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DECOUPLING EFFECTS OF ENERGY-RELATED CO_2 EMISSIONS IN CHINA: A LMDI-BASED ANALYSIS

This paper proposes an improved elasticity decoupling analytical framework to study decoupling effects of various CO_2 emission intensities. A new approach is introduced to express the decoupling elasticity index (DEI) with dynamic interval. Moreover, the driving mechanism for DEI are explored with logarithmic mean Divisia index (LMDI) method. The proposed framework is applied to study the decoupling effects of CO_2 emissions in China. It is found that the urbanization, industrialization and decline of proportion of coal consumption are important driving forces for CO_2 emission per capita, CO_2 emission intensity and CO_2 emission per energy consumption respectively.

Keywords: *energy-related CO_2 emissions; China; LMDI; decoupling elasticity index; driving forces.*

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ЗНИЖЕННЯ ВПЛИВУ ВИКИДІВ CO_2 В ЕНЕРГЕТИЧНІЙ ГАЛУЗІ КИТАЮ: АНАЛІЗ НА ОСНОВІ ІНДЕКСУ ДИВІЗІА ЗА ЛОГАРИФМІЧНОЮ СЕРЕДНЬОЮ

У статті запропоновано аналітичний підхід до дослідження зниження впливу викидів CO_2 на різних підприємствах. Новий метод дозволяє вивести індекс еластичності зниження впливу через динамічний інтервал, а також за допомогою індексу Дивізіа за логарифмічною середньою. Пропонована методологія застосовується для вивчення викидів CO_2 в Китаї. Встановлено, що урбанізація, індустріалізація і зниження частки споживання вугілля є важливими чинниками зниження кількості викидів CO_2 на душу населення, інтенсивність викидів CO_2 та викидів CO_2 в перерахунку на споживання енергії відповідно.

Ключові слова: *викиди CO_2, пов'язані з енергетикою; Китай; індекс Дивізіа за логарифмічною середньої; індекс еластичності зниження впливу; рушійні сили.*
Табл. 6. Рис. 3. Форм. 18. Літ. 14.

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СНИЖЕНИЕ ВЛИЯНИЯ ВЫБРОСОВ CO_2 В ЭНЕРГЕТИЧЕСКОЙ ОТРАСЛИ КИТАЯ: АНАЛИЗ НА ОСНОВЕ ИНДЕКСА ДИВИЗИА ПО ЛОГАРИФМИЧЕСКОЙ СРЕДНЕЙ

В статье предлагается аналитический подход к исследованию снижения влияния выбросов CO_2 на различных предприятиях. Новый метод позволяет выразить индекс эластичности снижения влияния через динамический интервал, а также посредством индекса Дивизиа по логарифмической средней. Предлагаемая методология применяется для изучения выбросов CO_2 в Китае. Установлено, что урбанизация, индустриализация и снижения доли потребления угля являются важными факторами снижения количества выбросов CO_2 на душу населения, интенсивность выбросов CO_2 и выбросов CO_2 в пересчете на потребление энергии соответственно.

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Ключевые слова: *выбросы CO_2, связанные с энергетикой; Китай; индекс Дивизиа по логарифмической средней; индекс эластичности снижения влияния; движущие силы.*

1. Introduction.

Climate change has become a global issue contemporarily, which seriously impacts sustainable development. A lots of evidences show that human activity is the important driving force to cause climate changes (IPCC, 2007). Following the rapid worldwide economic growth, the energy consumption is soaring to high levels and as a result great amount of CO_2 is being emitted to the atmosphere. Therefore, human activity must be limited to the tolerable capacity of the environment. Considerable research efforts have been dedicated to address the issues related to CO_2 emissions reduction. One such example is the decoupling theory which is proposed to analyze the quantitative relationship between human activity and environmental stress.

As defined in OECD (2003), decoupling refers to the process of breaking the relationships between economic growth and environmental damage. Previous researches on decoupling methods aimed to analyze the change of aggregated value, such as energy consumption, pollution emissions and waste output, following the change of GDP (Sjostrom & Ostblom, 2010; Steinberger & Roberts, 2010; Browne, O'Regan & Moles, 2011). In this paper, we provide a new method to analyze the change of intensity values, such as CO_2 emission per unit of GDP (CEI), CO_2 emission per capita (CEPC) and CO_2 emission per unit of energy consumption (CEPEC) with the change of GDP, population and energy consumption.

Index Decomposition Analysis (IDA) is a well-established analytical framework to study change in the aggregate indicator such as energy consumption/CO_2 emissions due to the changes in several predefined factors (Ang & Zhang, 2000). It has been widely applied in different areas for policymaking (Ang, 2004). Several earlier studies have attempted to integrate IDA and decoupling approach to analyze variation trends in CO_2 emissions. For instance, Lu, Lin & Lewis (2007) studied the decomposition and decoupling effects of CO_2 emissions from highway transportation in several economies using the arithmetic mean Divisia index (AMDI) method and the decoupling ratio as proposed by OECD (2003). De Freitas & Kaneko (2011) decomposed the decoupling of CO_2 emissions and economic growth in Brazil using the log mean Divisia index (LMDI) and the decoupling ratio. Oh, Wehrmeyer & Mulugetta (2010) used the LMDI and decoupling ratio to analyze the energy-related CO_2 emissions in South Korea. Diakoulaki & Mandaraka (2007) proposed decoupling effort index and analyzed the decoupling relationship between CO_2 emissions and manufacturing output in the EU manufacturing sector using the refined Laspeyres model. Wang, Liu, Zhang & Li (2013) combined the LMDI and the decoupling effort index to study the decoupling between energy-related CO_2 emissions and economic growth in Jiangsu province of China. Andreoni & Galmarini (2012) researched the decoupling status between economic growth and energy-related CO_2 in Italy using Sun's complete decomposition method. The aforementioned research efforts have been performed according to the framework of OECD's decoupling ratio and Diakoulaki's decoupling effort index. Tapio (2005) developed the decoupling elasticity index to perform the decoupling analysis. However, based on our knowledge and review of the literature, none of the research attempted to study the decoupling effect of CO_2 emissions based on Tapio's framework with decomposition method, and focus on the intensity values. In this paper, we propose a novel decoupling approach by combining LMDI with Tapio's decoupling elasticity index. In addition, we replace the interval [0.8–1.2] as in Tapio (2005) by a dynamic interval [A–B] as the dividing line for coupling and decoupling. The LMDI-based decoupling approach is finally applied to study the decoupling effects of energy-related CO_2 emissions in China.

The rest of this article is organized as follows. In Section 2, we propose the LMDI-based decoupling framework after briefly introducing LMDI and decoupling approaches. Section 3 describes the data used in our empirical study. In Section 4 we use the proposed approach to analyze the decoupling effects of energy-related CO_2 emissions in China. Section 5 concludes this study with some policy implications.

2. Methodology.

2.1. LMDI approach. Among different IDA methods listed in (Ang & Zhang, 2000), the LMDI method has been recommended for use due to its well established theoretical foundation, adaptability, ease of use and result interpretation and other desirable properties in the context of decomposition analysis (Ang, 2004). Since Ang (2004), more and more researchers use LMDI to study the driving forces of CO_2 emissions. In this paper, we employ the additive LMDI method to analyze the driving forces of CO_2 emission intensity (CEI), CO_2 emission per capita (CEPC) and CO_2 emission per unit energy consumption (CEPEC).

CO_2 emission intensity (CEI) can be described as:

$$C^Y = \frac{C}{Y} = \sum_{i=1}^{3} \frac{C_i}{Y_i} \frac{Y_i}{\sum_{i=1}^{3} Y_i} = \sum_{i=1}^{3} C_i^Y S_i^Y, \tag{1}$$

where $i = 1,2,3$ denotes primary, secondary and tertiary industry respectively, C_i denotes CO_2 emission by industry i, and Y_i denotes value added in industry i. C_i^Y refers to the CO_2 emission intensity for industry i, and S_i^Y denotes the share of industry i's value added in GDP. If ΔC^Y denotes the change of CO_2 emission per unit GDP from period 0 to T, then the intensity effect and structure effect can be calculated as:

$$\Delta C^Y = \Delta C^Y_{int} + \Delta C^Y_{str} \tag{2}$$

$$\Delta C^Y_{int} = \sum_{i=1}^{3} \left(C_{iT} \Big/ \sum_{i=1}^{3} Y_{iT} - C_{i0} \Big/ \sum_{i=1}^{3} Y_{i0} \right) \ln\left(\frac{C_{iT}}{Y_{iT}} \frac{Y_{i0}}{C_{i0}} \right) \Big/ \ln\left(\frac{C_{iT}}{C_{i0}} \frac{\sum_{i=1}^{3} Y_{i0}}{\sum_{i=1}^{3} Y_{iT}} \right) \tag{3}$$

$$\Delta C^Y_{str} = \sum_{i=1}^{3} \left(C_{iT} \Big/ \sum_{i=1}^{3} Y_{iT} - C_{i0} \Big/ \sum_{i=1}^{3} Y_{i0} \right) \ln\left(\frac{Y_{iT}}{\sum_{i=1}^{3} Y_{iT}} \frac{\sum_{i=1}^{3} Y_{i0}}{Y_{i0}} \right) \Big/ \ln\left(\frac{C_{iT}}{C_{i0}} \frac{\sum_{i=1}^{3} Y_{i0}}{\sum_{i=1}^{3} Y_{iT}} \right) \tag{4}$$

CO_2 emission per capita (CEPC) can be described as:

$$C^P = \frac{C}{P} = \sum_{i=1}^{2} \frac{C_i}{P_i} \frac{P_i}{\sum_{i=1}^{2} P_i} = \sum_{i=1}^{2} C_i^P S_i^P, \quad (5)$$

where C_i denotes CO_2 emissions in urban ($i = 1$) or rural ($i = 2$) area, P_i denotes the population in urban ($i = 1$) or rural ($i = 2$) area. The CO_2 emission per capita is consisting of 2 parts: the first part i.e. C_i^P is measured with CO_2 emission per capita in urban or rural area as the intensity index. The second part i.e. S_i^P is measured with urban or rural population proportion as the structure index. ΔC^P expresses the change of CO_2 emission per capita from period 0 to T, which is decomposed into structural contribution (ΔC^P_{int}) and intensity contribution (ΔC^P_{str}) as:

$$\Delta C^P = \Delta C^P_{int} + \Delta C^P_{str} \quad (6)$$

$$\Delta C^P_{int} = \sum_{i=1}^{2}\left(C_{iT} \Big/ \sum_{i=1}^{2} P_{iT} - C_{i0} \Big/ \sum_{i=1}^{2} P_{i0} \right) \ln\left(\frac{C_{iT}}{P_{iT}} \frac{P_{i0}}{C_{i0}} \right) \Big/ \ln\left(\frac{C_{iT}}{C_{i0}} \frac{\sum_{i=1}^{2} P_{i0}}{\sum_{i=1}^{2} P_{iT}} \right) \quad (7)$$

$$\Delta C^P_{str} = \sum_{i=1}^{2}\left(C_{iT} \Big/ \sum_{i=1}^{2} P_{iT} - C_{i0} \Big/ \sum_{i=1}^{2} P_{i0} \right) \ln\left(\frac{P_{iT}}{\sum_{i=1}^{2} P_{iT}} \frac{\sum_{i=1}^{2} P_{i0}}{P_{i0}} \right) \Big/ \ln\left(\frac{C_{iT}}{C_{i0}} \frac{\sum_{i=1}^{2} P_{i0}}{\sum_{i=1}^{2} P_{iT}} \right) \quad (8)$$

CO_2 emission per unit energy consumption (CEPEC) is described as follows:

$$C^E = \frac{C}{E} = \sum_{i=1}^{3} \frac{C_i}{E_i} \frac{E_i}{\sum_{i=1}^{3} E_i} = \sum_{i=1}^{3} \alpha_i \frac{E_i}{\sum_{i=1}^{3} E_i} = \sum_{i=1}^{3} C_i^E S_i^E, \quad (9)$$

where $i = 1,2,3$ denotes coal, oil and natural gas respectively. E_i denotes consumption of energy i. α_i denotes CO_2 emission coefficient (emission factor) of energy i. C_i denotes CO_2 emission from consumption of energy i. Similar to CEPC, the CEPEC is also consisting of 2 parts: the first part C_i^E is measured with CO_2 emission per energy consumption in coal, oil and natural gas, as the intensity index. It can be simplified as the CO_2 emission coefficient of coal, oil and natural gas. The second part S_i^E is measured with the consumption proportion of energy i as the structure index. Let ΔC^E represent the changes of CO_2 emission per energy consumption from period 0 to T, decomposing this into intensity contribution ΔC^E_{int} and structural contribution ΔC^E_{str} as:

$$\Delta C^E = \Delta C^E_{int} + \Delta C^E_{str} \quad (10)$$

$$\Delta C^E_{int} = \sum_{i=1}^{3}\left(C_{iT} \Big/ \sum_{i=1}^{3} E_{iT} - C_{i0} \Big/ \sum_{i=1}^{3} E_{i0} \right) \ln\left(\frac{C_{iT}}{E_{iT}} \frac{E_{i0}}{C_{i0}} \right) \Big/ \ln\left(\frac{C_{iT}}{C_{i0}} \frac{\sum_{i=1}^{3} E_{i0}}{\sum_{i=1}^{3} E_{iT}} \right) \quad (11)$$

$$\Delta C^E_{str} = \sum_{i=1}^{3}\left(C_{iT} \Big/ \sum_{i=1}^{3} E_{iT} - C_{i0} \Big/ \sum_{i=1}^{3} E_{i0} \right) \ln\left(\frac{E_{iT}}{\sum_{i=1}^{3} E_{iT}} \frac{\sum_{i=1}^{3} E_{i0}}{E_{i0}} \right) \Big/ \ln\left(\frac{C_{iT}}{C_{i0}} \frac{\sum_{i=1}^{3} E_{i0}}{\sum_{i=1}^{3} E_{iT}} \right) \quad (12)$$

The above compositions are used to structure the LMDI-based decoupling model, as shown in Eq. (16), Eq. (17) and Eq. (18) in Section 2.3.

2.2. Decoupling approach. Decoupling approach aims to analyze the change of environmental stress value, such as aggregated CO_2, following the change of GDP. The decoupling elasticity index (DEI) as common used indicator developed by Tapio (2005) can be expressed as:

$$GDP\ elasticity\ of\ CO_2\ emission = (\Delta C/C)/(\Delta Y/Y), \quad (13)$$

where C denotes the CO_2 emission, and Y denotes the gross domestic product (GDP). Tapio defines the area for which the value of $(\Delta C/C)/(\Delta Y/Y)$ lies between 0.8–1.2 as the coupling status. The area for all other values of $(\Delta C/C)/(\Delta Y/Y)$ is defined as the decoupling status. The coordinate system is further classified into strong negative decoupling, expansive negative decoupling, expansive coupling, weak decoupling, strong decoupling, recessive decoupling, recessive coupling and weak negative decoupling.

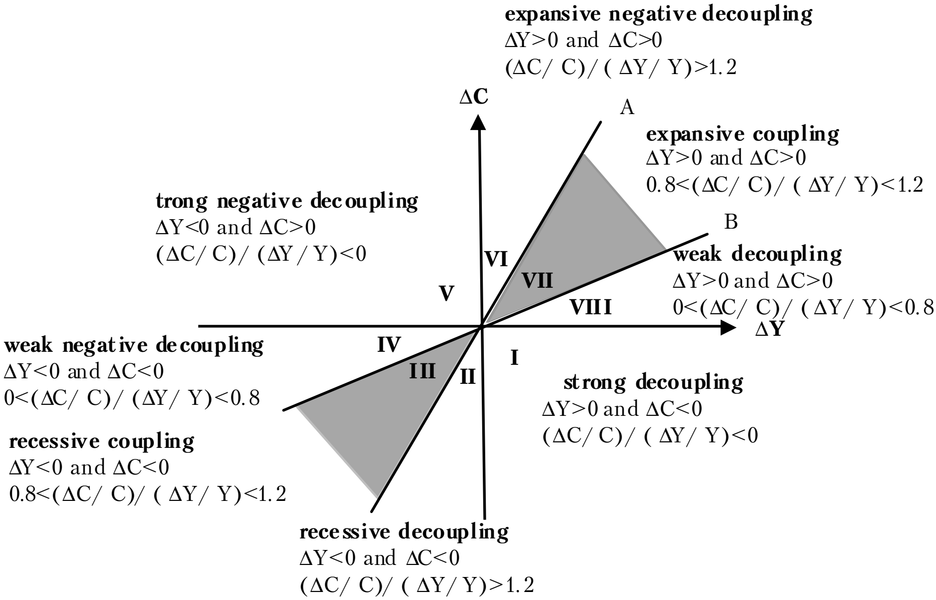

Figure 1. **The degrees of coupling, decoupling and recouping as defined by Tapio (2005)**

In this paper, we are striving to further improve the Tapio's method from two aspects: Firstly, we replace the static predefined interval of [0.8–1.2] with a dynamic interval [A–B], which is determined by $A = (Y_0/C_0)(\Delta C/\Delta Y) = (Y_0/C_0)tan(\pi/6)$ and $B = (Y_0/C_0)(\Delta C/\Delta Y) = (Y_0/C_0)tan(\pi/3)$, thus dividing the top right and bottom left quadrant into 3 equal parts. Secondly, Tapio used absolute value of CO_2 change (ΔC), whereas we focus on intensity values, such as CO_2 emission per unit of GDP. We use the derivative to present the decoupling elasticity ($(\Delta C/C)/(\Delta Y/Y)$) as $E = (dC/dY)(Y/C)$, and the decoupling elasticity of CO_2 emission intensity to GDP as $E = [d(C/Y)/dY][Y/(C/Y)]$, the relationship between them can be deduced as Eq.:

$$\overline{E}=\frac{d(C/Y)}{dY}\frac{Y}{C/Y}=\frac{Y\cdot dC/dY-C}{Y^2}\frac{Y}{C/Y}=\frac{dC}{dY}\frac{Y}{C}-1=E-1 \quad (14)$$

Therefore,

$$\frac{d(C/Y)}{dY}=\frac{C}{Y^2}(E-1) \quad (15)$$

If $E<1$, because $C>0$, so $d(C/Y)/dY<0$. It illustrates that, at a fixed value of GDP, if CO_2 emission grows slower than GDP i.e. ($(\Delta C/C)/(\Delta Y/Y)<1$). Thus the CO_2 emission intensity (C/Y) will be reduced with the growth of GDP, causing the most desirable effect. If $E>1$, the coupling emerges, the results will be reversed as the CO_2 emission intensity will be growing with the GDP growth. According to Eq. (14), both $(\Delta C/C)/(\Delta Y/Y)$ and $[\Delta(C/Y)/(C/Y)]/(\Delta Y/Y)$ can be used as the dividing mark, and the 4 quadrants of Fig. 2 are thus divided into 8 parts:

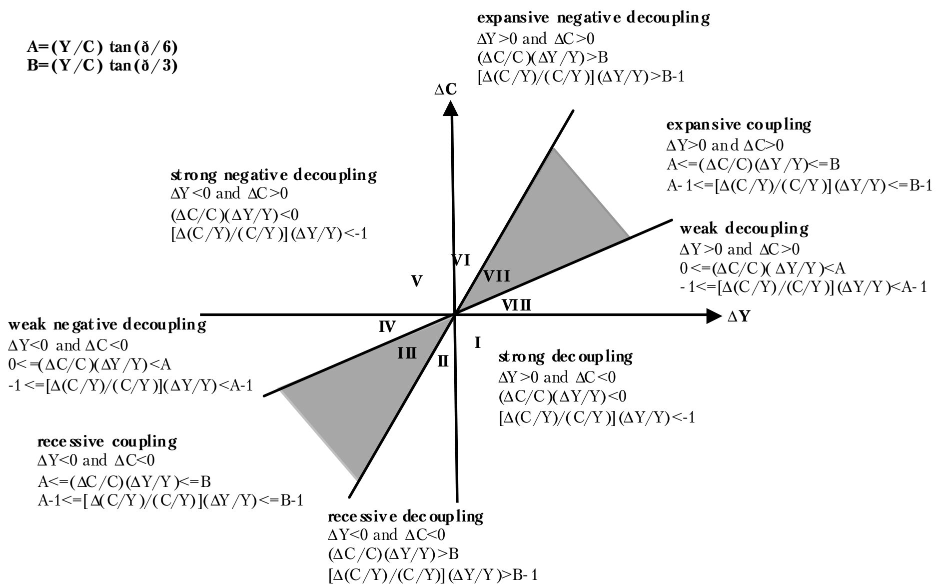

Figure 2. **The degrees of decoupling/coupling of CO_2 emission change (ΔC) to GDP change (ΔY)**

The relationship between the 8 sectors in Fig. 2 can be manifested as the U-shaped curves or environmental Kuznets curves as shown in Fig. 3.

The U-shaped curve is useful to consider both CO_2 and GDP. Referring to Fig. 3, the interval "E" represents the most favorable state with the positive GDP growth and negative CO_2 growth, which is strong decoupling status. The intervals "A" and "I" represent the worst states with the negative GDP and positive CO_2 growth, that is strong coupling status, named as strong negative decoupling. DCB and FGH are the transitory states, they can arranged as D>C>B, which implies that state "D" is having fast GDP growth and slow CO_2 growth than states "C" and so on. Similarly, FGH can be arranged as F>G>H, which implies that state "F" is having slow decline of GDP and fast CO_2 decline than states "G" and so on.

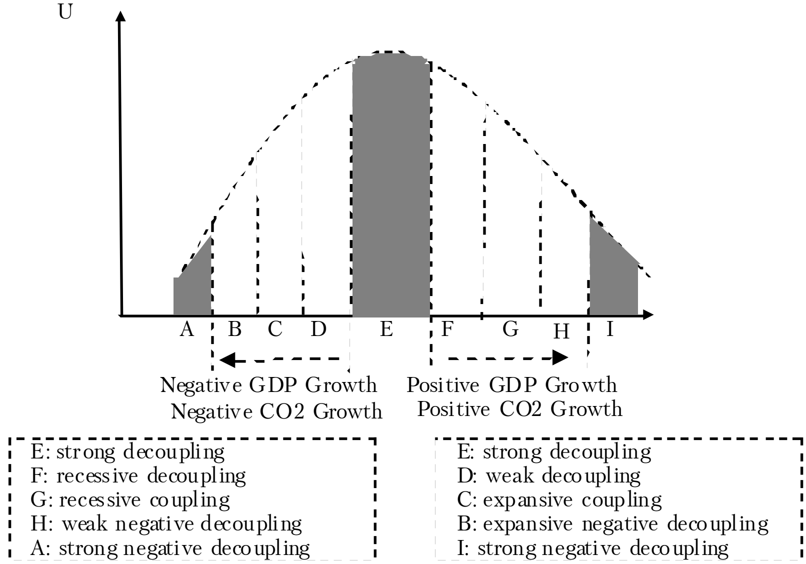

Figure 3. **Stages of the decoupling and coupling process**

2.3. LMDI-based decoupling approach. As shown in Fig. 2, the elasticity of CO_2 emission intensity to GDP ($[\Delta(C/Y)/(C/Y)]/(\Delta Y/Y)$) can be used as the dividing mark to classify the decoupling/coupling states. So we can decompose the $\Delta(C/Y)$ to intensity contribution and structure contribution using LMDI method. Then let us multiply $\Delta(C/Y)$ with $Y/[(C/Y)\Delta Y]$ which will break the elasticity of CO_2 emission intensity to GDP into intensity contribution and structure contribution. In the same way, we can further analyze the elasticity of CO_2 emission per capita to population ($[\Delta(C/P)/(C/P)]/(\Delta P/P)$) and the elasticity of CO_2 emission per unit energy consumption to energy consumption ($[\Delta(C/E)/(C/E)]/(\Delta E/E)$).

As $\Delta(C/Y)=\Delta C^Y_{int}+\Delta C^Y_{str}$ referring to Eq. (2). $[\Delta(C/Y)/(C/Y)]/(\Delta Y/Y)$ can be decomposed into two parts, part one is the intensity elasticity index (ε_{int}) and part two is the structural elasticity index (ε_{str}). As shown in Eq. (16) ε_{int} can be further decomposed into ε_{cei_i}, which is contribution from CO_2 emission intensity of the i^{th} sector. ε_{str} can be further decomposed into ε_{pro_i}, which is contribution from proportional change of i^{th} industry.

$$\frac{\Delta(C/Y)}{\Delta Y}\frac{Y}{(C/Y)}=\left(\Delta C^Y_{int}+\Delta C^Y_{str}\right)\frac{Y}{(C/Y)\Delta Y}=\varepsilon_{int}+\varepsilon_{str}=\sum_{i=1}^{3}\varepsilon_{cei\_i}+\sum_{i=1}^{3}\varepsilon_{pro\_i} \quad (16)$$

As $\Delta(C/P)=\Delta C^P_{int}+\Delta C^P_{str}$ referring to Eq. (6). $[\Delta(C/P)/(C/P)]/(\Delta P/P)$ can also be decomposed into two parts, part one is the intensity elasticity index (ε_{int}) and part two is the structural elasticity index (ε_{str}) as shown in Eq. (17). ε_{int} can be further decomposed into ε_{cei_1} and ε_{cei_2}, which are the contributions from CO_2 emission per capita in urban and rural areas, ε_{str} can be further decomposed into ε_{pro_1} and ε_{pro_2}, which are the contributions from structural changes with the proportional change of urban and rural population.

$$\frac{\Delta(C/P)}{\Delta P}\frac{P}{(C/P)}=\left(\Delta C^P_{int}+\Delta C^P_{str}\right)\frac{P}{(C/P)\Delta P}=\varepsilon_{int}+\varepsilon_{str}=\sum_{i=1}^{2}\varepsilon_{cei\_i}+\sum_{i=1}^{2}\varepsilon_{pro\_i} \quad (17)$$

As $\Delta(C/E)=\Delta C^E_{int}+\Delta C^E_{str}$ referring to Eq. (10), $[\Delta(C/E)/(C/E)]/(\Delta E/E)$ can be decomposed into two parts as before, part one is the intensity elasticity index (ε_{int}) and part two is the structural elasticity index (ε_{str}). ε_{int} can be expressed as ε_{cei_i}, which is the contribution from CO_2 emission per energy consumption of the i^{th} energy type. Similarly, ε_{str} can be expressed as ε_{pro_i}, which is contribution from proportional change of i^{th} energy type.

$$\frac{\Delta(C/E)}{\Delta E}\frac{E}{(C/E)}=\left(\Delta C^E_{int}+\Delta C^E_{str}\right)\frac{E}{(C/E)\Delta E}=\varepsilon_{int}+\varepsilon_{str}=\sum_{i=1}^{3}\varepsilon_{cei\_i}+\sum_{i=1}^{3}\varepsilon_{pro\_i} \quad (18)$$

3. Data.

In order to implement the proposed framework as in Eq. (1), (5) and (9), we collected the data for the period 1998–2010. The relevant data include: national GDP value, value added by the industry, population of urban and rural areas, national industrial and residential energy consumption and CO_2 emissions.

This data is collected from "China Statistical Yearbook 1999–2011" (CSY) by National Bureau of Statistics of China (NBSC), which is deflated to the 1998 value. The value added by the industry include that of primary industry (including farming, forestry, animal husbandry, side-line production and fishery), secondary industry (including producing and construction), and tertiary industry (including communications and transportation, storage, post and telecommunication, wholesale and retail) and is deflated to 1998 value by value added index. All value termed data are measured by Chinese Yuan (CNY). The energy consumption data represents cumulative consumption of coal, oil, natural gas and others. The energy consumption for primary, secondary, tertiary industry, urban and rural resident can be found in energy balance table 1998–2010.

On the national scale, we can use coal, oil and natural gas consumption to compute CO_2 emissions according to their emission factors. As industrial and residential sector don't use the coal, oil and natural gas directly, hence, we classify the CO_2 emissions for these two sectors into direct and indirect emissions. Direct emissions are defined as the CO_2 emitted directly from combusting fossil energy, we can use 20 kinds of final energy consumption from energy balance table to compute the direct CO_2 emissions, and the emission factors can be found in IPCC[3]. The indirect emissions are defined as the CO_2 emitted from using electricity and heat since no CO_2 emission factors are available. Therefore, we compute the CO_2 emissions for electricity and heat from the CO_2 emitted from the process of producing them.

4. Results and discussions.

Beside the quantity of CO_2 emitted, CEI, CEPC and CEPEC are the common indicators to analyze the characteristics of CO_2 emission considering the influence from GDP & structure, population & structure and energy consumption & structure[4].

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[3] 2006 IPCC guidelines for National Greenhouse Gas Inventories Vol. II provided the carbon factors in detail.

[4] due to the differences of assessment indicators for decarbonization, CEI, CEPC and CEPEC all are considered in this paper. All of them may be classified as the superclass named intensity indicator.

Thereby, we further employ the LMDI and LMDI-based decoupling approach to analyze the variation trends of CEI, CEPC and CEPEC in China.

4.1. Analysis for CEI. Decomposing the change of CEI according to Eq. (1–4) using LMDI, the distribution and trend of contributions with driving forces are shown in Table 1.

Table 1. **The decomposition of CEI (units: ton CO_2/10 thousands RMB)**

	1998-2010		1998-2001		2001-2004		2004-2007		2007-2010	
contribution	value	%	value	%	value	%	value	%	value	%
cei_1	0.001	-0.66	0.000	-0.67	0.003	9.42	0.000	1.79	-0.001	1.98
pro_1	-0.009	6.70	-0.002	3.45	-0.003	-7.63	-0.003	12.68	-0.002	2.33
cei_2	-0.207	149.17	-0.082	114.35	-0.004	-12.32	-0.042	161.78	-0.081	108.10
pro_2	0.092	-66.02	0.021	-28.53	0.031	93.63	0.024	-90.87	0.018	-24.07
cei_3	-0.032	23.17	-0.015	20.67	0.002	7.42	-0.010	37.80	-0.010	14.03
pro_3	0.017	-12.36	0.007	-9.28	0.003	9.47	0.006	-23.19	0.002	-2.37
cei_all	-0.239	171.68	-0.097	134.35	0.002	4.52	-0.052	201.37	-0.092	124.12
pro_all	0.100	-71.68	0.025	-34.35	0.032	95.48	0.026	-101.37	0.018	-24.11
total	-0.139	100.00	-0.072	100.00	0.034	100.00	-0.026	100.00	-0.074	100.00

As evident from Table 1 , the total CO_2 emission intensity (CEI) drops by 0.139 ton CO_2/10 thousands RMB. The CO_2 emission intensity in the secondary industry (*cei_2*) contributes 149.17% reduction of CEI and is the largest negative driving force. The proportion of the secondary industry (*pro_2*) contributes 66.02% of CEI growth and is the largest positive driving force. The contribution from CO_2 emission intensity of tertiary industry (*cei_3*) and the proportion of tertiary industry (*pro_3*) are similar to those for secondary industry in all the periods, but the values are smaller. The contributions from CO_2 emission intensity in primary industry (*cei_1*) and the proportion of primary industry (*pro_1*) are insignificant.

Decomposing the change of decoupling elasticity index (DEI) of carbon emission intensity (CEI) to GDP according to Eq. (16) using LMDI-based decoupling approach, the distribution and trend of contributions with driving forces are shown in Table 2.

Table 2. **The DEI decomposition of CEI**

	1998-2010		1998-2001		2001-2004		2004-2007		2007-2010	
critical value A-1	-0.079		-0.079		0.040		-0.019		0.026	
critical value B-1	1.762		1.762		2.120		1.942		2.079	
Decoupling	value	form	value	form	value	form	value	form	value	form
cei_1	0.001	EC	0.003	EC	0.020	WD	-0.002	EC	-0.009	WD
pro_1	-0.008	EC	-0.017	EC	-0.016	WD	-0.014	EC	-0.010	WD
cei_2	-0.178	WD	-0.572	WD	-0.026	WD	-0.184	WD	-0.477	WD
pro_2	0.079	EC	0.143	EC	0.199	EC	0.103	EC	0.106	EC
cei_3	-0.028	EC	-0.103	WD	0.016	WD	-0.043	WD	-0.062	WD
pro_3	0.015	EC	0.046	EC	0.020	WD	0.026	EC	0.010	WD
cei_all	-0.205	WD	-0.672	WD	0.010	WD	-0.229	WD	-0.548	WD
pro_all	0.086	EC	0.172	EC	0.203	EC	0.115	EC	0.106	EC
total	-0.120	WD	-0.500	WD	0.212	EC	-0.114	WD	-0.441	WD

The DEI driven by cei_2 and cei_3 presents the successive state of weak decoupling (WD) in all 4 periods. It implies that, the CEI in secondary and tertiary industry are decoupling to GDP growth in China. DEI driven by *cei_1* are expansive coupling (EC) → weak decoupling (WD) → expansive coupling (EC) → weak decoupling (WD) in the period 1998–2001, 2001–2004, 2004–2007, 2007–2010 respectively.

However, for the overall period of 1998–2010 it is EC. The DEI driven by *pro_2* exhibits the sequential state of expansive coupling (EC) → expansive coupling (EC) → expansive coupling (EC) → expansive coupling (EC), so it is still coupling to GDP, it indicates that the increasing proportion of secondary industry is strongly correlated to GDP growth in China. The DEI driven by *pro_1* and *pro_3* presents the sequential state of expansive coupling (EC) → weak decoupling (WD) → expansive coupling (EC) → weak decoupling (WD), while considering the time span 1998–2010, they present the state of EC. In the time span 1998–2010, the DEI driven by overall carbon emission intensity for all industries (*cei_all*) presents WD and the DEI driven by overall proportion for all industries (*pro_all*) presents EC over time. The total DEI presents the status WD except in the period 2001–2004, this can be attributed to have caused by the *cei_all*.

4.2. Analysis for CEPC. Decomposing the change of CEPC according to Eq. (5–8) using LMDI, the distribution and trend of contributions with driving forces are shown in Table 3.

Table 3. **The LMDI decomposition of CEPC (units: ton CO_2 per capita)**

	1998-2010		1998-2001		2001-2004		2004-2007		2007-2010	
contribution	value	%	value	%	value	%	value	%	value	%
cei_u	0.019	25.45	-0.003	-64.48	0.009	38.91	0.014	41.49	-0.001	-9.60
pro_u	0.024	33.26	0.005	128.01	0.005	22.66	0.006	18.87	0.007	56.67
cei_r	0.044	59.70	0.004	93.18	0.012	50.00	0.017	50.55	0.011	91.68
pro_r	-0.014	-18.41	-0.002	-56.68	-0.003	-11.57	-0.004	-10.92	-0.005	-38.75
cei_all	0.063	85.16	0.001	28.67	0.021	88.91	0.031	92.05	0.010	82.08
pro_all	0.011	14.84	0.003	71.33	0.003	11.09	0.003	7.95	0.002	17.92
total	0.074	100.00	0.004	100.00	0.023	100.00	0.034	100.00	0.012	100.00

As the composition results reflected in Table 3, carbon emission per capita in rural area (*cei_r*) contributes 59.70% growth of CEPC and is the largest positive driving force, population proportion in rural area (*pro_r*) contributes 18.41% reduction of CEPC and is the largest negative driving force in the time span of 1998–2010. Population proportion in urban area (*pro_u*) has the positive driving effect and *pro_r* has the negative driving effects in all 4 periods, which should be attributed to urbanization. The positive contribution from *pro_u* are larger than *cei_u* in the time span 1998–2010.

Further, decomposing the change of DEI of CEPC to population according to Eq. (17) using LMDI-based decoupling approach, the distribution and trend of contributions with driving forces are shown in Table 4.

As shown above, DEI driven by carbon emission per capita (*cei_all*) presents the sequential state of weak decoupling (WD) → expansive coupling (EC) → expansive negative decoupling (END) → expansive coupling (EC), and *cei_r* presents the sequential state of weak decoupling (WD) → expansive coupling (EC) → expansive coupling (EC) → expansive coupling (EC), which are remarkably coupling to population growth. Because population in rural area decreases with opposite trend of total population growth, DEI driven by *pro_r* presents the sequential state of strong decoupling (SD) → strong decoupling (SD) → strong decoupling (SD) → strong decoupling (SD). Because *cei_all* is the most important driving force for change of CEPC, DEI driven by total presents the sequential state of WD→EC→END→EC are consistent with *cei_all*, which are remarkably coupling to population growth too.

In the time span 1998–2010, *cei_u*, *pro_u* and *cei_r* are the positive driving forces and *pro_r* is the only negative driving force. Meanwhile, the *pro_r* is smaller than other 3 positive driving forces, so the state of DEI driven by total should be coupling.

Table 4. **The DEI of CEPC**

	1998-2010		1998-2001		2001-2004		2004-2007		2007-2010	
critical value A-1	6.673		6.673		6.280		4.631		3.227	
critical value B-1	22.019		22.019		20.840		15.894		11.681	
decoupling	value	form	value	form	value	form	value	form	value	form
cei_u	3.328	WD	-1.516	SD	6.157	WD	8.368	EC	-0.579	WD
pro_u	4.349	WD	3.010	WD	3.587	WD	3.806	WD	3.420	EC
cei_r	7.807	EC	2.190	WD	7.914	EC	10.195	EC	5.533	EC
pro_r	-2.408	SD	-1.332	SD	-1.832	SD	-2.203	SD	-2.339	SD
cei_all	11.135	EC	0.674	WD	14.071	EC	18.563	END	4.953	EC
pro_all	1.941	WD	1.677	WD	1.755	WD	1.603	WD	1.081	WD
total	13.076	EC	2.351	WD	15.827	EC	20.166	END	6.034	EC

4.3. Analysis for CEPEC. Decomposing the change of CEPEC according to Eq. (9–12) using LMDI, the distribution and trend of contributions with driving forces are shown in Table 5.

Table 5. **The decomposition for CEPEC (units: $kgCO_2$/tsce*)**

	1998-2010		1998-2001		2001-2004		2004-2007		2007-2010	
contribution	value	%	value	%	value	%	value	%	value	%
pro_coal	-80.113	105.35	-71.823	177.32	33.150	137.78	44.198	1201.79	-85.635	135.33
pro_oil	-38.636	50.81	21.465	-52.99	-10.732	-44.61	-53.662	-1459.12	4.294	-6.79
pro_natural gas	42.698	-56.15	9.852	-24.32	1.643	6.83	13.138	357.23	18.066	-28.55
total	-76.047	100.00	-40.506	100.00	24.061	100.00	3.678	100.00	-63.279	100.00

* tsce refers to ton of standard coal equivalent.

Coal, oil and natural gas constitute 91.4% of the total energy consumption till 2010 in China, and the proportion of each in the total energy consumption is relatively fixed. With the fixed CO_2 emission coefficient of each energy, the change of CEPEC is stagnated, see the total index of Table 5 in 1998–2010, the CEPEC is dropped 76.05 $kgCO_2$/tsce over time. The proportion of coal consumption (*pro_coal*) and the proportion of oil consumption (*pro_oil*) contributed 105.35% and 50.81% respectively to the reduction of CEPEC, and the proportion of natural gas consumption (*pro_natural gas*) contributed 56.15% to the CEPEC growth.

Further, decomposing the change of DEI of CEPEC to energy consumption size according to Eq. (18) using LMDI-based decoupling approach, the distribution and trend of contributions with driving forces are shown in Table 6.

The DEI driven by *pro_oil* and *pro_natural gas* present the sequential state of expansive coupling (EC) → expansive coupling (EC) → expansive coupling (EC) → expansive coupling (EC), which is coupling with energy consumption growth. The DEI driven by *pro_coal* presents the sequential state of WD→EC→EC→WD, which is consistent with the change of coal consumption proportion. In other words, the drop of coal consumption proportion deviates from energy consumption growth in 1998–2001 and 2007–2010 make the WD state. In general, the DEI driven by the combination of coal, oil and natural gas consumption is consistent with DEI driven by *pro_coal*, so *pro_coal* plays the most important role in determining the state of

DEI. It is worth noting that, during 1998–2010 the DEI driven by *pro_coal*, *pro_oil* and *pro_natural gas* all present EC state. This can be attributed to the change of proportion of coal, oil and natural gas is small, so the contributions to the change of DEI of CEPEC are small too, thus cannot reach the upper and lower critical values A-1 and B-1 respetively.

Table 6. **The DEI of CEPEC**

	1998-2010		1998-2001		2001-2004		2004-2007		2007-2010	
critical value A-1	-0.130		-0.130		-0.116		-0.125		-0.126	
critical value B-1	1.609		1.609		1.653		1.626		1.622	
decoupling	value	form	value	form	value	form	value	form	value	form
pro_coal	-0.024	EC	-0.282	WD	0.033	EC	0.058	EC	-0.223	WD
pro_oil	-0.011	EC	0.084	EC	-0.011	EC	-0.071	EC	0.011	EC
pro_natural gas	0.013	EC	0.039	EC	0.002	EC	0.017	EC	0.047	EC
total	-0.023	EC	-0.282	WD	0.033	EC	0.058	EC	-0.223	WD

5. Concluding remarks and policy proposals.

In this paper, we focus on the decoupling elasticity of intensity variables. LMDI method is used to explore the driving forces for total elasticity. At last, we analyze China's CO_2 emission driving forces and decoupling/coupling status from 1998 to 2010, some policy proposals are derived which are discussed as follows.

5.1. The industrialization was an important driving force for CEI. LMDI results show that, the decline of CEI of secondary industry contributes the most share of CEI variation. According to the decoupling analysis, the DEI driven by CO_2 emission intensity in secondary industry (*cei_2*) presents the state weak decoupling (WD) → weak decoupling (WD) → weak decoupling (WD) → weak decoupling (WD), so the decoupling happens obviously between the *cei_2* and GDP growth. The policy implication is that, although China is in industrialization, but still has the potential for reducing CO_2. Thereby, China has the potential to further lessen the CEI through achieving the decoupling *cei_2* and GDP growth. However, the secondary industry in China has the characteristic of being labor intensive and having high-CO_2 production which determines the industrialization in China is gradual, involving many factors, and the CO_2 emissions due to the secondary industry cannot be reduced in short period of time. Speeding up the change in industrial structure is necessary, but the technology innovation for secondary industry is essential for reducing CO_2.

5.2. The urbanization was an important driving force for CEPC. LMDI results show that CO_2 emission per capita in rural areas changes faster than in urban areas, which can be attributed to the transfer of population from rural to urban areas that reduces the population in rural and makes the CEPC in rural areas larger than before, so the urbanization turned into the important positive driving force to influence the CEPC. Therefore, in China, the urbanization is an equally important factor as the traditionall factors such as industrialization. Urbanization will cause the new demand for energy consumption. However, the growth of CEPC in urban areas will be slowed down, caused by expanded population, and the fast reduction of population in rural areas will foster the growth of CEPEC. Therefore, the policy implication is that government need to pay more attention to the change of energy consumption distribution following population transferred from rural to urban areas. Moreover, the government needs to take advantage of energy centralization mode in urban areas, it is an effective way to improve energy efficiency and reduce CO_2 emissions.

5.3. The decline of proportion of coal consumption was an important driving force for CEPEC. LMDI results show that, the change of CEPEC is stagnated, during the period 1998–2010, the CEPEC is dropped by 70.05 $kgCO_2$/tsce over time, the contribution from decline of proportion of coal consumption would be offset by the increases of proportion of oil and natural gas consumption. Therefore, the energy substitution among coal, oil and natural gas does not have the significant effect on the CEPEC decline. A more effective way to reduce the CEPEC can be adopted using the technology of cleaner production for coal utilization and renewable energy development. The latter is the more efficient way to achieve the energy substitution and reduce CO_2 emission in the long term.

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