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Research paper

Decoupling and driving forces of industrial carbon emission in a coastal city of Zhuhai, China

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ABSTRACT

To explore effective schemes of reducing carbon emission at the city level, this study evaluate the decoupling situation and the driving forces of industrial carbon emission in a coastal city of Zhuhai, China. Macro and micro analyses of evolutions of energy consumption, carbon emission, and industrial added value were conducted from 2006 to 2016. Carbon emission was decomposed at the overall and subdivided industrial level by using the logarithmic mean division index method (LMDI) method. Results showed that the industrial added value emerges sustainable increase tendency. Both energy consumption and carbon emission keeps continuous increase during the 11th five year period (11-FYP). They firstly decrease and then they present volatile change during the rest years of the 12-FYP. Rigorous incentives should be enacted to avoid the phenomenon of carbon emission increase rebound during the later phase of each FYP. There are no decoupling signals during the whole 11-FYP. Strong decoupling started to emerge during the 12-FYP. On a micro level, the decoupling phenomenon enhanced with the extension of the evaluation cycle. Furthermore, the economic output value is the main driving force factor of carbon emission, and the energy intensity effect is the dominant driver for reducing the industrial carbon emission during the 11-FYP. For the 12-FYP, the conjunctive role of the industrial structure effect, the energy intensity effect, the energy mix effect, and carbon emission factor effect drives carbon emission mitigation.

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1. Introduction

In order to be responsible in the global climate mitigation action, China has disclosed a series of emission reduction plans, such as reducing the carbon intensity (carbon emission per unit of GDP) by 60%–65% by 2030 compared to the 2005 level, and reach the peak of nation carbon emission in 2030 (Government, 2015). During the past decades, energy consumption of the industrial sectors accounts over 70% of the total final energy consumption in China, and industrial sector was the main sources of carbon emission in China (Wang and Yang, 2015). However, industrial sector acted as the economic growth engine in China. Therefore, controlling carbon emission of the industrial sector and seeking green development pathway are of significant importance to realizing the national carbon emission reduction target in China.

A lot of authors have analyzed the driving factors and contributors of reducing carbon emission of the industrial sector at the national scale (Xie et al., 2018; Wang et al., 2018), the

regional scale (Pappas et al., 2018), and the industrial scale (Chen et al., 2018a). Intensive land use, energy, labor, research and development investment, and capital are considered as the main influencing factors. City occupies only small portion of the earth but produces the majority of carbon emission. However, city is an organic unit of the social-economic activities for human beings. Cities are playing an upgrading important role of its efforts to reduce carbon emission in China. For example, China has launched three batches of low-carbon pilot cities to explore the local implementable approaches of reducing carbon emission which can be replicated and applied in a broader region (Li et al., 2018a). In addition, in order to control national energy consumption and carbon emission at the city/enterprise level, the national emission trading scheme was launched in 2017. Currently, only the electricity sector was covered in the national trading scheme because of data quality and availability. The further successful unveil of the comprehensive trading scheme will depend on accurate account of city and industrial emissions (Shan et al., 2018). On account of the lack of systematic and available of energy consumption data at the city level. Few previous studies focused on the analysis of carbon emission at the city level of the developed countries, especially the industrial carbon emission at the

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city level. Understanding the driving factors of industrial carbon emission and analyzing the relationships of carbon emission and industrial economic development at the city level are conducive to low carbon industry development policy.

Zhuhai can be selected as a dominant character of investigating low carbon development with good local ecological environment level. Zhuhai located on the western Pearl River estuary, covers 1732 km² and it has the longest coastline in China, Guangdong province. Zhuhai is a key point of the 21st-Century Maritime Silk Road. Since early in the 1980s, Zhuhai was selected as one of the four Special Economic Zones for economic-reform pilots in China. During the past thirty years, Zhuhai adheres to the principle of sustainable growth while pursuing economic growth (Lv et al., 2018). Today, Zhuhai is an exemplary city, which is famous for its livable environment of mountainous coastal landscape, comfortable maritime climate, and high environmental quality. It was awarded as the International Residential Environment Improvement by the United Nations in 1998 (Sheng and Tang, 2013), making it to be the third city in China to get this honor. In addition, Zhuhai was selected as the first pilot cities of the EU-China Low Carbon Eco-City in 2015 (Luo, 2015). The local government launched a series of concrete actions to promote low-carbon city development, advocated low-carbon lifestyle, and pursued low-carbon economy. Multi-layers of low carbon planning such as “the thirteenth Five-Year Plan of Green and Low-carbon Development of Zhuhai”, “Zhuhai Low-carbon Research”, “Low-carbon Development Plan of Hengqin New Area”, and “Low-carbon Development Plan of Dong’ao Island” have been promulgated by the local government with the aim of implementing its indicators of carbon intensity (carbon emission of per unit of GDP) and energy intensity (energy consumption of per unit of GDP) to be developed as the forefront of the national level. However, Zhuhai’s energy intensity is higher than that of Beijing, Shanghai, Hong Kong, and Macao. Zhuhai can be selected as an important case of low carbon development which is characterized by high-quality economy and high environment carrying capacity. Therefore, uncovering the driving forces of industrial carbon emission and the decoupling status of industrial carbon emission from GDP growth in Zhuhai has great theoretical and realistic significance.

Consequently, this work aims to investigate the comprehensive decoupling situations of Zhuhai’s industrial carbon emission not only from multi-layers of holistic industry and each subdivided industrial sectors, but also from different time scales of short term and long term during the past decade. Based on the fundamental analysis of emission status, the main driving forces of industrial carbon emission were recognized by applying the LMDI method, with the target of unveiling the mitigation paths and realizing sustainable industrial production. It is expected that this study can bring new insights for carbon emission reduction in other sectors of Zhuhai, and further promotes the other cities in the Guangdong-Hong Kong-Macao Greater Bay Area to combat climate change. The structure of this work was arranged as follows: the literature review was presented in Section 2, Methodology and data were expressed in Section 3, Results and discussions were elucidated in Section 4, and Section 5 draws the conclusion and gives the corresponding policy implications.

2. Literature review

During the past decades, issues of climate changes have becoming the hot topic among politicians, practitioners, and academics. Studying the decoupling situation of carbon emission from economic growth has received broad attention, for it can provide a reasonable indicator to assess the effectiveness of the related policies. In the published investigation of the decoupling state of the transport CO₂ emission and the GDP for the EU15

countries between 1970 and 2001 (Tapio, 2005), Tapio firstly presented the early theory and framework for decoupling Study. He indicated that it changed from expansive negative decoupling to expensive coupling regarding passenger transport. While it changed from weak decoupling to expansive negative decoupling in consideration of freight transport. Recently, Dasgupta and Roy (2017) studied the decoupling of the energy consumption in Indian manufacturing industries during 1973–1974 to 2011–2012. The activity growth was found to be the major driver of energy consumption growth. Nevertheless, decreasing energy intensity can neutralize a major portion of the energy consumption growth which results in a decoupling trend. Chang and Li (2017) reported the decoupling of the lock-in effect economic growth and CO₂ emission by structure adjustment, which implies that more attention should be paid to the main internal linkages in terms of CO₂ emissions within the economy in order to address better carbon mitigation policies. Xu et al. (2017) also analyzed the decoupling indicator of CO₂ emission due to fossil energy consumption from economic growth in China. The results verified that the decoupling was significantly enhanced by the economic output effect, and was greatly decreased by the energy intensity. Later on, Chen et al. analyzed the decoupling situation of embodied greenhouse gas emission in Macao from 2000 to 2013 (Chen et al., 2017). Most of the previous studies of decoupling focused on the situation of carbon emission from economic growth or energy consumption from economic growth. Considering the strong linkage of carbon emission and energy consumption, this work assessed the decoupling situation of carbon emission from energy consumption and energy consumption from the industrial economic growth.

In order to take effective measures to control carbon emission, decomposition analyses of carbon emission have been carried out to make in-depth discussions of the driving forces of carbon emission. The main decomposition methods are shown in Table 1 summarized from the previous literatures. For the decomposition of carbon emission, the structural decomposition analysis (SDA), the index decomposition analysis (IDA), and the production-theoretical decomposition analysis (PDA) are the three common methods (Zhang and Da, 2015). The SDA method is based on the input–output model. Su et al. applied the SDA method to decompose carbon emission of Singapore (Su et al., 2017). Exports and household related carbon emissions account for more than 90% of the total carbon emission in Singapore. For the city level, the SDA method was applied to analysis the driving mechanism and the underlying causes of carbon emission in Beijing (Wei et al., 2017). Results revealed that rapid economic growth and economic structure change are the main factors that led to rapid carbon emission increase. Li et al. (2018b) also studied the carbon emission drivers in Beijing with the SDA method from both the supply and the demand sides. Long and Yoshida (2018) further tried to quantify the emission responsibility from Tokyo, Japan with the SDA method considering Multi-regional input–output table. Results showed that transport sector accounted for the largest share of direct emission in Tokyo. While construction, energy supply, and private service sectors were the largest sources of indirect emissions. Although the application of the SDA method developed fast during the past years, nevertheless, this decomposition method can only be used additively because of the SDA method is confined to the application of the input–output table.¹

With the development of production theory, the PDA method was attracted increasing attention in the environmental and energy research area. The PDA method was firstly proposed by Zhou and Ang (2008). They used Shephard input distance functions and

¹ The main proposed decomposition methods are shown in Table 1 from the published literatures.

the data envelopment analysis in a joint production framework to decompose the aggregated CO₂ emissions. Later on, Zhang and Da (2013) applied this PDA method to investigate changes of energy related carbon emission decomposition in China. They concluded that energy consumption and economic growth are the two main factors inducing carbon emission increase, while carbon mitigation technical efficiency and energy use technology have slight effects on carbon emission. Zhang et al. (2013) further used this method to investigate the carbon emission decomposition for 25 OECD countries and China between 1998 and 2007. Empirical results indicated that economic growth was the dominant factor for carbon emission increase, while changes of GDP component and energy structure are two main divers to carbon emission reduction. By comparing the results of the China and the OECD countries, the authors further proposed the policy implications for China to mitigate carbon emission from an international angle. These above mentioned studies with the PDA method may face the problems of the infeasibility of DEA linear programming, so Wang et al. (2015) modified the traditional PDA method to analysis the driving factors behind carbon emission changes in China. They divided the variations of carbon emission into seven influencing factors across thirty provinces, and found that economic growth was the largest contributor for carbon emission increase. Moreover, energy usage technical efficiency changes have limited ability to relieve the pressure of carbon emission rapid increase, especially in the backward provinces. Overall, the obvious advantages of the PDA method are the low requirement of data quality and it can reveal the driving forces of carbon emission with the production efficiency and technology. The defect of the PDA method is that it cannot reflect the structure components of the influencing factors.

Comparing with the SDA method and the PDA method, the IDA method was a preferred method because of the advantage of decomposition without residuals (Ang, 2004). The logarithmic mean division index method (LMDI) was the most representative of the IDA decomposition method. In order to eliminate handling zero and negative values when uses the LMDI method, which is the only insufficiency in practical application, Ang and Liu published eight strategies (Ang and Liu, 2007) to address this problem. Mousavi et al. (2017) applied the LMDI method to quantify the key drivers of Iran's CO₂ emissions. This novelty is that the authors incorporated the effects of electricity import and export in the decomposition analysis. Results indicated that increased consumption was the main driver of Iran's carbon emission and the technology-related improvements only acted as auxiliary effect in mitigation. Based on the provincial panel data, the main factors driving energy-related carbon emission in China was decomposed into the energy intensity effect, the population effect, and the economic output effect by the LMDI method (Wang and Feng, 2017). It was verified that economic output effect was the main positive driving factor, and energy intensity was the dominant negative driving factor. Based on the extended LMDI method, Wang et al. (2017) extended the decoupling index to conduct the comparative decoupling analysis of energy-related carbon emission from electricity output of electricity sector in Shandong province. Results showed that during the study period, relative decoupling and no decoupling are the main status of the electricity power. In addition, electricity consumption and coal consumption play determinative role in Carbon emission. Later on, Shao et al. (2016) extended the LMDI model and employed it to analysis the techno-economic drivers of energy related carbon emissions. Not only were the conventional macroeconomic effects considered, but also the microeconomic effects such as the investment, research and development behaviors were taken into account. Results indicated that taking Shanghai as an example, the microeconomic effects were more sensitive to the energy

intervention compared to the macroeconomic effects, while the macroeconomic effect contributed more to the mitigation results at the present stage. Based on the review process of the published articles, Shenggang Ren and Xiao Hong (2014) concluded that the LMDI method is the most accurate and practical method in the current decomposition system. Chen et al. revealed the driving forces of energy-related carbon emission and the imbalance of trade-related emissions with the LMDI method (Chen et al., 2018b). By reviewing the published articles, it was found that the previous studies prone to pay more attention to CO₂ emission from national and regional perspectives. Metropolises such as Beijing and Shanghai also have been studied as an example. However, some important functional city with the features of good environmental background value needs further attention for the sake of sustainable development. Furthermore, the previous studies mostly concentrated on uncovering the driving forces of carbon emission. The in-depth research on driving forces and the corresponding decoupling status of each influence factor behind carbon emission for the functional city need be further investigated. Therefore, this study aims to analysis the decoupling and driving forces of industrial carbon emission in a coastal city of Zhuhai, China.

3. Methodology and data

3.1. Energy consumption and carbon emission

There are 34 sub sectors of the industrial sector in Zhuhai. It is difficult to meter energy consumption and carbon emission of the industrial sector directly. Hence, in this work, inventories of energy consumption and carbon emission of the industrial sector in Zhuhai City are calculated according to the national assessment method of carbon intensity reduction responsibility (Office NDaRCG, 2016). Quantification of energy consumption is based on the following equation:

$$EC = \sum_n \sum_i^j E_{i,j} \times \eta_{i,j} \quad (1)$$

where EC is total amount of energy consumption; n represents the 34 industrial sectors, such as mining and washing of coal, extraction of petroleum and natural gas, and manufacture of foods etc., the detailed catalog of the industrial sectors is shown in Table 2; $E_{i,j}$ represents the physical quantity of final energy consumption for different energy type. $\eta_{i,j}$ Stands for the conversion factors from physical units to coal equivalent for different energy types. For i , there are five energy types, which are coal, oil, gas, electricity, and heat. j denotes the sub energy types, and the detailed information of the energy type is shown in Table 3.

According to the national assessment method of carbon intensity reduction responsibility, carbon emission mainly considers the amount of energy consumption related emission, which is defined as the following equation:

$$CE = C \times C_k + O \times O_k + G \times G_k + E \times E_k \quad (2)$$

where C , O , G , and E are the standard quantity of coal, oil, gas and electricity consumption for the industrial sector, respectively. C_k , O_k , and G_k are the carbon emission factor for coal, oil, and gas, respectively during the combustion processes. According to the national guideline (Office NDaRCG, 2016), C_k , O_k , and G_k are 2.64, 2.08, and 1.63 tCO₂/tce, respectively. E_k is the emission factor of net input electricity, which considers the amounts of local inputs and outputs electricity.

Table 1
Representative literature of decomposition of CO₂ changes.

Authors	Research object	Method	Time span	Research conclusions
Su et al.	Investigate the drivers of carbon emission changes with the SDA method from the demand perspective	SDA	2000–2010	Exports and the household sector are the main contributors of emission
Long et al.	Quantify city-scale emission responsibility in Tokyo, Japan	SDA	2011	Transport sector accounted for the largest share of direct emission. While construction, energy supply, and private service sectors were the largest sources of indirect emissions
Wei et al.	Evaluate the driving factors of energy-related carbon emission generated by Beijing industries.	SDA	2000–2010	Economic growth and structure change are the main driving factors.
Wang et al.	Explore the main factors driving CO ₂ emission changes and to uncover feasible ways to reduce energy related CO ₂ emissions in China	LMDI	2000–2014	Economic output effect and energy intensity effect are the main positive and negative driving factor, respectively.
Babak et al.	quantify driving forces of CO ₂ emissions in Iran	LMDI	2003–2014	Increased consumption was the main driver of carbon emission in Iran
Wang et al.	Figure out what the influencing factors are and how they work to change the CO ₂ emission during electricity generation.	LMDI	1995–2012	Electricity output and coal consumption are the determinative factors of carbon emission. Relative decoupling” and “no decoupling” were the main states during the study period.
Shao et al.	Uncovering the effects of investment and R&D activities in the index decomposition studies of carbon emission	LMDI	1994–2011	Expanding output scale was mainly responsible for industrial related carbon emission in Shanghai
Zhang et al.	Find out the driving force and structural characteristic of carbon emission	PDA	1998–2007	Economic growth mainly contributes to carbon emission increase, while changes of GDP component and energy structure are two main divers to carbon emission reduction
Wang et al.	Research on the driving factors behind carbon emission changes in China	PDA	2005–2010	Economic development was the largest factor of increasing carbon emission, energy structure and low energy efficiency were the second and third influencing factor, respectively

3.2. Decoupling model

Not only the decoupling situation of carbon emission from economic growth, but also the decoupling state of carbon emission from energy consumption and the decoupling results of energy consumption from economic growth are evaluated in this work. The decoupling results are calculated according to the following equation which is based on the Tapio model:

$$\xi(CE, IAV) = \frac{\Delta CE/CE}{\Delta IAV/IAV} = \frac{\Delta CE/CE}{\Delta EC/EC} \times \frac{\Delta EC/EC}{\Delta IAV/IAV} \quad (3)$$

$$= \xi_1(CE, EC) \times \xi_2(EC, IAV)$$

where $\xi(CE, IAV)$ is the decoupling elastic index. For a given period, ΔCE is the variance of carbon emission for the industrial sector, and ΔIAV is the variance of the industrial added value. The intermediate variable of energy consumption was applied to decompose the decoupling elasticity of the carbon emission and the industrial added value. $\xi_1(CE, EC)$ was designed as the emission decoupling factor, and $\xi_2(EC, IAV)$ was set as the consumption decoupling factor.

As shown in Fig. 1, there are eight kinds of status and judgment standards for the decoupling situation based on the Tapio Model. They are strong decoupling, weak decoupling, expansive coupling, expansive negative decoupling, strong negative decoupling, weak negative decoupling, recessive coupling, and recessive decoupling. When $\Delta IAV > 0$, the smaller ξ value denotes the greater decoupling degree. This indicates that the dependence of industrial carbon emission from industrial economic added value is weakening. When $\Delta IAV < 0$, the bigger ξ value means the worse decoupling degree, which indicates that the dependence of carbon emission from economic growth is enhancing.

The strong negative decoupling is the worst situation and on the contrary, the strong decoupling is the most satisfactory state.

3.3. Driving forces of carbon emission

The growth of Zhuhai's industrial CO₂ emission can be attributed to five sources: variation of industrial economic scale, industrial structure changes, energy intensity changes, energy structure changes, and carbon emission factor changes. By considering the kaya identity, carbon emission in this work can be expressed as follows:

$$CE = \sum_{i=34}^{j=4} C_{ij} = \sum_{i=34}^{j=4} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} \quad (4)$$

where Q is total industrial added value of Zhuhai City, and Q_i is the industrial added value for industrial sector i . E_i is the total energy consumption for industrial sector i , and E_{ij} is energy consumption of industrial sector i related with energy type j . C_{ij} is carbon emission of industrial sector i related with energy type j .

For simplification, Eq. (4) can be changed in to the following equation:

$$CE = \sum_{i=34}^{j=4} Q S_i I_i e_{ij} M_{ij} \quad (5)$$

Based on the LMDI method (Ang, 2005), variation of CO₂ emission (ΔC) between a target year t and a base year 0 can be decomposed in to the following effects:

(a) The economic output effect (denoted by ΔQ), reflecting changes of industrial added value in Zhuhai city.

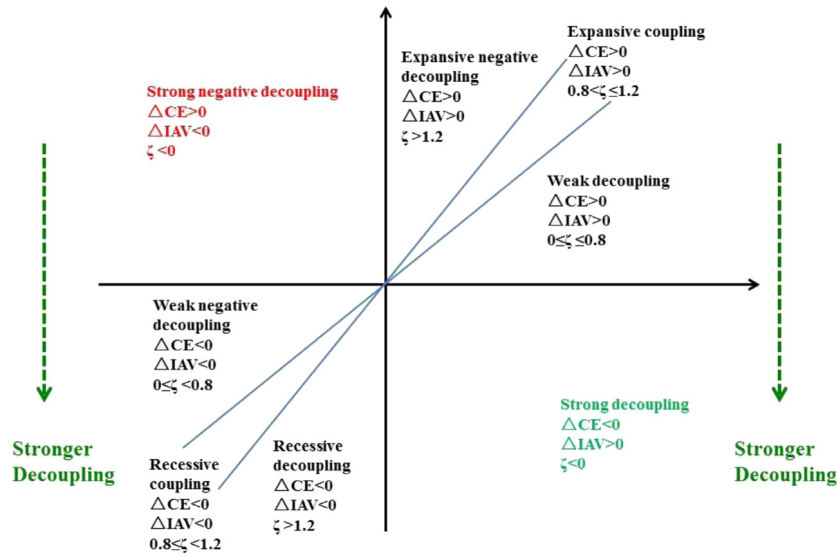


Fig. 1. Judgments matrix of decoupling based on Tapio model.

Table 2

Catalog of industrial sectors in Zhuhai City.

Serial number	Name of industrial sector
S1	Extraction of Petroleum and Natural Gas
S2	Processing of Farm and Sideline Food
S3	Manufacture of Food
S4	Manufacture of Wine, Beverage and refined tea
S5	Textile Industry
S6	Manufacture of Textile Garments, Apparel
S7	Leather, Fur, Feather and Related Products, and Footwear
S8	Timber Processing, Bamboo, Cane, Palm Fiber & Straw Products
S9	Manufacture of Furniture
S10	Papermaking and Paper Products
S11	Printing and Record Medium Reproduction
S12	Manufacture of Culture, Arts, Sports and Entertainment Articles
S13	Petroleum Refining, Coking and Nuclear fuel processing
S14	Manufacture of Raw Chemical Materials and Chemical Products
S15	Manufacture of Medicines
S16	Manufacture of Chemical Fibers
S17	Manufacture of Rubber and Plastic Products
S18	Nonmetal Mineral Products
S19	Smelting and Pressing of Ferrous Metals
S20	Smelting and Pressing of Nonferrous Metals
S21	Metal Products
S22	Manufacture of General-purpose Machinery
S23	Manufacture of Special-purpose Machinery
S24	Manufacture of Automobile
S25	Manufacture of Railway, Ship, Aeronautics and Other Transport Equipment
S26	Manufacture of Electrical Machinery and Equipment
S27	Manufacture of Computers, Communication Equipment and Other Electronic Equipment
S28	Manufacture of Instruments and Meters
S29	Other Manufactures
S30	Comprehensive Utilization of Waste
S31	Manufacture of Metal Products, Machinery and Equipment Maintenance
S32	Production and Supply of Electric Power and Heat Power
S33	Production and Supply of Gas
S34	Production and Supply of Water

(b) The industrial structure effect (denoted by $\Delta S_i = \Delta Q_i/Q$), reflecting changes in the relative shares of industrial added value.

(c) The energy intensity effect (denoted by $\Delta I_i = \Delta E_i/Q_i$), reflecting variations in the ratio of industrial energy consumption to industrial added value.

Table 3

Catalog of energy type information in Zhuhai industrial sector.

Energy type	Sub energy type
Coal	Raw coal
	Coal products
	Coke
	Blast furnace gas
	Converter gas
Oil	Gasoline
	Kerosene
	Diesel
	Fuel oil
	Liquefied petroleum gas
	Other petroleum gas
Gas	Natural gas
	Liquefied natural gas
Heat	Heat
Electricity	Electricity

(d) The energy mix effect (denoted by $\Delta e_{ij} = \Delta E_{ij}/E_i$), reflecting variations in the relative shares of energy types in total energy consumption.

(e) The carbon emission factor effect (denoted by $\Delta M_{ij} = \Delta C_{ij}/E_{ij}$), reflecting changes in the ratio of carbon emission to energy consumption for a given energy type.

Therefore, the decomposition of carbon emission can be changed into additive forms as follows:

$$\Delta C = C_t - C_0 = \Delta C_Q + \Delta C_S + \Delta C_I + \Delta C_e + \Delta C_M \quad (6)$$

Time interval in this work starts in 2006 and ends in 2016. The determinations of ΔC_Q , ΔC_S , ΔC_I , ΔC_e , and ΔC_M are shown as the following equations:

$$\Delta C_Q = \sum_{ij} W_{ij}(C_{ij}^T, C_{ij}^0) \times \ln \frac{Q_T}{Q_0} \quad (7)$$

$$\Delta C_S = \sum_{ij} W_{ij}(C_{ij}^T, C_{ij}^0) \times \ln \frac{S_T}{S_0} \quad (8)$$

$$\Delta C_I = \sum_{ij} W_{ij}(C_{ij}^T, C_{ij}^0) \times \ln \frac{I_T}{I_0} \quad (9)$$

$$\Delta C_e = \sum_{ij} W_{ij}(C_{ij}^T, C_{ij}^0) \times \ln \frac{e_T}{e_0} \quad (10)$$

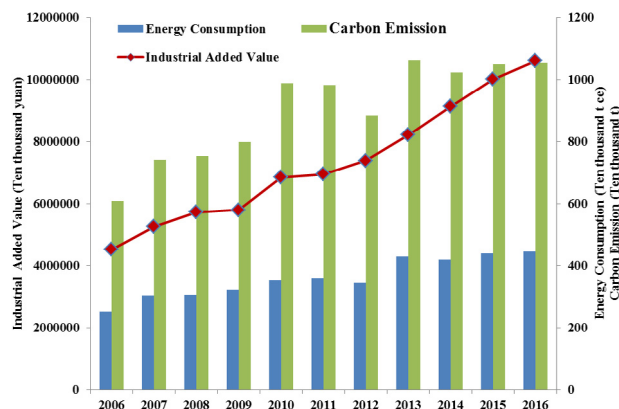


Fig. 2. Evolutions of energy consumption, carbon emission, and industrial added value for Zhuhai industrial sector from 2006 to 2016.

$$\Delta C_M = \sum_{ij} W_{ij}(C_{ij}^T, C_{ij}^0) \times \ln \frac{M_T}{M_0} \quad (11)$$

$$\text{where } W(C_{ij}^T, C_{ij}^0) = \begin{cases} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} & C_{ij}^T C_{ij}^0 \neq 0 \\ C_{ij}^T & C_{ij}^T = C_{ij}^0 \\ 0 & C_{ij}^T C_{ij}^0 = 0 \end{cases} \quad (12)$$

3.4. Data sources

According to the statistical data, the number of the enterprises above designed size accounts for more than 95% of the whole industrial sector in Zhuhai City. Consequently, the data of the above-scale industrial was applied to represent the whole industrial sector in this work. The corresponding data of energy consumption, carbon emission, industrial, added value, energy intensity, and carbon intensity originates from the Chinese energy statistical year book (from 2006 to 2016) (China Energy Statistical Yearbook, 2006–2016) and the Zhuhai statistical year book (from 2006 to 2016) (Zhuhai Statistical Yearbook, 2006–2016). Carbon emission factor of different energy types originated from the local statistical bureau. In order to guarantee comparability, the industrial added value is converted into the comparable price based on 2010.

4. Results and discussion

4.1. Energy consumption and carbon emission

Fig. 2 gives the evolutions of industrial energy consumption, carbon emission, and industrial added value for the Zhuhai industrial sectors from 2006 to 2016. As shown, the industrial added value emerges sustainable increase tendency from 2006 to 2016. During the 11-FYP (2006–2010), the industrial added value increases 51.5% and there is a continued economic growth during the 12-FYP (2011–2015) with an increment of 44.1%. The industrial added value in 2016 (10,596,749.89 ten thousand yuan) is 2.45 times larger than that in 2006 (4,513,121.5 ten thousand yuan), indicating that the industrial sector experienced a rapid develop stage during the past decade. This is because the local government introduced a large numbers of advanced manufacturing enterprises, high-tech manufacturing enterprises, and equipment manufacturing enterprises during the past ten years.

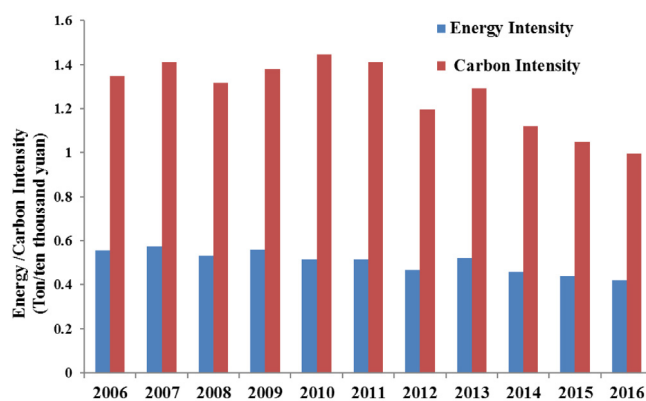


Fig. 3. Changes of energy intensity and carbon intensity for Zhuhai industrial sector from 2006 to 2016.

During the 11-FYP, the industrial energy consumption keeps continuous increase. It firstly decrease then increase during the 12th five year period. The difference of energy consumption during the rest three years of the 12-FYP is not obvious. The industrial energy consumption in 2016 (444.4 ten thousand tce) increases 77.1% compared to that in 2006 (250.9 ten thousand tce). This indicates that the energy consumption experienced relative rapid growth although the industrial added value increases continually. In the future, the industrial energy consumption should be controlled in order to seek green and sustainable development.

The variation of the industrial carbon emission is similar to the characteristics of energy consumption. As shown in Fig. 2, the amount of carbon emission maintains sustained increase during the 11-FYP. However, the carbon emission firstly decreases, and then it fluctuates from 2013 during the 12-FYP. In addition, the industrial carbon emission peaks at 2013 during the past decade.

Fig. 3 provides the variations of the industrial energy intensity and carbon intensity for the Zhuhai industrial sector from 2006 to 2016. As seen, the industrial energy intensity (the ratio of energy consumption to industrial added value) firstly decreases from 2006 to 2008, and then it keeps a slow decline trend from 2009 to 2016. The industrial energy intensity reduction suggests the technological progress and the improvement of energy efficiency in the industrial sector. The energy intensity in 2016 (0.42 tce/ten thousand yuan) decreases 24.6% compared to that of 2006 (0.56 tce/ten thousand yuan). This indicates the effect of green development in the Zhuhai industrial sector. This may attributed to the facts that (i) the developments of the high added value industrial sectors such as the manufactures of computers and communications, manufactures of electrical machinery and equipment, and manufacture of automobile in the past decade in Zhuhai. (ii) energy-saving technology and schemes are applied in the energy-intensive industrial sectors such as papermaking and paper products, manufacture of raw chemical materials and chemical products, non-metal mineral products, smelting and pressing of ferrous metals, and smelting and pressing of nonferrous metals. The carbon intensity experienced a short sharp decrease period and then it had a continued growth during the 11-FYP. The carbon intensity emerges a generally decrease trend since 2011, because for the past years, carbon productivity improved in the Zhuhai industrial sector.

Fig. 4 shows the carbon emission structure for different industrial sectors. As shown, the sectors of S10 (papermaking and paper products), S14 (manufacture of raw chemical materials and chemical products), S16 (manufacture of chemical fibers), S17 (manufacture of rubber and plastic products), S18 (nonmetal

Table 4

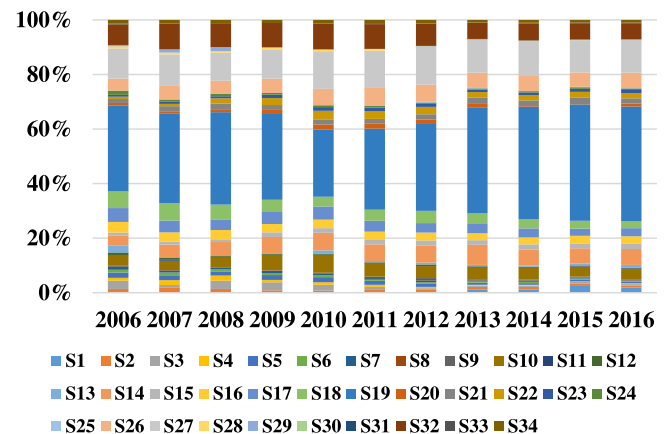
Detailed decoupling situation of carbon emission from industrial added value for industrial sectors.

	Short Term										Middle Term	Long Term	
Sector	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2006-2010	2011-2016	2006-2016
S1	SD	RC	SND	RC	WD	WD	WD	SD	END	RC	RC	WD	WD
S2	END	SD	SD	SND	END	WND	ED	SD	WD	SD	WD	SD	WD
S3	SD	END	SD	SD	SD	SD	SD	SD	WD	END	SD	SD	SD
S4	END	WD	SD	SND	RC	SD	SD	SD	SD	WND	END	SD	SD
S5	RD	RD	RC	WND	SD	SD	SD	SD	SD	SD	WD	RD	SD
S6	RD	RD	SD	WD	RD	WD	SD	WND	RD	RD	WD	SD	SD
S7	SD	SD	END	WD	SD	SD	SD	END	RD	RD	SD	SD	SD
S8	WD	RC	SND	WD	SND	SD	SD	END	EC	WD	END	SD	WD
S9	SD	SND	SND	END	RD	END	WD	WD	SD	SD	SD	WD	WD
S10	SND	SD	WD	EC	SD	WND	WD	SD	SD	WD	WD	SD	WD
S11	WD	SD	SND	WD	SD	SND	SD	RD	WD	SD	WD	WD	WD
S12	SND	RD	WD	WD	SD	WND	WD	SD	RD	WD	SD	RD	SD
S13	SD	WD	WD	END	SD	WD	SD	RD	END	EC	SD	WD	SD
S14	RC	WD	WD	WD	SD	WND	END	SD	WND	WD	WD	WD	WD
S15	WD	WD	SND	WD	SD	SND	WD	WD	SD	WD	WD	WD	WD
S16	WD	WND	WND	WD	RD	RC	WD	SD	END	SND	WD	SD	WD
S17	WD	WND	RD	END	RD	RD	WD	RD	SD	WD	EC	SD	WD
S18	EC	WND	WND	SD	EC	WND	WD	SD	RD	SD	SD	SD	SD
S19	END	WD	SD	SD	SND	RD	WD	SND	SND	SD	WD	SND	WD
S20	SND	SND	WD	WD	SD	RC	SND	SD	SD	END	EC	RD	WD
S21	EC	WD	SD	WD	SD	END	WD	SD	SND	SD	WD	WD	WD
S22	WD	END	WD	END	SD	SD	SD	SD	END	RD	EC	SD	WD
S23	WD	WD	EC	WD	SD	RD	SD	SD	WD	WD	WD	SD	WD
S24	SD	SD	SD	END	SD	SD	WD	WD	END	SD	SD	SD	SD
S25	SD	SD	SD	SD	SD	SND	SD	WND	END	SD	WD	SND	WD
S26	EC	SD	WD	END	WD	WND	WD	SD	SD	WD	WD	SD	WD
S27	END	SD	SND	WD	SD	RD	WD	SD	SD	WD	END	SD	WD
S28	WD	RD	SD	EC	SD	RD	WD	SD	SD	EC	WD	SD	SD
S29	SND	SND	RD	RC	RD	SD	SND	SND	SD	SD	RC	WD	RC
S30	END	SD	SND	WD	WD	SD	SND	RD	END	RD	END	RC	END
S31	WD	WD	WD	WD	WD	SD	SD	WD	SD	SD	WD	WD	WD
S32	END	SD	WD	EC	SD	RD	SD	WD	SD	SD	WD	SD	WD
S33	SD	END	SD	END	SD	SND	SD	SND	SD	WD	SD	END	WD
S34	WD	RD	WD	EC	END	SD	SD	WD	SD	WD	WD	SD	WD

mineral products), S19 (smelting and pressing of ferrous metals), S27 (manufacture of computers, communication equipment and other electronic equipment), and S32 (production and supply of electric power and heat power) are the dominant contributors of carbon emission. The summation of carbon emission for these sectors account for 75% of the total industrial carbon emission. As shown, during the 11-FYP, the sectors of S10, S17, and S27 decrease first and then increase rapidly. While change tendency of the sectors of S18 and S19 are quite opposite, namely, carbon emissions of these two sectors increase firstly and then descend sharply under the driving force of technical progress. Carbon emission of S14 increases consciously and carbon emission of S16 decreases monotonically. For the 12-FYP, except S11 and S19, almost carbon emissions of all the other sectors decrease with slight fluctuation.

4.2. Decoupling situation

The decoupling results of the entire industry sector from 2006 to 2016 were shown in Fig. 5. Fig. 5a shows that during the 11-FYP, most of the decoupling situations of carbon emission from energy consumption were expansive coupling or expansive negative decoupling, which means that carbon emission of the industrial sector was closely linked with energy consumption.

Carbon emission structure**Fig. 4.** Carbon emission structure for different industrial sectors.

It is noted that for the first year of the 12-FYP, strong decoupling emerges for the relationship of carbon emission and energy consumption. This may due to the fact that energy structure

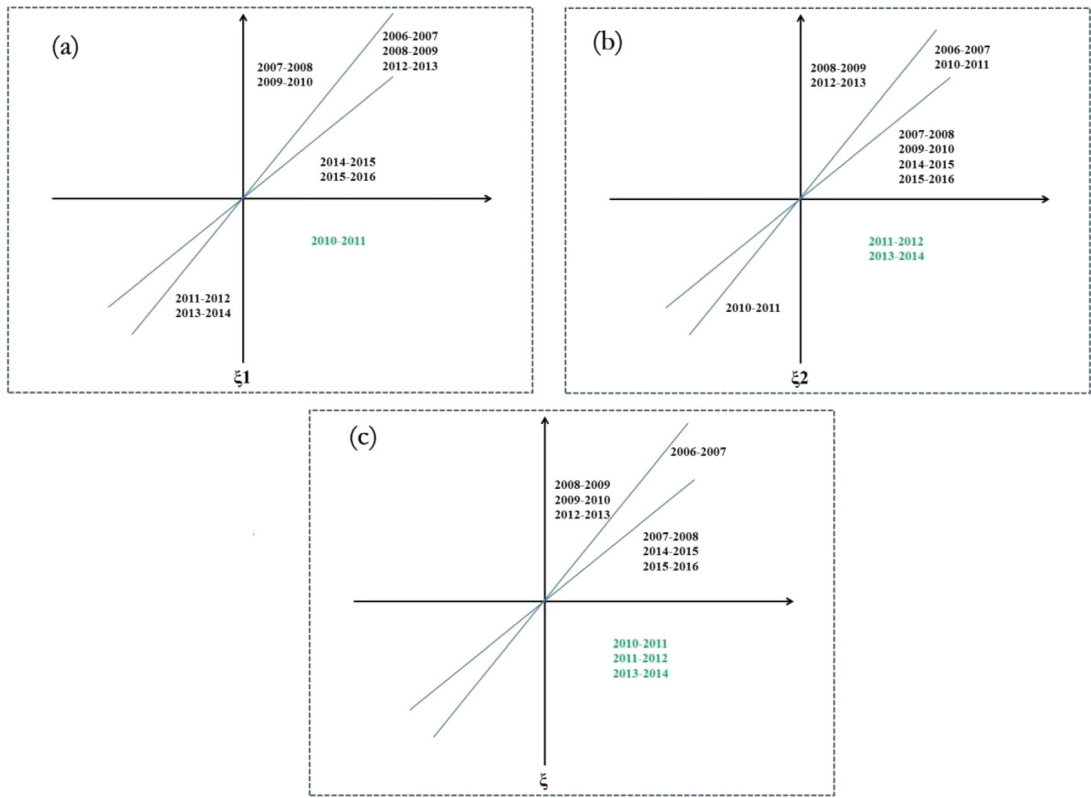


Fig. 5. Decoupling results of Zhuhai industrial sector from 2006 to 2016.



Fig. 6. Overall decomposition results of carbon emission for Zhuhai industrial sector from 2006 to 2016.

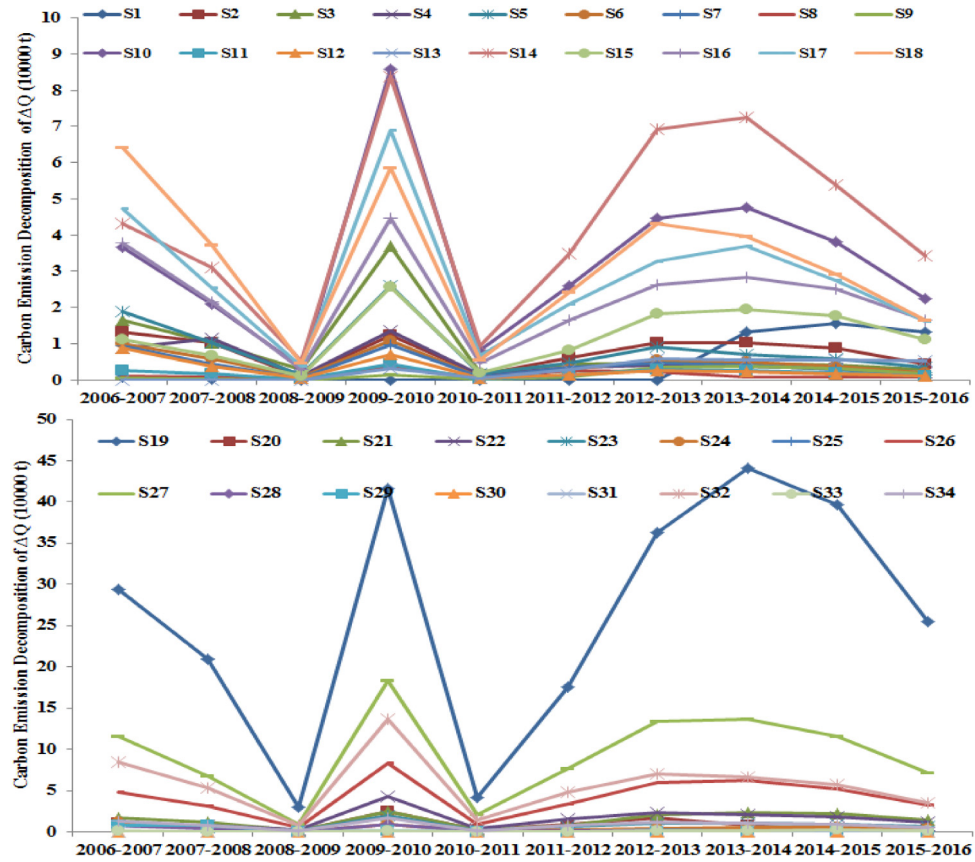


Fig. 7. Carbon emission decomposition of ΔC_Q for Zhuhai industrial sector from 2006 to 2016.

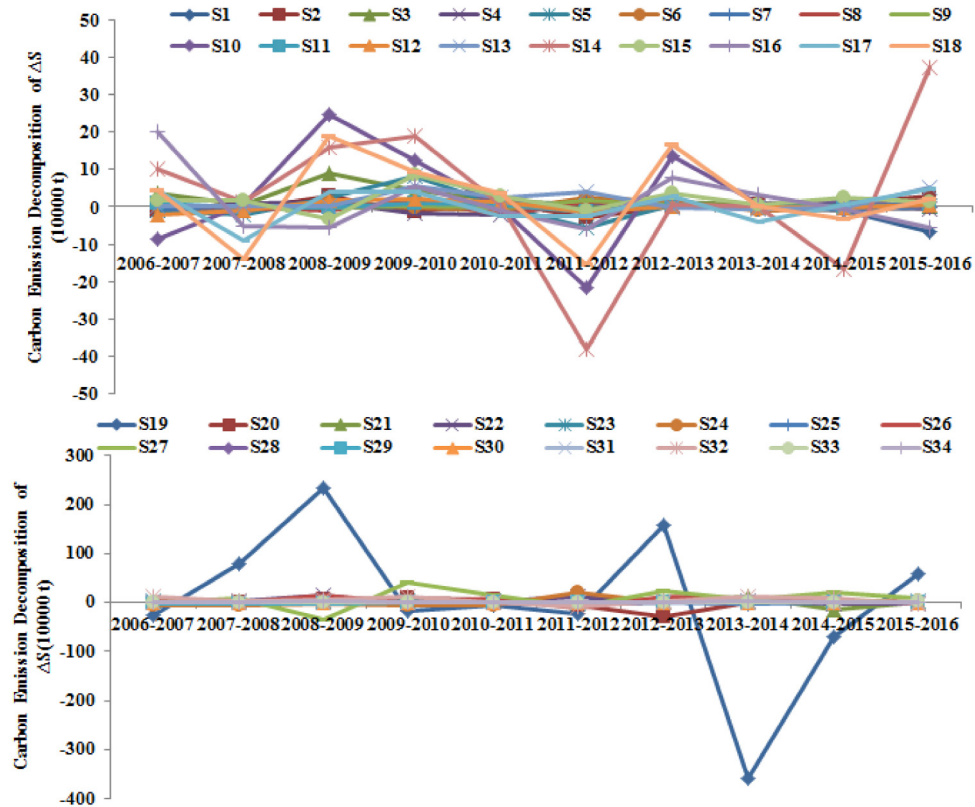


Fig. 8. Carbon emission decomposition of ΔC_S for Zhuhai industrial sector from 2006 to 2016.

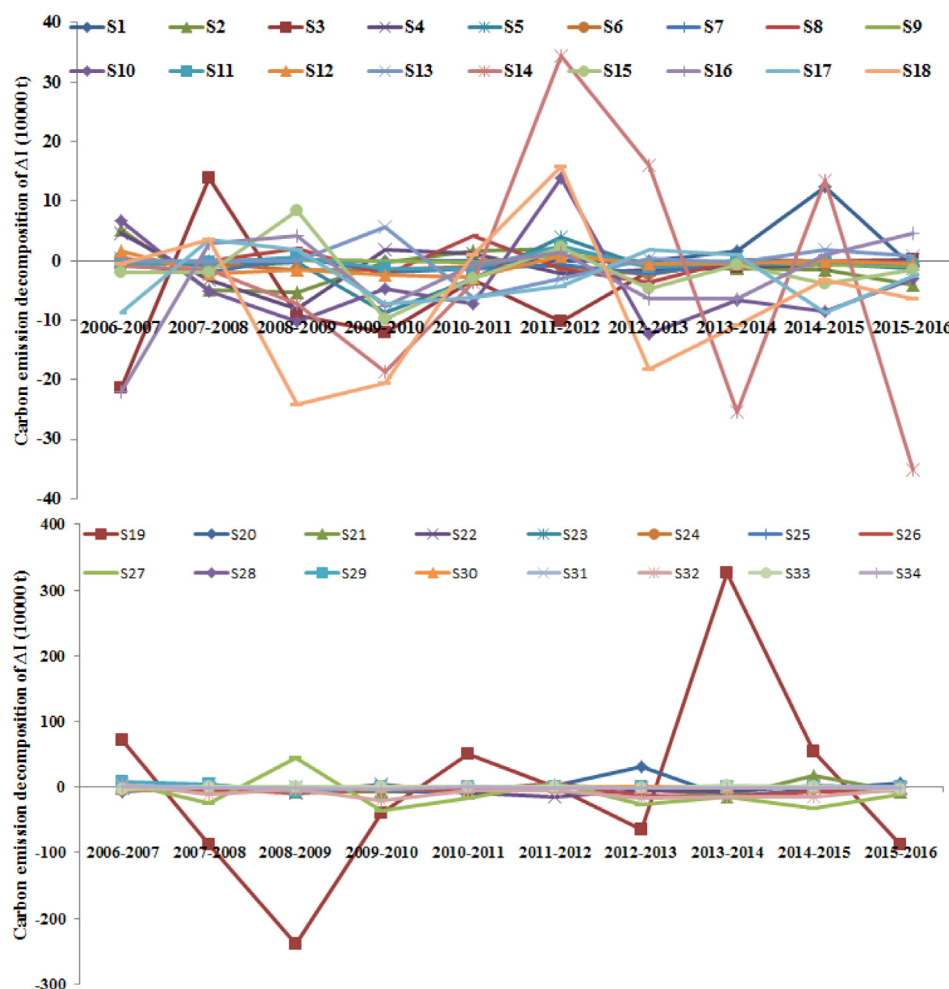


Fig. 9. Carbon emission decomposition of ΔC_i for Zhuhai industrial sector from 2006 to 2016.

turns to be cleaner under the general principal of low carbon development. The decoupling situations during 2011–2012 and 2012–2013 regress to recessive coupling and expansive coupling, which indicates that the change rate of carbon emission almost equals to that of energy consumption. During the remaining time of the 12-FYP, the decoupling situation transfers into weak decoupling, this suggests that the increase pace of carbon emission is obviously smaller than that of the energy consumption.

As shown in Fig. 5b, the decoupling state of energy consumption from industrial added value denotes not decoupling during the 11-FYP. The decoupling situation changed from expansive coupling and expansive negative decoupling to weak decoupling. For the initial period of the 12-FYP, the decoupling situation is recessive decoupling, which indicates that the decrease pace of energy consumption is obviously than that of the industrial added value. It is comforted that during the rest time of the 12-FYP, the decoupling situation of between energy consumption and the industrial added value becomes strong decoupling or weak decoupling, revealing a decoupling trend. As shown in Fig. 5c, for the main stage of the 11-FYP, there are few signals of decoupling between carbon emission and economic output. However, it is noted that since 2010, the decoupling situation of carbon emission and the industrial added value mainly emerges strong decoupling or weak decoupling. This is because on one hand, at a macro level, the local government implements low carbon development policy to control carbon emission. On the other hand, at the micro level during the 12-FYP Zhuhai focused

on high-end service, high-end manufacturing and high-technical industry to promote economic transformation.

Table 4 shows the detailed decoupling situation of carbon emission from industrial added value for industrial sectors. To evaluate the decoupling states objectively, the evaluation period was divided into three types, i.e., ST (short term), MT (middle term), and LT (long term). For the short term evaluation during the 11-FYP, the decoupling states of the 34 industrial sectors can be characterized as three categories. (i) Sectors of S1, S3, S7, S11, S13, and S15 presented strong decoupling or weak decoupling situation at the beginning, then experienced non-decoupling stage, and displayed strong decoupling or weak decoupling at the end of the 11-FYP. (ii) Sectors of S2, S4, S6, S18, and S19 were characterized as showed the non-decoupling state at the beginning, then experienced short strong or weak decoupling situation and presented non-decoupling situation at the end of the 11-FYP. (iii) The rest sectors displayed strong decoupling and non-decoupling situation alternatively during the 11-FYP. For the 12-FYP with short term, the decoupling situation can also be divided into three kinds: (i) S5, S9, S10, and S15 presented strong decoupling or weak decoupling situation during the entire 12-FYP. (ii) S1, S6, S7, S8, and S13 showed decoupling state firstly and then progressed as non-decoupling state at the end. (ii) The majority of the rest sectors firstly presented non-decoupling situation then evolved as the decoupling situation at the end. Generally, most industrial sectors presented more situations of strong decoupling or weak decoupling situation during the 12-FYP compared to that during the 11-FYP. For the 11-FYP with middle term evaluation,

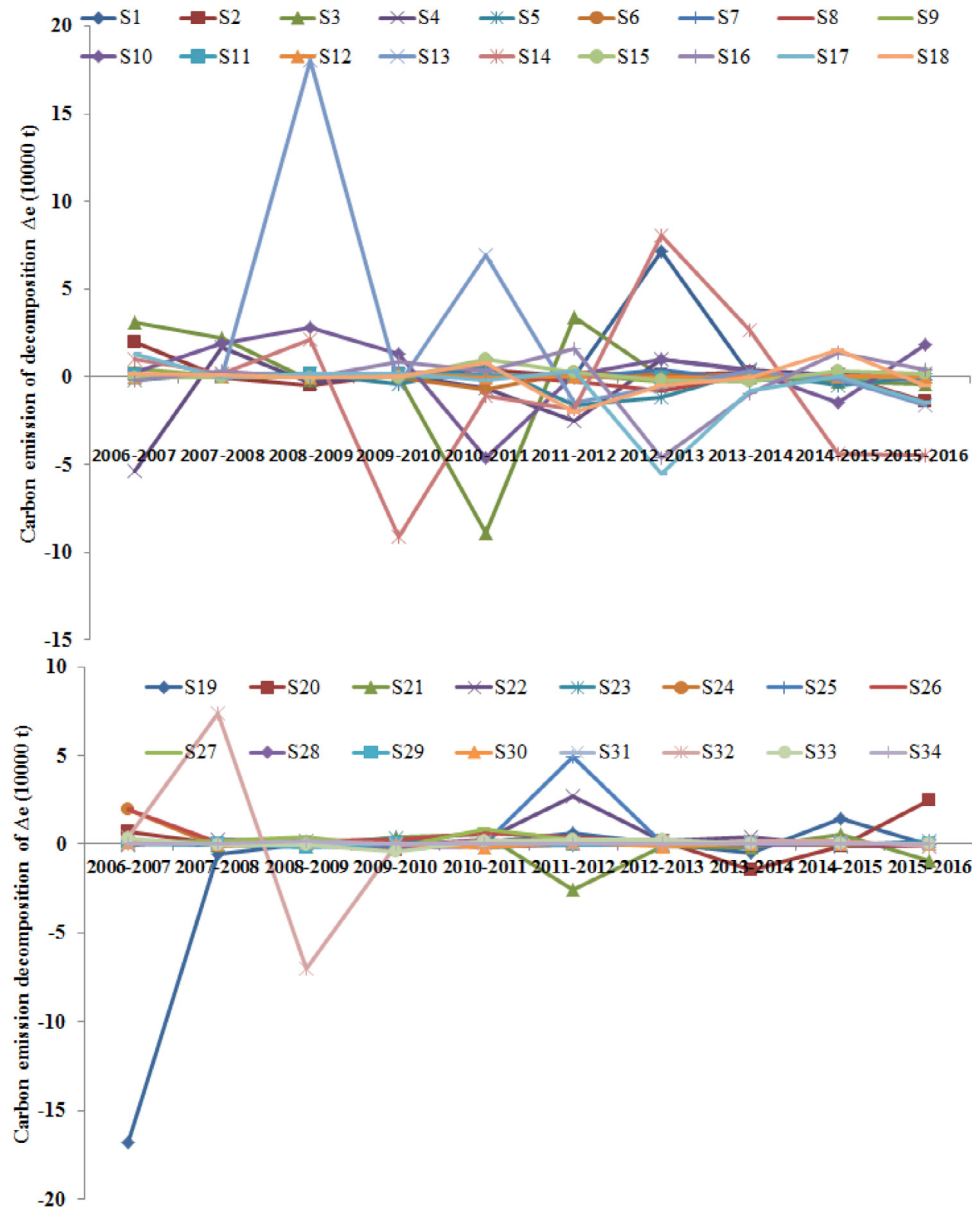


Fig. 10. Carbon emission decomposition of ΔC_e for Zhuhai industrial sector from 2006 to 2016.

except sectors of S1, S4, S8, S17, S20, S22, S27, S28, S9, and S30 presented non-decoupling situation, the rest 24 sectors showed strong decoupling or weak decoupling. In addition, during the 12-FYP, only 7 sectors (S5, S12, S19, S20, S25, S30 and S33) showed non-decoupling situation. It is satisfying that except sector 29 showed as recessive coupling and sector 30 displayed expansive negative decoupling, the rest 32 sectors displayed strong decoupling or weak decoupling situation for the long term decoupling evaluation. This demonstrated a relative low carbon development stage for the Zhuhai industrial sector during the 11-FYP and the 12-FYP.

4.3. Driving forces of carbon emission

Fig. 6 gives the overall decomposition results of carbon emission for Zhuhai industrial sector from 2006 to 2016. It is noted that except the brief period of 2010–2012 and 2013 and 2014, the variation of the total carbon emission is negative, carbon emission in the rest years maintains continued growth. As shown, ΔC_Q is always positive during the past decade, which means that

the economic output always plays positive function on carbon emission for Zhuhai industrial sector. As regards the industrial structure, ΔC_S keeps positive during the 11-FYP, indicating that the industrial structure effect is positive for carbon emission and the industrial structure is heavy during this period. With the industrial transformation and upgrading, the high-tech industrial sector such as the manufacture of computers, communication equipment and other electronic equipment was strengthened, and the industrial structure was optimized. Hence, ΔC_S started to become negative value during the 12-FYP, which helps reducing carbon emission. In addition, during the 11-FYP, ΔC_I is almost always negative and its absolute value is relative large, suggesting that the energy intensity effect is the primary driver for reducing the industrial carbon emission for Zhuhai. This is benefited from the industrial energy-saving and the breakthrough of high technology. However, on account of the backward effect of energy-saving measures during the 12-FYP, ΔC_I is fluctuated by positive and negative value. The variation of ΔC_e is relatively smaller compared to that of ΔC_Q , ΔC_S , and ΔC_I , suggesting the adjustment of energy mix effect have minor contributions of

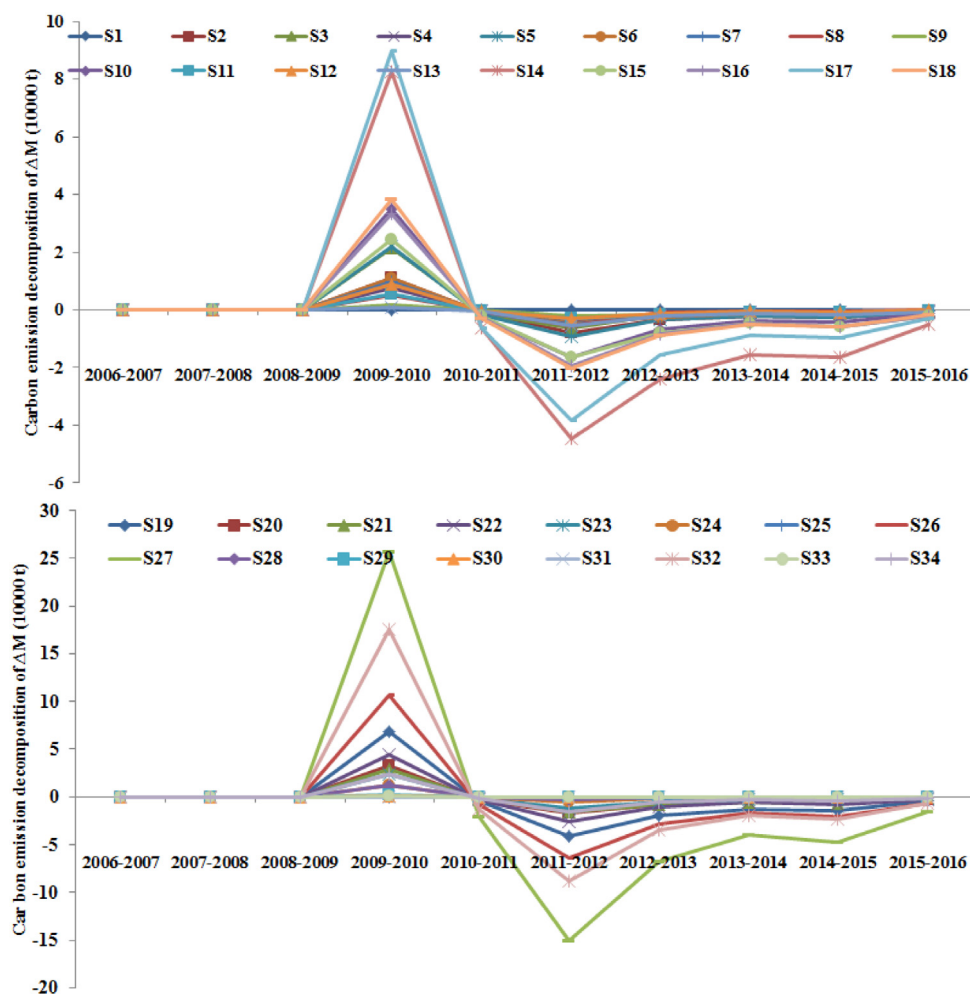


Fig. 11. Carbon emission decomposition of ΔC_M for Zhuhai industrial sector from 2006 to 2016.

increasing or reducing the industrial carbon emission in Zhuhai. The change of ΔC_M during the 11th five period is mild, and ΔC_M is always negative during the entire 12-FYP which is resulted from the improvement of the clean power generation. In general, the economic output effect always has increment effect for the industrial carbon emission during the past decade. Furthermore, the energy intensity effect is the dominant driver for reducing the industrial carbon emission in Zhuhai during the 11-FYP. Moreover, during the 12-FYP, carbon emission reduction for Zhuhai's industrial sector is conducted under the conjunctive role of the industrial structure effect, the energy intensity effect, the energy mix effect, and carbon emission factor effect.

Fig. 7 gives the evolution of carbon emission decomposition of ΔC_Q for subdivided industrial sector of Zhuhai from 2006 to 2016. As seen, ΔC_Q for each subdivided industrial sector is positive, showing an increment effect on carbon emission. Changes of ΔC_Q for subdivided industrial sector presented inverted U shapes during the 11-FYP. In addition, U shapes emerged for variation of ΔC_Q for subdivided industrial sector during the 12-FYP. It is shown in Fig. 7 that the industrial sectors of nonmetal mineral products, smelting and pressing of ferrous metals, and manufacture of computers, communication equipment and other electronic equipment play the leading role in the decomposition dynamic of carbon emission for the economic output effect.

As given in Fig. 8, for the decomposition of industrial structure effect, except S19, the general tendency is that a U shape curve emerged in the 11-FYP, and a decline trend linked to the U shape

at the end of the 11-FYP. It is also shown that two U shape curves presented during the 12-FYP. Although the overall decomposition of industrial structure effect is positive during the 11-FYP, the structure adjustments of the subdivided sectors of manufacture of medicines, manufacture of rubber and plastic products, and nonmetal mineral products had some impacts on reducing carbon emission. However, the structure adjustment in the sector of smelting and pressing of ferrous metals has the main increment effect on carbon emission during this period. Furthermore, during the 12-FYP, the coordinated structure adjustment of papermaking and paper products, manufacture of raw chemical materials and chemical products, manufacture of rubber and plastic products, nonmetal mineral products, and smelting and pressing of ferrous metals pushed the de-carbonization process of Zhuhai's industrial sector. As for the energy intensity effect, Fig. 9 shows that ΔC_I for the most subdivided industrial sectors is negative during the 11-FYP. For the 12-FYP with carbon emission decomposition of ΔC_I , manufacture of raw chemical materials and chemical products contributed the main positive value during the initial phase, then smelting and pressing of ferrous metals contributed the main positive effect during the later phase.

Fig. 10 gives the evolution of decomposition for energy mix effect. There is no obvious regular variety, and the increase and decrease trend alternatively emerges. Petroleum refining, coking and nuclear fuel processing has the main increment effect on the carbon emission decomposition for energy mix effect. The main sectors for reducing carbon emission with the energy mix effect are manufacture of food, and smelting and pressing of

ferrous metals. In addition, Fig. 11 indicates that carbon emission decomposition for carbon emission factor effect during the entire 11-FYP is positive, playing catalytic effect on industrial carbon emission. Additionally, ΔC_f is negative for each subdivided industrial sector during the whole 12-FYP, which promotes the progress of carbon emission reduction. Moreover, the main contributors of reducing carbon emission with the carbon emission factor effect are the manufacture of raw chemical materials and chemical products, manufacture of rubber and plastic products, manufacture of computers, communication equipment and other electronic equipment, as well as production and supply of electric power and heat power.

5. Conclusions and policy implications

This study provided the evidences of carbon emission decoupling status and the carbon emission decomposition results at the coastal city of Zhuhai from 2006 to 2016. It is the first time to assess Zhuhai's emission decoupling and analysis the corresponding driving force from the perspective of industrial. This study not only evaluated the decoupling situation of carbon emission from economic growth, but also the decoupling situations of carbon emission from energy consumption and energy consumption from economic growth are evaluated. In addition, the microanalyses of decoupling situation for subdivided industrial sectors are carried out through long term, middle term, and short term evaluation. The influencing factors include the economic output effect, the industrial structure effect, the energy intensity effect, the energy mix effect, and the carbon emission factor effect are adopted to analysis carbon emission decomposition.

The results reveal that the industrial added value emerges sustainable increase tendency from 2006 to 2016. The increment of the industrial added value during the 11-FYP and the 12-FYP are 51.5% and 44.1%, respectively. Variation of carbon emission is similar to that of energy consumption. Both energy consumption and carbon emission keeps continuous increase during the 11-FYP. They firstly decrease and then they presented volatile during the rest years of the 12th five year period. The results enlightened that controlling of energy consumption and carbon emission should be enhanced and maintain continuity. The local government should enact rigorous incentives to avoid the phenomenon of carbon emission reduction in the previous phase and then rebounded during each five year period.

From the perspective of emission structure, the sectors of papermaking and paper products, manufacture of raw chemical materials and chemical products, manufacture of chemical fibers, manufacture of rubber and plastic products, nonmetal mineral products, smelting and pressing of ferrous metals, manufacture of computers, communication equipment and other electronic equipment, and production and supply of electric power and heat power are the dominant contributors of carbon emission, which accounts for more than 75% of the total industrial carbon emission in Zhuhai. Hence, the policy implication is that applying effective measures focused on these key industrial sectors should be taken seriously. The local government should adopt schemes to decrease energy consumption and optimize energy mix in these major emission sectors from the perspectives of top design. For example, the potential of renewable energy in heat and electricity supply should be developed. In addition, energy-conserving and high-tech technologies should be encourages to improve energy efficiency. The decoupling results indicate that carbon emission is strongly linked with energy consumption during the 11-FYP, and it started to display strong decoupling during the 12-FYP. Similarly, during the 11-FYP, there are very few signals of decoupling of energy consumption from industrial added value, nor did the carbon emission from the industrial added value. It is comforted

that both energy consumption and carbon emission emerged strong decoupling or weak decoupling from the industrial added value during the 12-FYP. On a micro level, the decoupling phenomenon enhanced with the extension of the evaluation cycle. For the short term level, the decoupling and non-decoupling situation emerged alternatively for each subdivided industrial sector, which enlightened that the subdivided industrial sector should improve their production efficiency and add better value in each production link. However, for the long term evaluation, 32 industrial sectors displayed strong decoupling or weak decoupling situation of carbon emission from the economic output value, which showed a cleaner production tendency emerges gradually from the 11-FYP to 12-FYP in Zhuhai's industrial sectors from the long term perspective. The policy implication is that in order to decoupling energy consumption and carbon emission from economic increase, the local government should continually support the high-tech manufacture sectors such as manufacture of computers, communication equipment and other electronic equipment.

The decomposition results indicate that the economic output value is the main driving force factor of carbon emission for the industrial sector in Zhuhai. During the 11-FYP, the energy intensity effect is the dominant driver for reducing the industrial carbon emission. In addition, the conjunctive role of the industrial structure effect, the energy intensity effect, the energy mix effect, and carbon emission factor effect is the main driving force for carbon emission reduction. From the micro level's angle, the implication is that the adjusting industrial structure, reducing energy intensity, and upgrading technology in the industrial sectors of nonmetal mineral products, smelting and pressing of ferrous metals, manufacture of medicines, manufacture of rubber and plastic products, manufacture of raw chemical materials and chemical products, and petroleum refining, coking and nuclear fuel will play positive in reducing carbon emission. Furthermore, the industrial share should be inclined to the high-tech industrial sector such as the manufacture of computers, communication equipment and other electronic equipment.

Declaration of competing interest

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

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