Driving forces in energy-related carbon dioxide emissions in east and south coastal China: commonality and variations

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Abstract: As the world's top carbon dioxide emitter, China is expected to reach its emissions peak by 2030. East and south coastal China contribute nearly one-third of the emissions in China, and therefore play a critical role in achieving the national goal of emission control. This study analyzes the driving forces of east and south coastal China's energy-related emissions and their provincial characteristics by applying the logarithmic mean divisia index method. The emissions in this region were found to double from 2000 to 2012, along with three and twofold increase in the economy and energy consumption. The result suggests a persistent connection between economic growth and emission even in this socioeconomically advanced region. The per capita emissions are lower than most regions of China at a given economic level, and are expected to be lower than select developed nations when reaching their corresponding economic levels. Energy efficiency has been the leading force in reducing emission growth, and we differentiate the provinces into three distinct low-carbon developmental stages. There is no significant influence from either the economic or energy structure change, indicating great emission reduction potential from structure decarbonization especially when compared to advanced nations. These results suggest that the dual effort of enhancing energy efficiency and decarbonizing the economic and energy structure would probably serve the goal of total emission control more effectively and efficiently, and factor driven emission reduction strategies are needed in these geographically and socioeconomically similar regions. The study expands on the current knowledge by analyzing the interprovincial commonality and variation of this pilot region in China, and therefore provides a stepwise view of the emission driving forces for emerging economies.

Keywords: decomposition analysis; CO_2 emission; driving force; coastal China; provincial feature

1. Introduction

Over the past decade, China has become the world's second largest economy and the top carbon dioxide (CO_2) emitter (*Jos et al., 2013*), attracting global concerns of its environmental impact (*Liu et al., 2013*). Hence, China plays a key role in reducing global emissions. On November 12, 2014, it took a step in pledging to "stop its emissions from growing by 2030 at the latest" (*Schiermeier, 2014*). On June 30, 2015, in an official document submitted to the Secretariat of the United Nations Framework

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Convention on Climate Change, the Chinese government solemnly committed to cut its CO_2 emissions per unit of gross domestic product (GDP) by 60–65% by 2030 relative to its 2005 levels, and peak CO_2 emissions around 2030 and make best efforts to peak early (*UNFCCC，2015*). Though the targets are clearly set, challenges remain as to how to realize the dual goals of curbing energy use and emissions while sustaining economic growth. Given China's vast geographic scale and diverse regional developmental stages, it is essential to acquire a strategic understanding of the carbon emission characteristics and the underlying driving forces in its different regions, in order to establish a broadly acceptable and efficient emission reduction agenda.

East and south coastal China, especially the coastal provinces of Shandong, Jiangsu, Zhejiang, Fujian, and Guangdong plus Shanghai municipality (hereafter referred to as "the Region" [1] or the "six coastal provinces", Figure 1), were the earliest regions to carry out the reform and opening up policy since 1978 and the pilot ship for most of the nation's strategic programs. It includes China's two strategic economic zones – the Yangtze River Delta region including the entire territory of Jiangsu, Shanghai, and Zhejiang, and the Pearl River Delta consisting of most parts of Guangdong – and accounts for one-third of the total national emissions during 2003–2010 (*Guan et al., 2012*). It is also the region with the highest energy efficiency in China but bear the higher emission reduction targets set by the central government (*He et al., 2013*), taking up earlier emission reduction responsibility than the less developed regions (*Zhou et al., 2014*). Though geographically occupying a small area of China (Figure 1), the six coastal provinces account for nearly 30% of the national population and contribute almost half of the national GDP (*NBSC, 2001–2013a*). From the global perspective, the Region's GDP is 76.2% and 19% of that of Japan and the European Union (EU), respectively, and it contributes to nearly 8% of the world's carbon emissions (*IEA, 2013*). It occupies twice the area of Japan or Germany and its

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[1] The classification of east and south coastal China in this study is slightly different from that in Zhou *et al.* (2014), which defined Shanghai, Jiangsu, and Zhejiang as belonging to the eastern coast and Fujian, Guangdong, and Hainan as belonging to the southern coast. This study focuses on the economically developed provinces in southern and eastern costal China, which were among the first to implement the reform and opening up policies. Shandong is included as an eastern coastal province because it has similar economic and energy structure as the other five provinces (*NBSC, 2001–2013a*), and has been categorized as an eastern costal China province on various occasions (*Fang, 2007*). Hainan is excluded because it is an island province with a per capita GDP below the national average *(NBSC, 2001–2013a*).

population is 3 times that of Japan or 79% of that of the EU. Therefore, it is an important region to study the driving forces and emission reduction potential.

Despite the Region's importance, none of the previous studies, to our knowledge, has focused solely on this region. Song *et al.* (2015) analyzed the energy consumption and carbon emissions in the Yangtze River Delta region, and attributed their growth mainly to increasing economic development and population. Other studies looked at the individual provinces under the national framework, and this may have contributed to the discrepancies in assessment of the provinces in different studies. For example, Wang *et al.* (2013) found that Shanghai and Guangdong, together with Beijing, attained the highest energy and environmental efficiency, while Guan *et al.* (2014) found Guangdong and Jiangsu to be the only two provinces to become cleaner in both individual industry and economic composition.

Therefore, this study chooses the vital yet rarely studied coastal region, and presents a detailed analysis on the driving forces of its energy- related emissions. The goal is to identify the provincial lessons for China to achieve its emission reduction target, by province targeted policies and strategies. An integral understanding of the emission performance and the underlying driving forces of the Region not only will help address the 8% of the world's CO_2 emissions but also will provide guidance for the less developed regions of China that want to follow the path to prosperity of this coastal region.

The rest of the paper is organized as follows. The next section provides a literature review on the driving forces of China's carbon emissions. Section 3 and section 4 respectively present methods and the data adopted in this study. Section 5 reports and discusses the results of seven underlying driving forces and their relative contributions at both the regional and provincial scale. Section 6 derives the conclusions and the policy implications of this study.

2. Literature Review

Previous studies have advanced the knowledge base on the carbon emission characteristics of China in the following aspects:

2.1. The forces generally affecting energy -related CO_2 emissions

There is widespread scientific agreement that CO_2 emissions often relate to four types of forces and their combinations: (i) economic forces including economic growth and international trade; (ii) energy efficiency related forces, for example, energy intensity, per capita energy, and electricity consumption; (iii) structure related forces, for example, the economic structure, energy structure and structure of the manufacturing industry; and (iv) population-related forces such as population size and household numbers, and urbanization rate (*Minx et al., 2011; Fan et al., 2013; Zhu and Wei, 2015; Wu et al., 2005; Zhang et al., 2009; Tan et al., 2011; Tunc et al., 2009; Paul et al., 2004; Pani et al., 2010; O'Mahony et al., 2012*).

2.2. The relative importance of different forces, and their comparison with developed nations

Yao *et al*. (2014) found economic development to be the main driving force for emission growth in all G20 countries, while the offsetting effect due to improved energy efficiency was especially pronounced in emerging countries like China. Structural change in both economic and energy structure has become increasingly important in balancing emissions in most developed economies, whereas in China it has been contributing to growth in emissions for the past two decades (*Yao et al., 2014; Guan et al., 2014*). Emissions mostly come from industry, while the other sectors generally exhibit good performance in reducing emissions (Xu *et al.*, 2014), and it is especially pronounced in the less developed provinces due to the utilization of energy-intensive technologies (*Liu et al., 2012*).

2.3. The energy and CO_2 emission performance and reduction potential of the different regions

Guan *et al*. (2014) found that despite of the great improvement in energy efficiency, the movement toward a more carbon-intensive economic structure, in particular coal-fired electricity generation, metal processing, and cement production, had contributed positively toward the 3% increase in carbon intensity between 2002 and 2009 in China. On one hand, eastern and coastal China were found by various studies to have the highest energy efficiency, followed by central and western China (*Wang et al., 2013; Wang et al., 2014; Yu et al., 2012*). On the other hand, Wang and Wei (2014) showed that no region performed efficiently in CO_2 emissions, which the authors attributed to the real estate boom leading to a large number of energy-intensive projects. Chen and Yang (2015) studied the driving forces of CO_2 emissions in China’s 29 provinces and found that the eastern provinces showed the largest emission growth, and suggested that emission reduction policies should be formulated to accommodate these regional disparities.

2.4. The consequence allocation of reduction targets considering the responsibility, capacity, and potential

Yi *et al.* (2011) used a top-down model and calculated that the coastal provinces of Shanghai, Shandong, and Guangdong and the northern provinces of Hebei, Shanxi, and Liaoning should bear a higher reduction burden, under full consideration of equality, capacity, responsibility, and potential. Two additional coastal provinces, namely Jiangsu, Zhejiang, and the northern province of Inner Mongolia were recommended to shoulder higher allocations if potential was not taken into consideration. Another clustering analysis by Yu *et al.* (2012) also suggested the "high emission–low per capita" provinces of Jiangsu, Zhejiang, Guangdong, and Shandong should be given the highest reduction allocation.

Though the previous studies used the logarithmic mean divisia index (LMDI) analysis, they only analyzed the aggregate results of the entire nation or various regions with little attention paid to interprovincial commonalities and disparities in the driving forces of carbon emissions. In addition, most such studies focused only on the economic sector, whereas the residential sector accounts for abundant emissions and the two sectors have very different driving forces (*Fan et al., 2013*). In this study, we decompose carbon emissions into the economic sector and the residential sector, and analyze the relative impacts of the seven driving forces.

3. Methods

3.1. Estimation of CO_2 emissions

The energy-related CO_2 emissions were calculated following the 2006 IPCC National Greenhouse Gas Inventories (*IPCC, 2006*), as shown in Eq. (1)

$$C = \sum_i C_i = \sum_i (E_i \cdot NCV_i \cdot CC_i \cdot COF_i \cdot 44/12) \qquad (1)$$

where C_i represents the CO_2 emissions of the i type of energy (for the 15 energy types including raw coal，cleaned coal，other washed coal，briquettes，coke，crude oil，gasoline，kerosene，diesel oil，fuel oil，natural gas，liquefied petroleum gas，refinery gas，coke oven gas and other gas); E_i, NCV_i, CC_i, and COF_i represent the consumption, the average net calorific value, the carbon emission coefficient, and the carbon oxidation factor of the *ith* type of energy, respectively. The fraction 44/12 is the ratio of molecular weights of CO_2 and C. The COF_i values are recommended by the Energy Research Institute of Chinese National Development and Reform Commission

(*NDRC-ERI, 2011*). This study applies the CC_i values provided by Peters *et al.* (2006) for the 15 types of final energy, and assume them to be constant over the study period.

3.2. LMDI decomposition

A number of methods to identify the underlying driving forces on CO_2 emissions have been developed, among which the structural decomposition analysis (SDA), the index decomposition analysis (IDA), production-theoretical decomposition analysis (PDA), and stochastic impact by regression on population, affluence, and technology (STIRPAT)[2] models are the most well known (*Hoekstra et al., 2003; Mohammadi et al., 2013; Zhou et al., 2010*). Zhou and Ang (2008) provided a detailed introduction and comparison of the various methods. In short, SDA is based on input–output analysis in quantitative economics, and therefore has very high data requirement (such as detailed energy consumption and production output in each industrial sector) (*Hoekstra et al., 2003*). However, these data are collected every 2–3 years, therefore leading to time lags in policy analysis. The PDA approach requires solving a series of complex linear programs, which may be computationally difficult for someone who is not familiar with linear programming. Besides, it cannot estimate structural effects such as energy or economic structure, which are identified to have significant effects in numerous studies. As a widely applied IDA method, LMDI estimates the effect of individual factors through the weighted average logarithmic changes of its relevant variables (*Ang et al., 1998*). This method can run on an annual basis owing to the generally easy availability of the required data, and is perfect in decomposition based on multiple sectors without unexplained residuals. It is capable of accommodating zero values (this is preferred to STIRPSAT and other IDA methods), and easy to be adapted in studies and interpret results (*Ang, 2004*). After careful consideration of the theoretical foundation, data requirement, decomposition form, and some relevant index properties, LMDI method was chosen for this study.

Decomposition of the energy-related CO_2 emissions (*C*) was first put forward by the Kaya identity in Eq. (2) (*Kaya, 1990*):

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[2] Strictly speaking, STIRPAT is a statistical method rather than a decomposition method. Dietz and Rosa (1997) introduced the stochastic variables to the widely adopted IPAT identity which classifies all factors that have effects on the environment as three drivers: population size, affluence as represented by per capita consumption or production, and technology.

$$C = \frac{C}{E} \cdot \frac{E}{G} \cdot \frac{G}{P} \cdot P \quad (2)$$

where E is the energy use, G is the gross domestic product, and P is the population size. When we apply the rule behind the equation to every sector, Eq. (2) can be extended for multiple sectors in a region as

$$\begin{aligned} C &= \sum_i C_i + \sum_k C_k \\ &= \sum_i \left[\left(\sum_j ef^{\,j} \cdot \frac{E_i^j}{E_i} \right) \cdot \frac{E_i}{G_i} \cdot \frac{G_i}{G} \cdot \frac{G}{P} \cdot P \right] + \sum_k \left[\left(\sum_j ef^{\,j} \cdot \frac{E_k^j}{E_k} \right) \frac{E_k}{P_k} \cdot \frac{P_k}{P} \cdot P \right] \quad (3) \\ &= \sum_{n \in \{i,k\}} \left[\left(\sum_j ef^{\,j} \cdot \frac{E_n^j}{E_n} \right) \cdot \left(\frac{E_i}{G_i} \cdot \frac{G_i}{G} \cdot \frac{G}{P} + \frac{E_i}{P_k} \cdot \frac{P_k}{P} \right) \cdot P \right] \\ &= \sum_{n \in \{i,k\}} \left[es_n \cdot \left(e_i \cdot ins_i \cdot g + er_k \cdot ur_k \right) \cdot p \right] \end{aligned}$$

where i, j, k stand for the economic sector, energy type, and residence type, respectively, with $k = 1$ denoting urban and $k = 2$ denoting rural residence. Therefore, E_i^j, for example, stands for the consumption of fuel j in sector i. The terms ef, g, ins, e, and es represent carbon emission factor, the per capita GDP, share of the GDP for a specific sector, energy intensity of the sector, and the share of certain type of energy in that sector; er, ur, P represent the per capita energy consumption of rural or urban residence, share of the rural or urban population, and population scale[3]. In Eq. (3)，we first decompose the aggregate carbon emission of a province into two parts: emissions in economic sectors and emissions in residential sectors; then each item of the two parts is further decomposed into five driving forces (i.e., energy structure ($\sum_j ef^{\,j} \cdot \frac{E_n^j}{E_n}$)[4], energy efficiency ($\frac{E_i}{G_i}$), economic structure ($\frac{G_i}{G}$), economic development ($\frac{G}{P}$), and population size (P)), and four driving forces (i.e.，energy structure, per capita residential energy consumption ($\frac{E_k}{P_k}$)，urbanization ($\frac{P_k}{P}$)、population (P)), respectively.

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[3] Detailed descriptions of all the parameters are provided in Table A1.

[4] Strictly speaking, this expression refers to energy structure (E^j_n/E_n) multiplied by the corresponding carbon emission factors (ef^j). Since the carbon emission factor of each energy is a fixed parameter during the study period, for the simplification of discussion, it is combined with the actual energy structure (E^j_n/E_n) to represent the driving force of energy structure.

Since both parts include the energy structure effects and population size effect, the nine driving forces can be merged into seven.

To quantitatively analyze the relative contribution of the different forces with time, the LMDI model (*Ang, 2005*) is applied to Eq. (3). Therefore, the change of CO_2 emissions from year t to year $t + 1$ can be decomposed into seven driving forces in the following form

$$\Delta C = C_{t+1} - C_t = \Delta C_g + \Delta C_{ins} + \Delta C_e + \Delta C_{er} + \Delta Cur + \Delta Cp + (\Delta C_{es} + \Delta C_{esr}) \quad (4)$$

The seven driving forces[5] are used to represent the four types of effects described in the introduction, and the results are calculated using the equations listed in Appendix A. This study includes six economic sectors (i.e., agriculture, industry, construction, transport，storage, and post, wholesale and retail trade, and hotels and restaurants; and other service sectors). Based on the above two equations, this study calculates the industrial versus residential CO_2 emissions separately considering the different driving forces behind their energy consumptions.

4. Data sources and processing

Annual GDP and sectoral data for the provinces between 2000 and 2012 were obtained from the provincial Statistical Yearbooks (*Statistics Bureau of Fujian, Guangdong, Jiangsu, Shandong, Shanghai and Zhejiang, 2001–2013*). All data were converted to the 2000 constant prices by using provincial GDP deflation factors. Sectoral shares in GDP were calculated by dividing the sum of the sectoral GDP by the total GDP.

Data on the annual energy consumption by the six economic sectors as well as the rural and urban residents were obtained from the Chinese Energy Statistic Yearbooks (*NBSC, 2001–2013b*). Then, energy-related CO_2 emissions of each economic sector or residential consumption were calculated from two parts: 1) direct CO_2 emissions from the direct use of the 15 fuels, as estimated based on Eq. (1); and 2) indirect emissions from heat and electricity consumption, calculated from fuel combustion in the power plants and then redistributed to each sectoral and residential consumption proportional to their consumptions given in the energy balance tables.

Population and urbanization rates are obtained from the China Statistic Yearbook (*NBSC, 2001–2013a*) and verified with the Fifth National Census dataset (*Lin, 2010*). The population related data (such as per capita GDP or per capita CO_2 emissions) of a

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[5] Detailed definitions are provided in Table A2.

province was represented by the residential population, rather than the registered population, at the end of a calendar year, since the former is more closely related to residential energy consumption.

Although there have been some criticism about the reliability of Chinese official statistics (*Feng et al., 2009; Peters et al., 2007; Sinton, 2001*), it is the main source of the nation's economic and energy data, and has been widely used in different studies on China's economy and environment. Therefore, this study uses the above statistical data without discussing its possible uncertainties.

5. Results and Discussion

5.1. Regional emission trend and driving forces

Total emissions. Total CO_2 emissions of the Region have doubled from the beginning of this century (Figure 2A). This is in line with the three and twofold increase in GDP and energy consumption, respectively, suggesting a persistent connection between economic development and energy consumption. As the pioneer region to carry out the reform and opening up policy in China, these provinces are heavily involved in manufacturing and international trading. For example, in 2012 the Region's imports and exports reached US$1122 billion and US$1560 billion, respectively, accounting for 61% and 76% of the nation's total amounts, and 6.0% and 8.5% of the world's share. Its production of synthetic fibers, clothing, color television, and integrated circuits contributed to 90%, 71%, 79%, and 81% of the total national production (*NBSC, 2001–2013a*). Energy wise, coal contributes on average 60% of total primary energy consumption and it is mainly used in the thermal power plants to generate electricity. High-agglomeration manufacturing leads to a large proportion of energy use in the energy-intensive industries. For instance, in 2008, the manufacture of computers, communication equipment, and other electronic equipment, manufacture of textiles, plastic products, and educational and sports goods in this Region contributed to 87%, 78%, 65%, and 78% of their corresponding national final energy consumption (*NBSC, 2011*). Energy intensity is about 27% lower than the national average, but still 1.5 times higher than the world average, or 2.9 times higher than that of the United States. Given China's increasing participation in the global economic chain, and the dominant role the Region has been playing, it is essential to deploy effective regional mitigation strategies to further seek and adapt to sustainably strong and healthy development.

On the other hand, the annual emission growth has gradually slowed down since 2005. For example, in 2012 the emission growth of Shanghai, Fujian, and Guangdong dropped 3.8, 3.3, and 2.8 percentage points, respectively, compared to the previous year. As a result, the actual increase rate of Shanghai was only 0.38%. Though the slowdown of emission growth since 2005 is partially a reflection of the economic downturn associated with the global financial crisis, it also indicates that the implementation of the “Eleventh Five -Year Plan” on energy savings and emission reduction has been working (Lei *et al.,* 2011).

Impacts of driving forces. As shown in Figure 2B, economic development and energy efficiency are the leading forces that contribute positively (with a cumulative impact of 99.4%) and negatively (-24.8%) to emission growth, respectively. Population size, per capita residential energy consumption and economic structure also contribute to emission growth, and improved energy structure generally offset emission growth. But the overall impacts from these forces are much less significant. During our study period, the energy efficiency of the Region has dropped 19% while both economic and energy structures have been relatively stable. For example, the structure of the six economic sectors changes from 11:44:6:8:12:20 in 2000 to 4:52:5:8:12:19 in 2012; coal and oil occupied about 80% of the total energy consumption throughout the time. Therefore the structure forces have not been effective in addressing carbon intensity, making energy efficiency the dominating force to inhibit emission growth. One reason for this different pattern of change could be it is hard and time consuming to adjust structures while relatively easy to improve energy efficiency. The other reason could be related to the previous national climate policies that focus on reducing carbon intensity, which has not been strict enough to motivate industries to relocate their business and change the structure, and could not compensate for potential emission growth due to economic development. This result suggests a great space for future improvement in the structure related forces.

Per capita emissions. Per capita emissions increase continuously during the study period. Nevertheless, at a given economic level their per capita emissions are lower than most provinces in China (Figure 3A). From a global perspective, the economic level of the Region falls far behind those of the selected developed nations (Figure 3B), and a previous study shows that economy at this level is close to the developed nations such as US and UK in their early 20th century, or France and Japan in their middle 20th century (Figure 1 of Jakob *et al.*, 2014). The same study also showed that the emissions versus economic trajectory of China has been closely tracking the historical emissions of France and Japan at the same economic level, the latter of which continued to grow until its corresponding economic level reached around US$15,000. Above that economic level, the trajectory of all developed nations in the selection began to turn downward, though at different speeds and consistency (*Jakob et al., 2014*).

Projected into the future, the per capita emissions of the Region can be expected to be lower than the selected developed nations. Wang and Wei (2014) found an N-shaped Kuznets curve between industrial CO_2 emissions efficiency and GDP per capita for 30 Chinese capital cities, which showed an initial efficiency enhancement followed by a stage of efficiency decrease or decelerated increase, and then a further efficiency increase once the income reaches above roughly US$12000.The deceleration or decrease of CO_2 efficiency was attributed to the vast establishment of energy-intensive industrial projects during the infrastructure development stage. Since all six provinces except Shandong have reached or exceeded this critical inflection point, it is expected to see greater efficiency improvement in their CO_2 emissions in the near future, and therefore the possibility of their reaching the developed world's human developmental standard with lower per capita emissions. As shown in Figure 3B, the emission versus economic development trajectory of these six provinces shows a reversal or leveling off of emission growth when the GDP per capita gets above US$10,000, which is in general agreement with the findings of Wang *et al.* (2014) and is sufficiently lower than that of the developed nations shown in Jacob *et al.* (2014).

5.2 Provincial characteristics

The annual growth rate of energy-related CO_2 emission follows the following order: Shanghai (3.78%) < Guangdong (7.74%) < Zhejiang (9.45%) < Jiangsu (9.92%) < Fujian (11.86%) < Shandong (13.15%) (Table S1). On the basis of the three criteria of per capita GDP, CO_2 emissions intensity, and the annual growth rate of energy-related CO_2 emission, and applying the K-means cluster analysis (*Kanungo et al., 2002*) using SPSS19.0, the six provinces are divided into three low-carbon developmental stages: stage I with the fastest growing annual emissions, highest emission intensity, and lowest economic development level among the six provinces;

stage II with median emission growth and emission intensity transiting from higher to lower; and stage III with slow growth in emissions, high level of low carbon development, and economic development.

Stage I provinces Stage I provinces include Shandong and Fujian. Shandong has seen the largest and most rapid increase in the total emissions among the six provinces (Figure 4), and it contributes >30% towards the entire emissions of the region. The high CO_2 emissions are most likely caused by the large share of coal in its energy consumption (Table S2), the small share of its tertiary industry (Table S3), and the high energy intensity of its industry sector (Table S4). Taking the year 2010 for example, 92% of the electricity generated by the thermal power plants in Shandong was produced by coal; the share of GDP from the tertiary industry was only 33.8%, and energy intensity of its industry sector was almost 3 times that of Shanghai.

Emission growth has consistently outgrown economic development in both provinces, since the positive forces contribute to the emissions at increasing rates, and the negative contributions of energy efficiency is barely noticeable (Table 1). Energy efficiency actually increased the emissions up to 2009 before it began to offset the emission growth (Figure 4). In Fujian, the energy structure has been more effective in offsetting emission growth, which is mainly due to the increased share of clean energy (Fujian Development and Reform Commission, 2011).

Stage II provinces. Stage II provinces include Jiangsu, Zhejiang and Guangdong. Similar to stage I provinces, economic development is the single most important force driving up the emissions (Figure 4). Energy efficiency is the leading force in slowing down the emission growth, followed by energy structure. The combined impact ranges from -22.4% to -58.9%, much more significant than the stage I provinces. Population size and per capita residential energy consumption begin to take visible significant roles (in the range 12.8%–33.8%) in driving up the emissions, and the combined effects have been increasing over the past several years (Table 1). Economic structure still contributes positively to the emissions, except for Zhejiang where the cumulative contribution (1.7%) has become negligible.

Stage III provinces With an annual emission increase rate of 3.78%, Shanghai is categorized as a stage III province. In Shanghai, carbon intensity has dropped by 55% since 2000, and it is the only place where the emissions induced by economic development has been nearly canceled out (about 97%) by improved energy efficiency (Figure 4). Population size emerges as the next important force driving up the emissions, which is somewhat similar to the pattern found in the developed countries (*Dietz et al., 1997; Xu et al., 2014*). A weak decoupling between economic development and carbon emissions appears to emerge, which may be attributed to the substantial improvement in energy efficiency.

The high energy efficiency is likely due to the significant reduction in energy intensity of the industry sector (Table S4) and to a lesser degree to the increasing share of the service industry, which is around 10%–18% higher than the other five provinces (Table S3). In fact, Shanghai is found to be the only place in this region whose economic structure has been contributing negatively to emissions. The 8.0% positive contribution of the energy structure is, however, beyond expectation for provinces at this stage. The same positive effect is also found in Jiangsu (3.4%), indicating an overall strong resistance and even rebound in energy structure change during the study period.

Table 1. Contribution of the seven driving forces to the overall CO_2 emission change in the six provinces from 2000 to 2012.

	Economic development		Population size		Economic structure		Energy efficiency		Energy structure		Per capita energy consumption		Urbanization[6]	
	Impact (%)	Trend	Impact (%)	Trend	Impact (%)	Trend	Impact (%)	Trend	Impact (%)	Trend	Impact (%)	Trend	Impact (%)	Trend
Shanghai(III)	**171.1**	↓↑	**86.3**	↓↑	**–3.2**	↓	**–165.3**	↓↑	**8.0**	↓	**3.3**	↑	**–0.2**	↑
Guangdong(II)	**114.1**	↓↑	**22.6**	↓↑	**10.8**	↑↓	**–48.1**	↓↑	**–10.8**	↑↓	**11.2**	↑	**0.1**	↓
Jiangsu(II)	**110.2**	↓↑	**6.8**	↓↑	**9.5**	↓↑	**–36.4**	↓↑	**3.4**	↑↓	**6.0**	↑	**0.5**	↓→
Zhejiang(II)	**97.9**	↓↑	**14.5**	↑	**1.7**	↑↓	**–15.8**	↓	**–6.6**	↓	**8.6**	↑	**-0.3**	↓
Fujian(I)	**84.5**	↓↑	**7.0**	↓↑	**11.7**	↓↑	**–2.8**	↓↑	**–11.4**	↓	**10.7**	↓	**0.4**	↓
Shandong(I)	**82.9**	↑	**4.9**	↑	**9.2**	↑↓	**–1.3**	↓	**–3.8**	↓	**7.7**	→	**0.4**	↓↑

Black and red numbers indicate positive and negative contribution to emission increase, respectively. "↑", "↓", and "→" indicate that the relative contribution to emission increase has increased, decreased, or remained constant, respectively. Therefore, "– +" means the first negatively then positively contribute to the emission growth, and "↓↑" means the impact first decreases and then increases.

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[6] Only the change in residential energy related CO_2 emissions is counted towards the contribution of urbanization.

6. Conclusions and policy implementations

This study has shown that the total energy-related CO_2 emission of the east and south coastal China has doubled from 2000 to 2012 despite substantial improvement in energy efficiency. This indicates that, in spite of the government’s intention to lessen the coupling between economic development and emission growth, current policies emphasizing carbon intensity reduction are insufficient to achieve such a goal. Per capita emissions have first increased and then leveled off over the past years since 2000, suggesting the potential of this region to achieve the developed world's human developmental standards with lower per capita emissions.

Economic development and energy efficiency are found to be the leading forces contributing positively and negatively to emission growth, respectively, which is in agreement with previous findings at the national level. Population size, per capita residential energy consumption and economic structure also contribute to emission growth, and improved energy structure generally offset emission growth. But the overall impacts from these forces are much less significant. At the provincial scale, however, the signs and relevance of these influences vary, and the provinces were categorized into three developmental stages by cluster analysis. Several general pattern and associated policy recommendations are drawn from these results, in the hope of finding the step-by-step connection between the advanced and less developed regions.

First of all, energy efficiency played the determinant role in differentiating the low-carbon development stages. Its effect varies from lack of improvement in stage I provinces to offset 15%–48% of emissions growth in stage II provinces, and further to nearly cancel economic-induced emissions in stage III provinces. These results suggest that, although the emissions have increased and may continue to increase for a certain period, policies on carbon intensity reduction did make a positive and fast impact. Targeted measures on energy efficiency enhancement could serve as the timely steps for emission reduction, and should be developed or reinforced in all sectors, particularly in the industry sector. This not only applies to the stage I and stage II provinces in the Region but is particularly important also for the vast majority of the other provinces following the footsteps of coastal China, and the technology and experience developed in the Region could be fully utilized.

Second, the structural decarbonization effect has not been utilized. Shanghai was found to be the only place among the six provinces to benefit slightly from economic structural change to reduce carbon emissions. Nationwide, Guangdong and Jiangsu were found to be the only two provinces whose production structure became greener, while Shanghai actually suffered 16% loss in production structure decarbonization. Despite the discrepancy, a similar conclusion can be drawn that the overall economic structure effect has not been fully realized either in this socioeconomically and technologically advanced region or for the nation as a whole. Therefore, strategic plans to promote structural change toward less energy-intensive services and high value-added goods as well as switch to low-carbon energy structure should buy additional emission reduction potential when the marginal effect of the energy efficiency decreases.

Last but not least, under the new national goal of reaching its carbon emissions peak by 2030, individual regions should take differentiated measures to decrease CO_2 emissions oriented to the local conditions. For example, since over 90% of the coal and fossil oil in the Region is imported either from within China or from aboard, it is in a good position to improve the energy structure by substituting some imported coal with natural gas; its coastal location also makes it the best place to utilize renewables such as wind and tidal energy. This would substantially lighten the energy outsource burden and release notable emission space for the rest of the nation.

In summary, east and south coastal China are the pilot ship for most of the nation's strategic programs. The stage structure and the provincial commonality as well as difference in the emission driving forces found in this study would provide practical guidance for the rest of China. Our results suggest the dual efforts of structural de-carbonization and energy efficiency improvement will help China to avoid another potential boom in emissions while its less developed regions chase economic prosperity. The earlier this coupling strategy is implemented, the better it would serve the peak emission control goal. Looking beyond China, the results may also shed some light on other developing regions that look upon east China to implement voluntary emission reductions while achieving the entitled human development standard.

Some limitations of this study also exist. This study only provides an initial interpretation of the energy-related CO_2 emissions based on the decomposition method, and it is confined to the period from 2000 to 2012 due to the lack of statistical data. Given the general time lag between policy implementation and the corresponding impacts, future research considering the dynamics of the force at a longer time frame should provide more insight for policy recommendations.

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Appendix A

Table A1. The meanings and settings of all parameters used in calculation.

Parameter	Meanings and settings
C	Total energy-related CO_2 emissions(t)
E	Total energy consumption(t of standard coal equivalent)
G	Gross domestic product(GDP)(Yuan, at 2000 constant price)
P	Population size(persons)
C_i	CO_2 emissions of the ith type of energy(t)
E_i	Consumption of the ith type of energy(t of standard coal equivalent)
NCV_i	Average net calorific value of the ith type of energy (KJ/kg or KJ/m^3)
CC_i	Carbon emission coefficient of the ith type of energy (kg/GJ or m^3/GJ)
COF_i	Carbon oxidation factor of the ith type of energy
k	$k = 1$ denotes urban and $k = 2$ denotes rural
$\sum_i C_i$	Sum of the i types of energy-related CO_2 emissions(t)
$\sum_k C_k$	Sum of urban and rural residential direct energy consumption related CO_2 emissions(t)
ef^j	Carbon emission factor of the jth type of energy(t/t or t/ m^3)
E_i^j	Consumption of energy *j* in sector *i* (t or m^3)
E_k^j	Direct consumption of energy j in urban or rural(t or m^3)
E_k	Total energy consumption of rural or urban residence(t of standard coal equivalent)
P_k	Urban or rural population size(persons)
n	Sector (economic or residential sector) which consumes energy
$g\ (=\frac{G}{P})$	Per capita GDP (Yuan/ capita, at 2000 constant price)
$ins_i(=\frac{G_i}{G})$	Share of the GDP for a specific economic sector i
$e_i\ (=\frac{E_i}{G_i})$	Energy intensity of a specific economic sector i (t of standard coal equivalent)
$es_n(=\sum_j ef^j \cdot \frac{E_i^j}{E_i})$	Share of certain type of energy in economic or residential sector(t of standard coal equivalent)
$er_k(=\frac{E_i}{P_k})$	Per capita energy consumption of rural or urban residence(t of standard coal equivalent)
$ur_k(=\frac{P_k}{P})$	Share of the rural or urban population

Table A2. The seven driving forces of energy-related CO_2 emissions

Force	Definition	Unit of measurement
Economic development（ΔC_g）	**Per capita GDP**, meaning the change of energy-related CO_2 emissions introduced by economic growth	10,000 Yuan per capita per year（at 2000 constant prices）
Economic structure（ΔC_{ins}）	**Share of the six individual sectors in the total GDP.** The six sectors include: a) agriculture，b) industry，c) construction，d) transport，storage and post，e) wholesale, retail trade and hotel, restaurants，and f) other service sectors. This factor represents the potential change of carbon intensity due to structure change.	%
Energy structure（$(\Delta C_{es} + \Delta C_{esr}$）	**Share of individual energy type in the total energy consumption of a production or residential sector,** represents the contribution towards CO_2 emissions from the change in both the industrial and municipal energy mix.	%
Energy efficiency（ΔC_e）	**Energy consumption of production sectors divided by GDP,** which indicates the change of energy-related CO_2 emissions due to the energy intensity of economic activities and residential consumption.	Tce per 10,000 Yuan (at 2000 constant prices)
Per capita residential energy consumption（ΔC_{er}）	**Per capita residential energy consumption used directly for lighting, heating, and cooking, etc.**	Tce per capita
Population size（ΔCp）	**The residential populations (instead of the registered population) at the end of a year**, which represents the contribution of population growth to CO_2 emissions change	number
Urbanization（ΔCur）	**The ratio of urban vs. rural population**, which means the change in direct residential energy consumption and therefore the related CO_2 emissions due to the varying urban vs. rural population ratio.	%

The detailed decomposition formulas of the driving factors for the economic sectors are (*Ang, 2005*):

Economic development: $\Delta C\mathrm{g} = \sum_i W_i \ln \frac{g_{t+1}}{g_t}$ (A.1)

Economic structure $\Delta C_{\mathrm{ins}} = \sum_i W_i \ln \frac{ins_{i(t+1)}}{ins_{i\mathrm{t}}}$ (A.2)

Energy efficiency ： $\Delta C\mathrm{e} = \sum_i W_i \ln \frac{e_{i(\mathrm{t}+1)}}{e_{i\mathrm{t}}}$ (A.3)

Energy structure of the economic sectors： $\Delta C\mathrm{es} = \sum_i W_i \ln \frac{\sum_{i=1}^{f} ef^{\,j}.S_{i(t+1)}{}^{j}}{\sum_{i=1}^{f} ef^{\,j}.S_{i\mathrm{t}}{}^{j}}$ (A.4)

Weighting function： $W_i = \frac{C_{i(t+1)} - C_{i\mathrm{t}}}{\ln C_{i(t+1)} - \ln C_{i\mathrm{t}}}$ (A.5)

The driving factors for the residential sectors are calculated as follows:

Per capita residential energy consumption ： $\Delta C\mathrm{er} = \sum_k \varphi_k \ln \frac{er_{k(t+1)}}{er_{k\mathrm{t}}}$ (A.6)

Urbanization ： $\Delta C_{ur} = \sum_k \varphi_k \ln \frac{ur_{\mathrm{k}(\mathrm{t}+1)}}{ur_{\mathrm{kt}}}$ (A.7)

Energy structure of the residential sectors ： $\Delta \mathrm{C}_{\mathrm{esr}} = \sum_k \varphi_k \ln \frac{esr_{k(t+1)}}{esr_{\mathrm{kt}}}$ (A.8)

Population size ： $\Delta C_{\mathrm{P}} = \Delta C_{\mathrm{P1}} + \Delta C_{\mathrm{P2}} = \sum_k \varphi_k \ln \frac{P_{k(t+1)}}{P_{k\mathrm{t}}} + \sum_i W_i \ln \frac{P_{i(t+1)}}{P_{i\mathrm{t}}}$ (A.9)

Weighting function： $\varphi_k = \frac{C_{k(t+1),res} - C_{\mathrm{k}t,res}}{\ln C_{k(t+1),res} - \ln C_{\mathrm{k}t,res}}$ (A.10)

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Figure captions:

Figure 1. Location and general information of the study area.**[a]**

[a] *P*, *E* represent percentages of population and energy consumption of the six individual provinces with respect to the national population and total energy consumption in 2012, and the data are calculated from data on the 2012 national statistics (NBSC). CRTs represent the carbon emission intensity reduction targets in the 12th Five Year Plan, and the data are from NDRC.

Figure 2. (A) Total energy-related CO_2 emissions of the coastal region from 2000 to 2012 (red) and its annual emission growth rate (green). (B) The cumulative impacts of different driving forces on the total CO_2 emissions.

Figure 3. (A) Per capita GDP and CO_2 emission from 2000 to 2010 in the 30 provinces in China. The curves for the six provinces are thickened for comparison. (B) Per capita GDP and CO_2 emission in the six coastal provinces, with respect to the national average and representative developed countries.

Figure 4. Impact of the seven driving forces on the energy-related CO_2 emissions (*Y*-axis in million tons) in each province for the period from 2000 to 2012 (*X*-axis).