ENERGY-RELATED CARBON EMISSIONS AND ITS INFLUENCING FACTORS DECOMPOSITION IN THE YANGTZE RIVER DELTA REGION, CHINA

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Abstract. With rapid economic growth, energy consumption and emission reduction have become one of the most urgent issues in the Yangtze River Delta region(YRD), China's first important economic circle. In this paper, we estimate the energy-related CO_2 emissions in the YRD during 2005-2016 using the emission measurement method provided by the IPCC (2006). In addition, the effects of various driving factors, such as population size, economic scale, industrial structure, energy intensity and energy structure, on CO_2 emissions in this region are quantitatively analyzed by applying the LMDI factor decomposition model. The results show that the primary influencing factors of CO_2 emissions in the YRD are economic growth and energy intensity. Population size and economic growth promoted CO_2 emissions during 2005-2016, and economic growth is the decisive driving factor. On the contrary, the industrial structure, energy intensity, and energy structure of the YRD have inhibitory effects, and energy intensity is the dominant factor among them to restrain the growth of CO_2 emissions. Besides, we discuss these results in detail and find that industrial structure and energy structure have great potential for CO_2 emission reduction in the YRD. Finally, we put forward corresponding sustainable policy suggestions for optimizing industrial structure and energy structure to promote low-carbon economic development.
Keywords: *energy, carbon emissions, factors decomposition, LMDI, Yangtze River Delta region, China*

Introduction

Global warming has become an environmental issue that many countries and regions have attached great importance to in recent years. The main reason for global warming is that with the growth of the world economy, human beings have used a large number of fossil fuels (such as coal, oil, etc.) for nearly a century, and the major component of greenhouse gas emissions is carbon dioxide (CO_2). According to the Kyoto Protocol, China does not have to undertake binding emission reduction tasks as a developing country. Still, China's rapid economic growth has brought increasing pressure to reduce CO_2 emissions as well. On September 3, 2016, China signed the Paris Agreement, pledging to reduce carbon emissions intensity by 40% to 50% by 2020 (Musa et al., 2018; Pan et al., 2018).

According to the International Energy Agency (IEA) report, China's CO_2 emissions accounted for about 27% of the total global CO_2 emissions in 2017, ranking first in the world, which will make China even more difficult to achieve emission reduction goals. As one of the three major economic circles in China, the Yangtze River Delta region (YRD) contributes 207.96 million tons of standard coal in 2016 to China's total energy consumption (Ding et al., 2018; Xiao et al., 2018). Therefore, it is of practical significance to analyze the CO_2 emission of energy consumption in the YRD. Given this, this paper calculated the overall energy-related CO_2 emissions in the YRD (Shanghai, Jiangsu, and Zhejiang) from 2005 to 2016 and used the factor decomposition model of the Logarithmic Mean Divisia Index (LMDI) to analyze the effects of population size,

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economic growth, industrial structure, energy intensity, and energy structure on CO_2 emissions of the YRD.

At present, in the methods for quantitatively studying CO_2 emissions, the commonly used decomposition methods mainly include Data Envelopment Analysis (DEA) (Wang et al., 2018a,b; Zhou et al., 2018), Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA) (Wang et al., 2018, 2018a; Meng et al., 2018b; Zou et al., 2018; Li et al., 2018a; Gu et al., 2018b), and the econometric model (Meng et al., 2018a; Zhao and Zhang, 2018b; Song, 2018). The Logarithmic Mean Divisia Index (LMDI) has been considered as an improvement in the exponential decomposition method. Compared with other decomposition methods, the LMDI model is more effective in studying the factor decomposition analysis, and its results are also more applicable. Furthermore, one crucial difference between the LMDI and other models lies in the form of weighted decomposition of residuals. The LMDI method can continue to calculate when the data appears zero and has no residual items in the decomposition process (Ang, 2004; Ang, 2007), which becomes a significant advantage. Therefore, it has been widely applied in recent decomposition studies.

There have been many studies on energy consumption or CO_2 emissions in the context of China by the LMDI decomposition method in recent years. These researches applying the LMDI decomposition model could be divided into two areas: one is the overall level, that is, the study of China's carbon emissions on a national scale; the other is the local level, that is, regional research on China's provinces or cities or parts of some regions. On a national scale, Liu et al. analyzed the changes in industrial carbon emissions from 36 industrial sectors in China based on a time series decomposition of the LMDI method (Liu et al., 2007). Zhang et al. presented a decomposition analysis of energy-related CO_2 emissions in China from 1991–2006 divided into three equal time intervals (Zhang et al., 2009). Wang et al. used the LMDI method to analyze the driving factors of carbon emission growth in China and found that the main positive driving factor is per capita GDP. In contrast, the main negative factor is the improvement of energy efficiency (Wang et al., 2010). Tan et al. (2011) examined the driving forces for reducing China's CO_2 emission intensity during 1998-2008, utilizing the LMDI technique. Jiao et al. (2013) used the LMDI model to forecast China's energy demand and CO_2 emissions in 2020 under five scenarios. They analyzed the contributions of five factors to CO_2 emissions in China's nine industries. Yang et al. (2020) analyzed the change in carbon emissions from China's fossil energy consumption by using a Kaya identity model and the LMDI method from 2006 to 2018. Some studies also concentrate on different specific industries in China, such as the cement industry (Xu et al., 2012), chemical industry (Lin et al., 2016), and petroleum refining and coking industry (Xie et al., 2016).

There are also plenty of studies on China's regions, provinces, and city level using the LMDI method. Liu et al. (2012) studied the regional and sectoral disparity and driving factors on greenhouse gas emissions in 30 Chinese provinces. Ren et al. (2012) assessed the drivers of industrial carbon emissions in China's nine economic regions. Zhou et al. (2017) conducted a comparative study on industrial carbon emissions in eight major regions of China. Similar LMDI-based literature also included studies in other specific regions in China, such as the Beijing-Tianjin-Hebei region (Zong et al., 2016), Yangtze River Economic Zone (Ye et al., 2020), Northwestern China (Li et al., 2020), Liaoning province (Yan et al., 2019), Shandong province (Dong et al., 2018), Inner Mongolia region (Tseng et al., 2019), Zhejiang province (Xia et al., 2017), Beijing

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(Cui et al., 2020), Tianjin (Wang et al., 2017), Shanghai (Zhao et al., 2009), and Guangzhou (Wang et al., 2019). Some existing studies are related to the YRD. For example, Zhu et al. (2017) analyzed the industrial energy-related CO_2 emissions of cities in the YRD and predicted the CO_2 reduction potential routes of these cities. Song et al. measured the carbon emissions related to energy consumption in the YRD from 1995 to 2010 and set up an incremental factor decomposition model of carbon emissions with the LMDI (Song et al., 2015). The two studies mentioned above have made relatively adequate research about the YRD. However, they preferred to focus on some cities in this region and only used a few types of fuels, such as coal, oil, and natural gas, to calculate. As we can see in the previous literature, studies on CO_2 emission factor decomposition of regions in China have not focused much on the YRD, especially applying multiple energy types, concentrating on a variety of industries, and focusing intensively on CO_2 emission driving factors of the YRD as a whole. Given this, this paper adopts six industries and ten types of fuels to calculate energy-related CO_2 emissions. Based on the LMDI factor decomposition model, quantitative analyses are made on the driving factors of CO_2 emissions, such as population size, economic growth, industrial structure, energy intensity, and energy structure, and the corresponding policy suggestions are finally proposed. The objective of this study is to analyze the impacts of these economic, social, energy and environmental factors on regional carbon emissions in the YRD by estimating the carbon emissions and decomposing their driving factors, then to identify trends in carbon emissions in the YRD by analyzing their path growth. This article is arranged as follows. Section 2 introduces CO_2 emission measurement method and data sources, Section 3 illustrates the factor decomposition model, Section 4 is an empirical analysis and discussion in detail, Section 5 concludes and puts forward corresponding policy suggestions.

Methodology and data

CO2 emission measurement methods

Energy-related CO_2 emissions of the YRD are calculated according to the measurement methods recommended by the Emissions Technical Guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006). The calculation formula is as follows:

$$\mathrm{C} = \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij} = \sum_{i=1}^{m}\sum_{j=1}^{n} E_{ij} \times R_j \tag{Eq.1}$$

where C is the total CO_2 emissions (unit: 10,000 tons); E_{ij} is the jth energy consumption in the ith industry (unit: 10,000 tons of standard coal); R_j is the CO_2 emission coefficient of the jth energy (unit: tce/t for fuels; tce/10^4m^3 for gas); and where m = 3, n = 10. Since the units of consumption of raw coal, clean coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and liquefied petroleum gas are 10,000 tons, while the unit of consumption of natural gas is 10000 cubic meters, we unified the units to 10,000 tons of standard coal. Carbon emission factors and standard coal coefficients of ten kinds of fuels are as follows (see *Table 1*.)

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Table 1. *Carbon emission factor and standard coal coefficient*

Fuels	Carbon Emission Factor （t/tce）	Standard Coal Coefficient (tce/t；tce/10^4m^3)
Raw Coal	0.7559	0.7143
Washed Coal	0.7559	0.9000
Coke	0.8550	0.9714
Crude Oil	0.5857	1.4286
Gasoline	0.5538	1.4714
Kerosene	0.5714	1.4714
Diesel	0.5921	1.4571
Fuel Oil	0.6185	1.4286
Liquefied Petroleum Gas	0.5042	1.7143
Natural Gas	0.4483	12.2900

Source: Converted from the IPCC Guidelines for National Greenhouse Gas Emission Inventory

Data sources

This paper selects six industrial sectors and classifies them into the primary industry, secondary industry, and tertiary industry, respectively. The primary industry includes "Agriculture, forestry, animal husbandry, fishery, and water conservancy", the secondary industry includes "industry" and "construction", and the tertiary industry includes "transport, storage and post", "wholesale and retail trades and hotels and catering services" and "other sectors". The data on the terminal energy consumption of the six industrial sectors in the YRD is derived from the "Regional Energy Balance Sheet (physical quantity)" of Jiangsu, Shanghai, and Zhejiang in China Energy Statistical Yearbook, 2006-2017.

The demographic and economic data are derived from the China Statistical Yearbook and the Statistical Yearbook of provinces(Shanghai, Jiangsu, and Zhejiang), 2006-2017. The population of each region is the resident population counted in the China Statistical Yearbook. Due to the impact of price changes, it is not suitable to directly use the nominal GDP of the current year for comparative analysis. Therefore, the economic data of this paper have been converted into prices based on 2005 to eliminate the price change impacts. CO_2 emissions data are calculated based on the consumption of various terminal energies and their carbon emission factors.

Decomposition model

For the factor decomposition of CO_2 emissions, Yoichi Kaya proposed the Kaya identity at a seminar organized by the UN's IPCC in 1989. Kaya identity combines carbon emissions on energy, population level, and economic scale to quantify the relative roles of key drivers of CO_2 emissions (Kaya, 1990):

$$C = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{C}{E} \quad \text{(Eq.2)}$$

where C is the CO_2 emissions; E is the total energy consumption; G is the gross product (GDP); P is the population size. In order to facilitate the analysis by industry and energy

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types, the endogenous factors of energy CO_2 emissions are decomposed according to the Kaya identity and rewritten into the following formula (Ang, 2005):

$$C = \sum_{i=1}^{3}\sum_{j=1}^{10} C_{ij} = \sum_{i=1}^{3}\sum_{j=1}^{10} P \times \frac{G}{P} \times \frac{G_i}{G} \times \frac{E_i}{G_i} \times \frac{E_{ij}}{E_i} \times \frac{C_{ij}}{E_{ij}} = \sum_{i=1}^{3}\sum_{j=1}^{10} P \times A \times S_i \times E_i \times N_{ij} \times R_{ij} \quad \text{(Eq.3)}$$

where C represents the total CO_2 emissions; C_{ij} the CO_2 emissions generated by the jth type energy consumption in the ith industry; E_{ij} the consumption of the jth energy in the ith industry; E_i the total energy consumption in the ith industry; G_i the industrial added value of the ith industry; G the gross domestic product (GDP) of the YRD; P the population size. Therefore, in the formula (3), A is the GDP per capita (economic growth factor); S_i the ratio of the industrial added value of the ith industry (industrial structure factor); E_i the energy consumption intensity of the ith industry (energy intensity factor); N_{ij} the proportion of the jth energy consumption of the ith industry (energy structure factor); R_{ij} the CO_2 emission coefficient of the jth energy of the ith industry (carbon emission factor).

The total CO_2 emission in the base period is set as C^0. In this paper, the year 2005 is taken as the base period, the total amount of CO_2 emissions in the t period is C^t, and the change of CO_2 emissions amount from the base period to the t period is ΔC, which means the comprehensive effect of CO_2 emissions. Thus, the influencing factors of energy-related CO_2 emission can be divided into population size effect ΔCp, economic growth effect ΔCa, industrial structure effect ΔCs, energy intensity effect ΔCe, energy structure effect ΔCn, and carbon emission factor effect ΔCr.

LMDI decomposition methods can be divided into "multiplicative" and "additive" decomposition methods. However, the final decomposition results of both methods are consistent. Based on *Equation 3*, this paper adopts the additive decomposition method as follows:

$$\Delta C = C^t - C^0 = \sum_i\sum_j \left(P^t A^t S_i^t E_i^t N_{ij}^t R_{ij}^t\right) - \sum_i\sum_j \left(P^0 A^0 S_i^0 E_i^0 N_{ij}^0 R_{ij}^0\right) = \Delta C_p + \Delta C_a + \Delta C_s + \Delta C_e + \Delta C_n + \Delta C_r \quad \text{(Eq.4)}$$

According to the actual situation in the YRD in recent years, the carbon emission coefficient of various energy sources in the YRD has not changed much. That is, the carbon emission factor effect ΔC_r can be considered zero, then *formula 4* can be rewritten as:

$$\Delta C = C^t - C^0 = \Delta C_p + \Delta C_a + \Delta C_s + \Delta C_e + \Delta C_n \quad \text{(Eq.5)}$$

The formula for the yearly effect of each factor is as follows (Ang and Liu, 2007; Zhu et al., 2017):

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Population size effect:

$$\Delta C_p = \sum_{i=1}^{3}\sum_{j=1}^{10} L\left(C_{ij}^{t-1}, C_{ij}^{t}\right) \ln\left[\frac{P^t}{P^{(t-1)}}\right] \quad \text{(Eq.6)}$$

Economic growth effects:

$$\Delta C_a = \sum_{i=1}^{3}\sum_{j=1}^{10} L\left(C_{ij}^{t-1}, C_{ij}^{t}\right) \ln\left[\frac{A^t}{A^{(t-1)}}\right] \quad \text{(Eq.7)}$$

Industrial structure effect:

$$\Delta C_s = \sum_{i=1}^{3}\sum_{j=1}^{10} L\left(C_{ij}^{t-1}, C_{ij}^{t}\right) \ln\left[\frac{S_i^t}{S_i^{(t-1)}}\right] \quad \text{(Eq.8)}$$

Energy intensity effect:

$$\Delta C_e = \sum_{i=1}^{3}\sum_{j=1}^{10} L\left(C_{ij}^{t-1}, C_{ij}^{t}\right) \ln\left[\frac{E_i^t}{E_i^{(t-1)}}\right] \quad \text{(Eq.9)}$$

Energy structure effect:

$$\Delta C_n = \sum_{i=1}^{3}\sum_{j=1}^{10} L\left(C_{ij}^{t-1}, C_{ij}^{t}\right) \ln\left[\frac{N_{ij}^t}{N_{ij}^{(t-1)}}\right] \quad \text{(Eq.10)}$$

where $L\left(C_{ij}^{t-1}, C_{ij}^{t}\right)$ in equations (6)-(10) is defined as

$$L\left(C_{ij}^{t-1}, C_{ij}^{t}\right) = \begin{cases} C_{ij}^{t} - C_{ij}^{t-1} / \left(\ln C_{ij}^{t} - \ln C_{ij}^{t-1}\right), & C_{ij}^{t} \neq C_{ij}^{t-1} \\ C_{ij}^{t}, & C_{ij}^{t} = C_{ij}^{t-1} \\ 0, & C_{ij}^{t} = C_{ij}^{t-1} = 0 \end{cases} \quad \text{(Eq.11)}$$

The formula for the cumulative effect of each influencing factor can be changed by replacing (t-1) in *Equations 6-11* with (t=0), which means the base period. To more intuitively and clearly reflect the contribution of each influencing factor on the comprehensive impacts, the formula for calculating the contribution of each factor effect can be rewritten as follows:

$$\delta_\mu = \text{sgn}(\Delta C)\frac{\Delta C_\mu}{\Delta C} \quad \text{(Eq.12)}$$

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$$\mathrm{sgn}(\Delta C) = \begin{cases} 1, & \Delta C > 0 \\ -1, & \Delta C < 0 \end{cases} \quad \text{(Eq.13)}$$

where δμ represents the contribution degree of each factor effect. When δμ >0, it indicates that the factor μ promotes the increase of CO_2 emission, and when δμ <0, it indicates that the factor μ inhibits the growth of CO_2 emission. sng(ΔC) denotes the direction of the change of energy consumption CO_2 emissions. If CO_2 emissions increase, sng(ΔC) is positive; otherwise, it is negative.

Results of factor decomposition

Results of LMDI decomposition

According to *formulas 5-10*, the driving factors of energy-related CO_2 emissions in the YRD can be decomposed into the effects of population size, economic growth, industrial structure, energy intensity, and energy intensity. As for the results of LMDI decomposition, the contribution values and the ratios of various factors to CO_2 emissions in the YRD are shown in *Table 2* and *Table 3*.

As can be seen in *Table 2*, in general, the annual contributions of population size factor and economic development fact to the energy-related CO_2 emissions in the YRD were positive from 2005 to 2016, indicating that economic development scale and population size were the main factors contributing to the increase of CO_2 emissions. *Table 3* shows that the effect of population size on CO_2 emissions was relatively small, while the impact of economic size was very significant, indicating that the effect of economic development was much higher than that of population size. The annual contribution of energy intensity effect to CO_2 emissions was negative during 2006-2015, and the absolute value of its cumulative effect and the ratio of cumulative contribution both placed the second rank among the five factors, indicating that the energy intensity effect was the essential factor to restrain the growth of CO_2 emissions in the YRD. The contribution values of industrial structure effect and energy structure effect to energy CO_2 emission varied during this period. However, on the whole, the cumulative effects of both factors were negative, which indicated that some changes in the YRD, such as the adjustment of industrial structure, the improvement of energy structure, the use of clean energy, or the awareness of carbon emission reduction, could effectively reduce the energy-related CO_2 emission during this period.

There are also some similar trends and high correlations among the total influencing effects, energy consumption, and energy-related carbon emissions in the YRD during this period (*Table 2, Figures 1,2*). From the perspective of total effects, according to *Table 2*, the cumulative impacts of all combined effects in the YRD were positive during 2005-2016. However, from the year-to-year effect, the yearly effects in 2011-2012, 2012-2013, and 2015-2016 are negative, indicating that the energy-related CO_2 emissions have declined in these three periods. It was just in line with the changes in the annual overall CO_2 emissions in these three periods, which can be seen in *Figure 1*. It can also be seen from *Figure 1* that the CO_2 emissions per capita in the YRD tended to be consistent with the overall CO_2 emissions. From 2005 to 2010, CO_2 emissions per capita maintained a slight upward trend. The CO_2 emissions per capita in 2011 also peaked at 0.85 tons per capita, and the total CO_2 emissions reached a peak of 144.12 million tons this year as well.

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Table 2. *Influencing factors of energy-related CO_2 emissions in the Yangtze River Delta, 2005-2016 (unit: 10,000 tons)*

Year	Population size		Economic growth		Industrial structure		Energy intensity		Energy structure		Total effects	
	ΔC_p	Accumulative effects	ΔC_a	Accumulative effects	ΔC_s	Accumulative effects	ΔC_e	Accumulative effects	ΔC_n	Accumulative effects	ΔC	Accumulative effects
2005-2006	160.29	160.29	1202.11	1202.11	51.04	51.04	-929.13	-929.13	-371.43	-371.43	112.89	112.89
2006-2007	190.26	350.56	1375.69	2577.80	-136.85	-85.81	-1081.30	-2010.43	40.59	-330.84	388.40	501.29
2007-2008	139.45	490.00	1139.29	3717.09	-123.60	-209.41	-859.82	-2870.24	33.65	-297.19	328.96	830.25
2008-2009	149.80	639.81	1094.16	4811.25	-80.95	-290.36	-667.75	-3538.00	-188.52	-485.71	306.74	1136.99
2009-2010	270.79	910.60	1192.51	6003.75	-25.55	-315.91	-824.06	-4362.06	-90.96	-576.68	522.72	1659.71
2010-2011	79.86	990.46	1205.97	7209.73	-97.02	-412.93	-719.52	-5081.58	211.67	-365.00	680.96	2340.67
2011-2012	61.40	1051.86	1147.93	8357.65	-185.86	-598.79	-1370.72	-6452.30	-478.20	-843.20	-825.45	1515.22
2012-2013	65.96	1117.82	1100.25	9457.91	-262.34	-861.13	-1136.37	-7588.67	-131.16	-974.36	-363.66	1151.56
2013-2014	36.22	1154.03	1042.04	10499.95	-145.52	-1006.65	-493.35	-8082.02	47.54	-926.82	486.93	1638.49
2014-2015	33.19	1187.23	1073.68	11573.63	-299.69	-1306.34	-349.74	-8431.76	-294.93	-1221.75	162.53	1801.01
2015-2016	70.11	1257.34	970.17	12543.80	-207.09	-1513.43	-1657.04	-10088.80	48.24	-1173.51	-775.62	1025.40

Table 3. *Contributions of various factors of energy-related CO_2 emissions in the YRD, 2005-2016 (unit: %)*

Year	Population size	Economic growth	Industrial structure	Energy intensity	Energy structure
2005-2006	21.55	161.61	6.86	-124.91	-49.93
2006-2007	24.88	179.92	-17.90	-141.41	5.31
2007-2008	17.66	144.25	-15.65	-108.87	4.26
2008-2009	44.51	325.12	-24.05	-198.42	-56.02
2009-2010	69.73	307.08	-6.58	-212.20	-23.42
2010-2011	6.46	97.48	-7.84	-58.16	17.11
2011-2012	13.51	252.55	-40.89	-301.56	-105.21
2012-2013	36.20	603.79	-143.97	-623.62	-71.98
2013-2014	8.52	245.04	-34.22	-116.01	11.18
2014-2015	11.78	380.88	-106.31	-124.07	-104.62
2015-2016	17.03	235.64	-50.30	-402.47	11.72
Cumulative contribution	271.81	2933.35	-440.85	-2411.70	-361.60

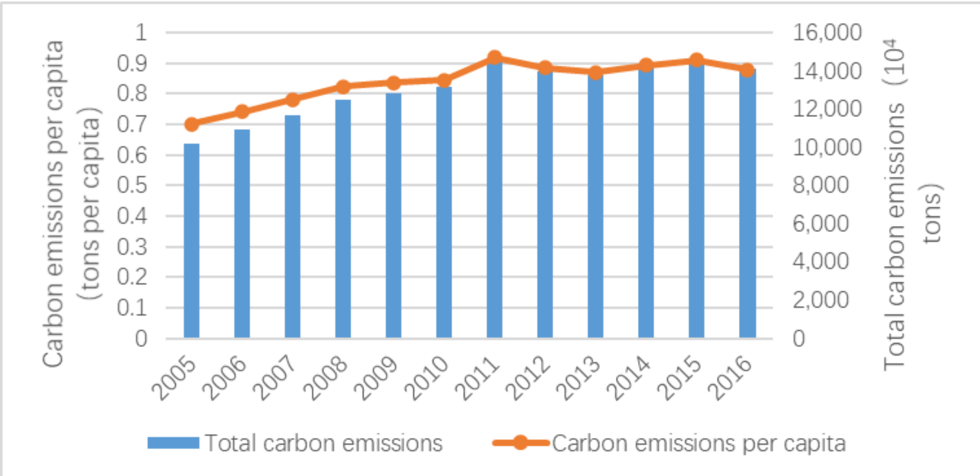

Figure 1. *Total and per capita CO_2 emissions in the YRD, 2005-2016*

After that time, both the per capita and total emissions began to decline. From 2000 to 2016, the resident population of the YRD was 144.69-160.10 million, with an annual growth rate of 1.00-1.02%, indicating that the resident population in the YRD increased slightly but was relatively stable. Therefore, the change of emissions per capita in this area was mainly due to the difference in the total CO_2 emissions. Compared with the Beijing-Tianjin-Hebei region, another important economic region in China, the Per capita carbon emissions in the YRD have a different trend. From 2005 to 2016, the per capita GDP of The Beijing-Tianjin-Hebei region has been on the rise, and the per capita carbon emissions basically showed an "inverted U-shaped" trend of first rising and then declining, reaching a peak of 1.47 tons per person in 2012. It shows that the low carbon economic development route of the YRD and the BTH is in different stages.

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By comparing with *Figure 2*, it can be found that the trend of the total energy-related CO_2 emissions was almost the same as that of energy consumption in the YRD, which means that the energy intensity was closely related to the CO_2 emission intensity during this period. The energy consumption per capita was also consistent with the overall energy consumption trend during this period. Since 2010, the total energy consumption in the YRD has reached more than 200 million tons of standard coal and peaked at 213.13 million tons in 2015. In the same year, the energy consumption per capita peaked, reaching 1.34 tons of standard coal per capita. The energy consumption per capita increased steadily from 2005 to 2011, indicating that with the rapid urbanization and economic growth, the demand for energy became higher and higher in the YRD.

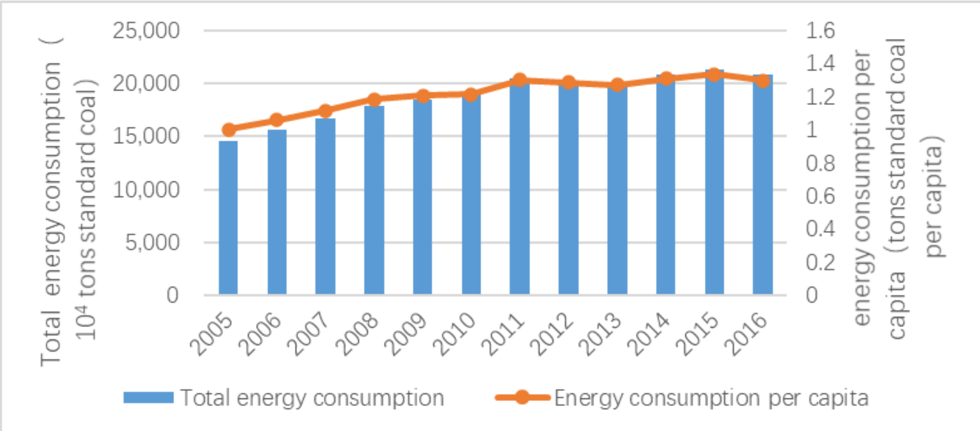

Figure 2. *Total and per capita energy consumption in the YRD, 2005-2016*

Analysis and Discussion

Population size effect

As can be seen from *Table 2* and *Table 3*, the annual effect and the contribution ratio of population size effect of CO_2 emissions in the YRD were always positive from 2005 to 2016, which promotes the increase of CO_2 emissions to some extent. First of all, the YRD has attracted a large number of non-native immigrants due to its economic development, environment, welfare, education, and other reasons, making it one of the leading destinations for population inflow in China. The resident population has been increasing from 144.69 million in 2005 to 160.09 million in 2016, an increase of about 10.6%. Secondly, to build the YRD into an international metropolitan region, its urbanization level has been increasing rapidly, which may also be the result of the increase of population size in the YRD. Increasing population size in the YRD leads to increasing demand, which leads to increasing energy consumption and CO_2 emissions. Although the population size was a promoting effect on the increase of the overall CO_2 emissions in the YRD, the positive effect is not so significant when compared with the economic effect, as shown in *Table 2* and *Table 3*.

Economic growth effect

GDP per capita can measure the average production capacity of a region by its market value of products and services produced in a certain period, and it can reflect not only the economic growth of this region, but also the material prosperity of the residents.

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This paper chooses GDP per capita as the index to measure economic scale and development. As shown in *Figure 3*, the GDP and GDP per capita in the YRD maintained the same steady growth trend from 2005 to 2016. The regional economy has been in a state of rapid and steady growth, the actual GDP per capita increasing from 28,500 yuan in 2005 to 75,600 yuan in 2016, and the average annual growth of the actual income per capita as high as 8.47%. Therefore, the rapid economic growth directly led to the increase of CO_2 emissions in the YRD.

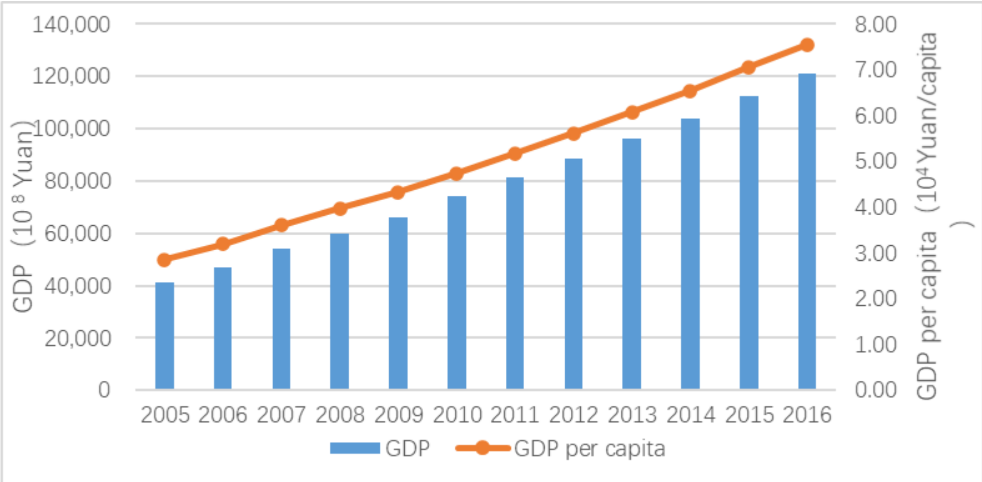

Figure 3. *GDP and GDP per capita of the YRD, 2005-2016*

As can be seen from the decomposition results of the model in *Table 2*, the continuous expansion of the economic scale in the YRD was the decisive factor causing the growth of energy CO_2 emissions. The yearly effect of the economic growth of the YRD has been positive in 2005-2016, indicating that the factor of economic growth directly leads to an increase in CO_2 emissions year by year. During 2011-2015, the year-to-year economic growth effect was almost declining. This may be because, during the 12th Five-Year Plan period, the economic growth of the YRD was facing unprecedentedly complex international and domestic environments. Affected by the 2008 financial crisis, there were still unstable and uncertain factors in the economic recovery. The economic operation modes of high foreign trade dependence, high investment, and high growth in the YRD were facing major adjustments, and the economic growth rate in this region was correspondingly slowing down. According to the contribution ratio of economic growth (see *Table 3*), the economic growth effect on energy-related CO_2 emissions in the YRD is all positive, reaching the highest in 2012-2013 (603.79%) and the lowest in 2010-2011 (97.48%). The contribution degrees in almost years were all over 100%. Energy consumption supported the regional economic development, and the economic development characterized by industrialization and urbanization of this region, in turn, promoted the increase of energy consumption and CO_2 emissions. Therefore, the growth of CO_2 emissions in the YRD was an inevitable consequence of its economic development.

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Industrial structure effect

According to *Table 2*, the yearly effect of industrial structure in the YRD was negative from 2005 to 2016, except for the positive impact from 2005 to 2006, which indicated that the industrial structure in the YRD had a specific inhibiting effect on energy-related CO_2 emission reduction.

Figures 4,5 show that the total energy consumption in the YRD is more consistent with the total energy consumption in the secondary industry from 2005 to 2016, and the trend remained relatively stable. From the perspective of industrial structure development, the industrial structure in the YRD presented a tendency of evolution from the primary industry to the secondary one, then to the tertiary one. The ratio of the tertiary industry in the YRD has been rising steadily, indicating that the industrial structure was developing in a more reasonable direction. It could be noted from *Table 3* that the industrial structure had a significant negative effect on CO_2 emissions during 2010-2015. The contribution value of the industrial structure effect rose sharply from -97.02 in 2011 to -185.86 in 2012, with most other years of this period exceeding -100, reaching the highest value of -299.69 in 2015. From *Table 3*, the contribution ratio of industrial structure suddenly rose from about -8% in 2011 to -41% in 2012, and the contribution ratio in 2013 was as high as -144%. It showed that during the period of the 12th Five-Year Plan, the industrial structure of the YRD has entered the stage of "reshuffle" and encountered the bottleneck of the transformation from capital-labor-intensive industry to technology-capital-intensive industry. The proportion of the secondary industry remained relatively flat, while the ratio of the tertiary industry continued to rise, in line with the optimization and up-gradation of the regional industrial structure. The YRD gradually entered the post-industrial society and began to shift the industrial structure upward to the tertiary industry, which is dominated by high value-added products and high-tech products, thus inhibiting the increase of CO_2 emissions to a certain extent.

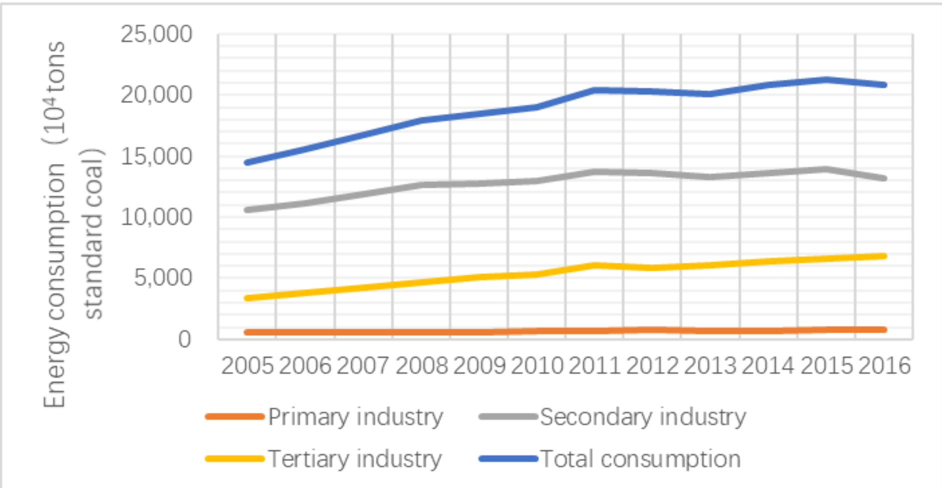

***Figure 4.** Energy consumption of the three industries in the YRD, 2005-2016*

As shown in *Figure 6*, the trend of "industry" or the secondary industry's CO_2 emissions in the YRD was utterly consistent with that of total CO_2 emissions during this period. It is well known that the major CO_2 emission industry in the YRD was the secondary industry. As the YRD was in an important stage of urbanization and

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industrialization during this period, with the manufacturing industry and especially the construction industry having sustained rapid development. If the CO_2 emissions of the secondary industry were controlled, the total CO_2 emissions could be reduced a lot. Therefore, to reduce the increment of CO_2 emissions in the YRD, the proportion of the secondary industry in the economy should be gradually reduced to a certain extent, and the tertiary industry should be vigorously developed. In addition, it could be a good policy choice to appropriately improve industrial technology to realize the transformation of industrial structure.

Figure 5. *The industrial added value of the three industries in the YRD, 2005-2016*

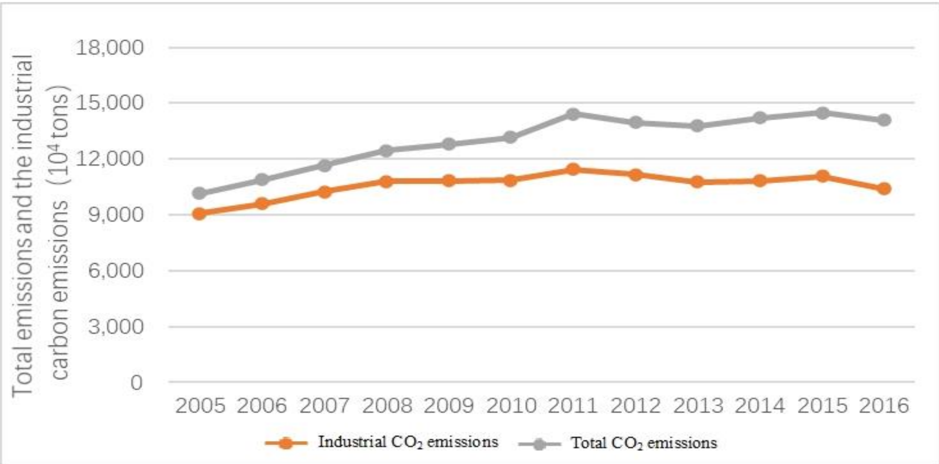

Figure 6. *Total CO_2 emissions and industrial CO_2 emissions in the YRD, 2005-2016*

Energy intensity effect

Energy intensity refers to the total energy quantity consumed per unit of GDP, and the reduction of energy intensity directly reflects the improvement of regional energy utilization efficiency and the level of energy conservation and emission reduction technologies. It can be seen from *Table 2* that the annual energy intensity of the YRD in 2005-2016 was all negative, indicating that the improvement of energy efficiency played

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a significant role in restraining CO_2 emissions from energy consumption. According to the change of energy consumption intensity of the YRD in 2005-2016 (see *Figure 7*), the absolute value of energy intensity contribution ratio in the YRD varied from 58.16% to 623.65%. The cumulative contribution of the energy intensity effect was as high as 2411.70%, ranking second among the five driving factors. It could be seen that energy intensity plays a significant role in inhibiting CO_2 emissions. The energy intensity effects in 2011-2012, 2012-2013, and 2015-2016 fluctuated greatly, which was mainly influenced by the dual factors of total energy consumption and economic growth. Although CO_2 emissions in the YRD are increasing year by year, the effect of energy intensity always played a role in restraining emissions to a large extent. Thus, improving energy utilization equipment and enhancing energy utilization efficiency are effective measures to control CO_2 emissions.

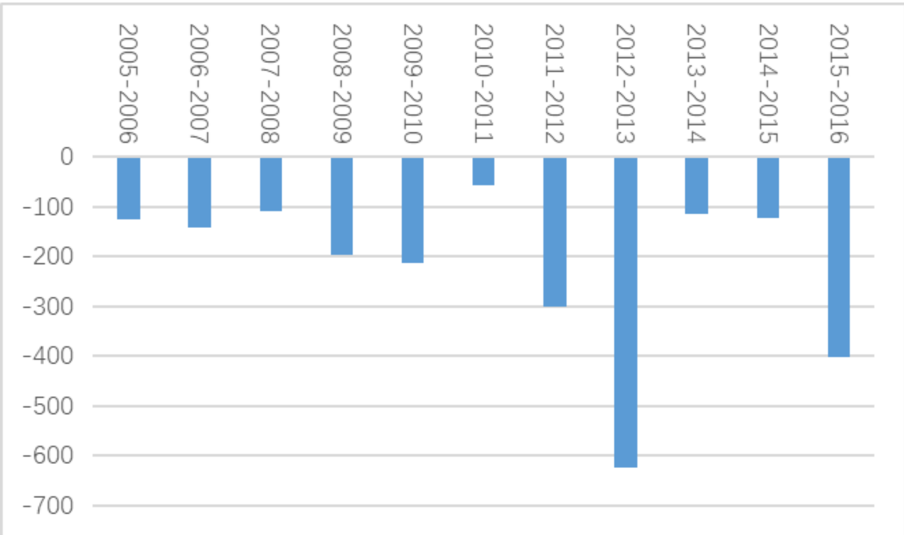

Figure 7. *Energy intensity effect contributions in the YRD, 2005-2016 (unit: %)*

Energy structure effect

According to *Table 2* and *Table 3*, during 2005-2016, the annual energy structure effect of the CO_2 emission in the YRD changed year by year, the negative effect of the energy structure leading to the reduction of CO_2 emissions while the positive effect leading to an increase. Since the impact of the negative effect was more apparent, the cumulative effect was correspondingly negative, indicating that the energy structure had an inhibitory effect on the growth of CO_2 emissions in the YRD. According to the carbon emission factors of fuels in *Table 1*, the carbon emission factor of coal is the highest, followed by oil, and the carbon emission factor of natural gas is the lowest. That is to say, given the other factors remaining unchanged, if the proportion of coal-based energy in the energy consumption structure declines substantially, the CO_2 emissions may decrease accordingly, even if the ratio of consumption of petroleum and natural gas increases.

As shown in *Figure 8*, during 2005-2016, the energy consumption structure of the YRD was characterized by the facts of coal as the main energy and oil as the auxiliary. The proportion of natural gas consumption increased year by year during this period, and the proportion of coal and oil consumption both decreased, indicating that the adjustment

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of energy structure in the YRD is starting to work in reducing emissions. Overall, the energy structure in the YRD has improved, and the proportion of coal consumption has decreased from 58.86% in 2005 to 49.85% in 2016. However, the coal-based energy consumption structure adjustment has not been entirely successful due to the energy endowment, so the YRD, as the most significant economic circle in China, having high technology level and many high-tech industries, still has a lot of room for improving its energy structure.

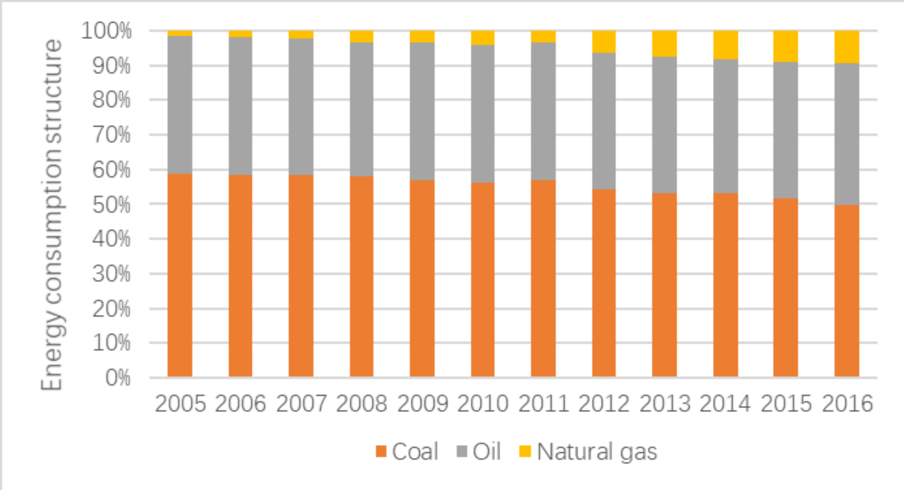

***Figure 8.** Consumption structure of coal, oil, and natural gas in the YRD, 2005-2016*

Conclusions and policy implications

In this paper, we calculated the energy-related CO_2 emissions in the YRD during 2005-2016 and analyzed its driving factors from the population size, economic scale, industrial structure, energy intensity, and energy structure by applying the LMDI model. We showed that the main promoting factor of energy-related CO_2 emission in the YRD is the economic scale, followed by population size. On the contrary, energy intensity had the most important inhibitory effect on CO_2 emissions, and industrial structure and energy structure also inhibited CO_2 emissions as a whole. However, the inhibitory effects of the two latter are far less than that of energy intensity, and the negative impact from the industrial structure is more evident than that from the energy structure.

To be specific, the cumulative effect of economic scale on the energy-related CO_2 emissions was a positive effect of 2933.35% in the YRD, with its absolute value ranking one among the five factors, and the cumulative effect of population size is 271.81%, with its absolute value ranking 5. While the cumulative effect of energy intensity showed a negative effect of -2411.50%, ranking 2 among the five factors, the cumulative effect of industrial structure is a negative effect of -440.85%, ranking 3, and the cumulative effect of energy structure is a negative effect of -361.6%, ranking 4.

At the same time, we found that the industrial sector was the main source of energy-related CO_2 emissions in the YRD, which could closely relate to the industrial structure of the "secondary, tertiary, primary" of the YRD nowadays. The total CO_2 emissions in the YRD showed an evident trend of increasing year by year, which may be related to the bottleneck of industrial transformation and upgrading and to the acceleration of urbanization and industrialization during this period. Some of the

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volatility may be related to domestic and international economic conditions, such as the fallout from the 2008 financial crisis. In general, energy consumption and CO_2 emissions in the YRD will continue to increase year by year for a long time in the future. Now we propose several relevant policy suggestions for improving industrial structure and energy structure in the YRD.

(1) For industrial structure, the industrial structure should be optimized to promote the development of green industries. The feasible policy is, on the one hand, to vigorously develop the high-tech industry and service industry, such as the IT industry ecological tourism, and to constantly increase the proportion of the tertiary industry. On the other hand, we can establish a reasonable industrial echelon, accelerate industrial innovation, and optimize the layout and strategy of regional pillar industries as well.

(2) For energy intensity, technological progress should be combined to improve energy utilization efficiency. The YRD has many well-known universities and research institutions in China, full of superior human resources. A large number of 985 and 211 universities and major research institutions there have strong research capabilities, and the YRD also has a relatively better transfer system for technology and a more mature market environment. It should actively explore the development paths of industry-education-research and strengthen the research and development in the field of CO_2 emission reduction technology. The local government can also increase the investment in energy-saving technology as much as possible and carry out technological innovation in promoting energy exploitation, conversion, and utilization, to improve the technical support capacity of CO_2 emission reduction. Moreover, it is well known that the production of renewable energy contributes to the reduction of CO_2 emissions more effectively than the use of natural gas. Renewable energy use and green energy production have become a long-term trend, so some economic incentive policies for renewable and green energy will greatly improve the energy intensity in the YRD.

(3) For energy structure, reasonable and coordinated ways should be chosen to improve the current energy consumption ratios. The proportion of coal consumption in the period from 2005 to 2016 showed a trend of substantial and stable decline. This trend is highly favorable to the improvement of the energy structure in the YRD. However, the sustainable rate of coal consumption still needs to be further studied and determined that could guarantee to complete the goals of the Paris Agreement. We need to proceed with the "coal to gas" plan in the YRD, reduce the raw coal consumption of direct burning, and use more clean energy such as wind, nuclear, solar, and biomass energy to reduce CO_2 emissions and environmental pressure. The energy efficiency can also be improved by increasing the consumption proportion of relatively cleaner energy such as electricity or natural gas.

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