 and 2018 for the effects of population, per capita GDP, energy efficiency and energy structure. Energy consumption carbon emissions increased rapidly from 2007 to 2011; the increase slowed from 2011 to 2014 and exhibited a slight decline from 2014 to 2016 but again increased through 2018.

We found that per capita GDP and energy efficiency were the main factors driving carbon emission effect, while the effects of population and energy structure were secondary. Increasing per capita GDP increased carbon emissions from 2007 to 2018. We suggest that reducing energy consumption per unit GDP could be an effective measure to reduce China's carbon emissions.

China has taken aggressive measures to cope with climate change, such as trials of carbon emission trading, carbon sequestration in forests and soils, improving energy efficiency and adjusting the country's economic and the energy structure to a degree. China should vigorously support the innovation of industrial technologies to improving energy efficiency, especially in high-energy-intensive industries, and sustainable development, further optimize the national economic structure, develop industries that consume less energy and replace fossil fuels with renewable energy.

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