

Using a new decoupling indicator (ZM decoupling indicator) to study the relationship between the economic growth and energy consumption in China

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Abstract The decoupling analysis has become an important tool to explore whether an economy is becoming less dependent on energy resources. Based on the LMDI (Log-Mean Divisia Index) method, this paper defines a new decoupling indicator (ZM decoupling indicator), which depicts the relationship between energy saving influence factors and energy driving influence factors. Then, the ZM decoupling indicator is utilized to explore the state of decoupling between economic growth and energy consumption in China. The main results are as follows: (1) The gap of economic structure between the secondary industry and tertiary industry gradually narrowed during the study period 1991–2012. (2) The economic growth effect (ΔE_g^t) was the critical factor in the growth of the final energy consumption in China. However, the energy intensity effect (ΔE_{ei}^t) played an important role in decreasing the final energy consumption. (3) Based on the definition of ZM decoupling indicator, only four decoupling statuses occurred in China over the study period: weak decoupling, expansive coupling, strong decoupling, and expansive negative decoupling.

Keywords ZM decoupling indicator · Energy consumption · LMDI method · Economic growth · China

1 Introduction

Nowadays, environmental pollution has become a serious issue in the world. GHGs (greenhouse gas) emission is the main reason of global warming. However, carbon dioxide (CO₂), among six kinds of GHGs, is the largest contribution to the greenhouse effect (IPCC, 1995). The burning of fossil fuels is the main source of CO₂ emission. Along with

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the economic development, more energy use has occurred. However, more than 87% of energy consumption in the world is fossil energy, which may cause a significant warming of the global climate (BP 2012). Thus, many researchers have paid attention to whether an economy is becoming less dependent on energy consumption.

The causal relationship between energy use or energy-related environmental degradation and economic growth can be explored by many methods, such as bivariate causality, correlation analysis, unit root testing, multivariate co-integration, simple regressions, and variance decomposition. (Climent and Pardo 2007). Among all the existing methods, the decoupling analysis is a useful method to study the relationship between economic growth (GDP) and energy consumption, or environment issue. Von Weizsäcker (1989) firstly introduced the notion of decoupling. Then, the concept has achieved global recognition as a significant conceptualization of successful economy–environment integration. Zhang (2000) firstly utilized the definition of decoupling to explore the relationship between China's carbon emissions and economic growth at the beginning of the 2000s. Later on, the OECD (2010) developed that concept into an indicator in 2002.

Currently, there are two decoupling methods, which were widely used to study the causal relationship between energy use or energy-related environmental degradation and economic growth. One is the Taipo decoupling method. Juknys (2003) defined three kinds of decoupling, i.e., primary decoupling, secondary decoupling, and doubled decoupling. Primary decoupling is defined as the decoupling of natural resources consumption from economic growth, and secondary decoupling is defined as the decoupling of environmental pollution from consumption of natural resources. When the primary decoupling and secondary decoupling happen at the same time, double decoupling occurs. Based on the decoupling elasticity concept given by Juknys, Tapio (2005) defined decoupling indicator when studying the decoupling status in the European transport industry and divided the decoupling indicator into decoupling, coupling, and negative decoupling. Then, he presented eight logical possibilities to distinguish decoupling state, namely recessive coupling, expansive coupling, weak negative decoupling, strong negative decoupling, expansive negative decoupling, weak decoupling, strong decoupling, and expansive decoupling.

By far, the Taipo decoupling method has been widely used to study the relationship between economic growth and energy consumption or environment issue (Ren and Hu 2012). For instance, Climent and Pardo (2007) utilized the Taipo decoupling method to investigate the relationship between Spanish economic growth and energy consumption. That method was utilized by Freitas and Kaneko (2011) to study the occurrence of a decoupling between Brazil's economic growth and energy-related CO₂ emission from 2004 to 2009. Zhang and Wang (2013a) also utilized the Taipo decoupling method to explore the decoupling status between energy-related CO₂ emission and GDP in Jiangsu Province (China) from 1995 to 2009. Based on the LMDI theory, Zhang et al. (2015) provided a way to find the deep reason that lead to the decoupling status.

Another notable decoupling method is defined based on IDA (index decomposition method). Based on the decomposition result of refined Laspeyres decomposition model, Diakoulaki and Mandaraka (2007) firstly defined a decoupling indicator to assess the real efforts undertaken in each country and their effectiveness in dissociating the economic and environmental dimensions of development. Ang (2004) gave a review of all decomposition techniques and concluded that the LMDI method was the best method to study influencing factors. Based on the LMDI method, Zhang and Wang (2013b) also defined a decoupling indicator, which was utilized to analyze the decoupling of electricity consumption from economic growth in China. That decoupling method was also used by Zhang and Guo

(2013) to evaluate the progress in decoupling energy consumption from per capita annual net income of rural households.

However, the decoupling indicator presented by Diakoulaki and Mandaraka, and Zhang and Wang only defines three kinds of decoupling status, i.e., strong decoupling, weak decoupling and no decoupling, which may not provide rational decoupling positions. Furthermore, the definition of decoupling indicator is determined by whether the economic activity effect is positive or negative. To overcome this problem, this paper redefines a new decoupling indicator (ZM decoupling indicator) based on the decomposition results of the LMDI method, which describes the relationship between energy saving influence factors and energy driving influence factors. Compared with the Tapio decoupling indicator, the ZM decoupling indicator can reflect which factor plays a positive role in the occurrence of decoupling state. By far, China has become the largest energy consumer in the world. Furthermore, about 90% of energy consumption in China is fossil energy, which may lead to more CO₂ emission. As a responsible country, China has taken more measures to cut its CO₂ emission. Thus, the ZM decoupling model is utilized to explore the state of decoupling between the economic growth and energy consumption in China over 1991–2012.

The remainder of this paper is organized as follows. Section 2 presents the methodologies of the study and related data. The main results are presented in Sect. 3. Finally, we conclude this study.

2 Methodology and data

2.1 ZM decoupling indicator

The final energy consumption in year t (E^t) can be expressed as a Kaya identity:

$$E^t = \sum_{ij} \frac{E_{ij}^t}{E_i^t} \times \frac{E_i^t}{G_i^t} \times \frac{G_i^t}{G^t} \times G^t = \sum_{ij} ES_{ij}^t \times EI_i^t \times S_i^t \times G^t \tag{1}$$

where t : the time in years; i : industrial sector; j : fuel type; E_{ij}^t : energy consumption of the j the fuel type of i the industrial sector in year t ; E_i^t : energy consumption of the i the industrial sector in year t ; G_i^t : the GDP of the i the industrial sector in year t ; G^t : the GDP in year t ; $ES_{ij}^t = \frac{E_{ij}^t}{E_i^t}$: the share of the j the energy form to total energy consumption of the i the industrial sector in year t ; $EI_i^t = \frac{E_i^t}{G_i^t}$: the energy intensity of the i the industrial sector in year t ; and $S_i^t = \frac{G_i^t}{G^t}$: the economic structure of the i the industrial sector in year t .

The decomposition method has become an important tool to investigate the influence factors governing energy consumption and its environment emission (Zhang et al., 2013). Currently, there are two famous decomposition techniques, i.e., SDA (structural decomposition analysis) and IDA. The advantage of IDA is the utilization of time series data. The IDA decomposition techniques also include two methods: the complete decomposition method and LMDI method. By comparing various IDA methods, Ang (2004) concluded that the LMDI method was the preferred method. Because there are the logarithmic terms in the LMDI formula, complications arise when the data set contains zero values. Ang and Liu (2007) presented eight strategies to handle zero values in LMDI method. Thus, the LMDI method is used to decompose energy consumption into several influence factors in

this paper. The detail of the LMDI method can be found in the reference (Ang and Liu 2007).

Thus, the change of the final energy consumption between a base year 0 and a terminal year t (ΔE_{tot}^t) can be expressed as the following formula based on the LMDI theory.

$$\Delta E_{\text{tot}}^t = E^t - E^0 = \Delta E_{\text{es}}^t + \Delta E_{\text{ei}}^t + \Delta E_{\text{s}}^t + \Delta E_{\text{g}}^t \tag{2}$$

where ΔE_{es}^t : the energy structure effect; ΔE_{ei}^t : the energy intensity effect; ΔE_{s}^t : the economic structure effect; and ΔE_{g}^t denotes the economic activity density effect. Each effect can be expressed as follows:

$$\Delta E_{\text{es}}^t = \sum_{ij} \frac{E_{ij}^t - E_{ij}^0}{\ln E_{ij}^t - \ln E_{ij}^0} \ln \left(\frac{\text{ES}_{ij}^t}{\text{ES}_{ij}^0} \right) \tag{2a}$$

$$\Delta E_{\text{ei}}^t = \sum_{ij} \frac{E_{ij}^t - E_{ij}^0}{\ln E_{ij}^t - \ln E_{ij}^0} \ln \left(\frac{\text{EI}_{ij}^t}{\text{EI}_{ij}^0} \right) \tag{2b}$$

$$\Delta E_{\text{s}}^t = \sum_{ij} \frac{E_{ij}^t - E_{ij}^0}{\ln E_{ij}^t - \ln E_{ij}^0} \ln \left(\frac{S_i^t}{S_i^0} \right) \tag{2c}$$

$$\Delta E_{\text{g}}^t = \sum_{ij} \frac{E_{ij}^t - E_{ij}^0}{\ln E_{ij}^t - \ln E_{ij}^0} \ln \left(\frac{G_i^t}{G_i^0} \right) \tag{2d}$$

The meaning of the above different factors is as follows: (1) The energy structure effect (ΔE_{es}^t) reflects the changes of energy type in total final energy consumption; (2) The energy intensity effect (ΔE_{ei}^t) reflects changes in the improvement in energy efficiency; (3) The economic structure effect (ΔE_{s}^t) reflects the changes in the relative shares of industry in total value added; and (4) The economic growth effect (ΔE_{g}^t) reflects the changes of economic growth. According to the definition of different factor, the economic growth effect (ΔE_{g}^t) is the main driving factor that leads to energy use. However, the energy structure effect, energy intensity effect, and economic structure effect are general effort referring to all actions directly or indirectly inducing a decrease in energy consumption. Thus, the effort in absolute (ΔF^t) during the period starting from the base year 0 up to year t can be represented as the sum of the three effect factors identified in Eq. (3):

$$\Delta F^t = \Delta E_{\text{es}}^t + \Delta E_{\text{ei}}^t + \Delta E_{\text{s}}^t \tag{3}$$

To assess the degree to which these efforts are effective in terms of the dissociation between economic growth and energy use, the decoupling index during the period from a base year 0 to a target year t , D^t , is defined as follows:

$$D^t = \frac{\Delta F^t}{\Delta E_{\text{act}}^t} \tag{4}$$

By referring to the decoupling state defined by Tapio (2005), this paper also defines eight kinds of decoupling state based on the definition of formula (4), as listed in Table 1.

Table 1 Criteria of decoupling indicator

	ΔF	ΔE_g	D'	Decoupling state
1	>0	>0	$D' \geq 0$	Expansive negative decoupling
2	<0	>0	$0 > D' \geq -0.4$	Expansive coupling
3	<0	>0	$-0.4 > D' \geq -1$	Weak decoupling
4	>0	>0	$-1 > D'$	Strong decoupling
5	>0	<0	$D' \leq 0$	Strong negative decoupling
6	<0	<0	$0.4 \geq D' > 0$	Weak negative decoupling
7	<0	<0	$1 \geq D' > 0.4$	Recessive coupling
8	<0	<0	$D' > 1$	Recessive decoupling

2.2 Data description

In this paper, the research period starts in 1991 and ends in 2012. All the energy data used in this paper are all collected from various issues of China Energy Statistical Yearbook (CESY, 1991–1996, 1997–1999, 2000–2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012). The energy unit is standard coal consumption in 10^6 tce (Mtce). Energy types used in China include coal, other washed coal, cleaned coal, coke, briquettes, coke oven gas, other gas and other coking products, crude oil, kerosene, gasoline, fuel oil, diesel oil, LPG, refinery gas and other petroleum products, heat, electricity and the other energy types.

The GDP is measured in billion yuan in constant 1991 price, which is collected from the China Statistical Yearbook (CSY 2014). The whole China economy is divided into three aggregated industries, namely the primary, secondary, and tertiary industry. The primary industry refers to agriculture and its related activities. The secondary industry sector only includes industry and construction. The tertiary industry sector consists of transport, storage, post, wholesale, retail trade and hotel, and restaurants.

3 Results and discussion

3.1 Decomposition result

Since the start of economic reforms and opening-up in the late 1970s, China has experienced spectacular economic growth. China’s GDP reached 17,157.33 billion Yuan (1991 price) in 2012 from 2178.16 billion Yuan in 1991, with an average annual growth rate of 10.33%. Along with the rapid economic growth, final energy consumption rose from 669.42 Mtce in 1991 to 2275.02 Mtce in 2012, representing an annual average growth rate of 5.98%. According to the formula (2) in Sect. 2.1, the decomposition results of the final energy consumption in China are listed in Table 2. As listed in Table 2, the economic growth effect (ΔE_g^t) was the critical factor in the growth of the final energy consumption in China. Furthermore, the economic growth effect (ΔE_g^t) made the continuous increase in the final energy consumption during the study period. Our results show that the energy structure effect (ΔE_{es}^t) played a minor role in the change of energy consumption in the study period. The positive role in decreasing energy consumption only occurred in 1993, 1994, and 1998.

Table 2 Decomposition of the final energy consumption in China during 1991–2012 (Mtce)

	ΔE_{es}^t	ΔE_{ei}^t	ΔE_s^t	ΔE_g^t	ΔE_{tot}^t
1991–1992	0.0042	−69.6427	20.4181	91.9196	42.6992
1992–1993	−0.0152	−90.0884	34.5774	95.6229	40.0968
1993–1994	−0.1132	−42.0886	−0.2007	95.6805	53.278
1994–1995	0.0692	−45.9788	6.7734	85.7833	46.6471
1995–1996	0.0345	−28.3415	4.7376	84.1065	60.5372
1996–1997	0.0106	−127.8094	1.8592	78.9399	−46.9997
1997–1998	−0.0070	−69.8840	−14.0544	64.5317	−19.4137
1998–1999	0.0000	−60.0161	−3.6482	62.0629	−1.6014
1999–2000	0.0040	−58.3846	3.2639	68.9210	13.8044
2000–2001	0.0025	−45.1354	−7.6751	69.1020	16.2939
2001–2002	0.0060	−25.9810	−3.7029	78.1335	48.4555
2002–2003	0.0435	43.4934	15.6902	95.3808	154.6079
2003–2004	0.1046	96.9663	3.2877	113.4813	213.8399
2004–2005	0.0213	−36.5073	20.8274	145.2213	129.5627
2005–2006	0.0184	−67.0784	11.6000	176.7548	121.2948
2006–2007	0.3174	−88.7893	−11.6171	210.9937	110.9048
2007–2008	0.2004	36.6907	2.4785	160.8463	200.2158
2008–2009	0.0084	−40.0992	−28.3609	167.7174	99.2658
2009–2010	5.2542	−131.9302	12.0035	197.4904	82.81787
2010–2011	0.0275	−11.2200	−1.9150	188.2323	175.1248
2011–2012	0.0039	−59.5168	−36.4930	165.1642	69.1583

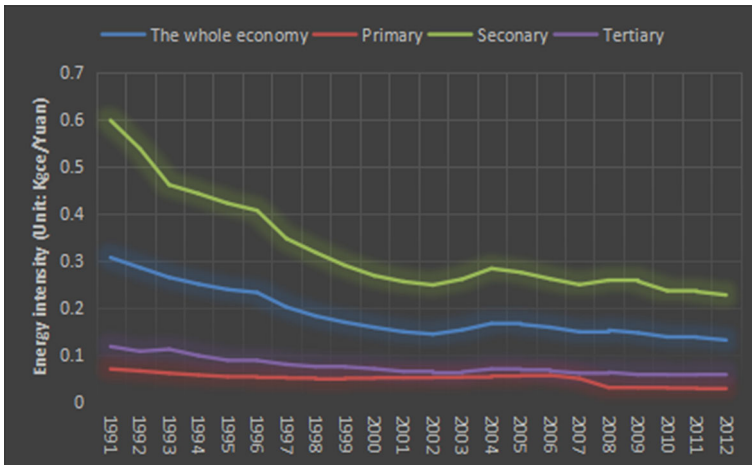


Fig. 1 Changes of energy intensity of different sector

As listed in Table 2, the energy intensity effect (ΔE_{ei}^t) played an important role in decreasing the final energy consumption in China except 2003, 2004, and 2008. As shown in Fig. 1, all the energy intensity presents a decline tendency except several years. The

energy intensity of the secondary is the largest, followed by the whole economy. However, the energy intensity of the primary industry is the smallest. Because the secondary industry accounted for more than 75% of total final energy consumption, the energy intensity of the secondary industry played a determined role in the total energy consumption.

Followed by the energy intensity effect (ΔE_{ei}^t), the economic structure effect (ΔE_s^t) only played a positive role in the decrease in energy consumption in 9 years, as listed in Table 2. Figure 2 presents the tendency of economic structure in China over 1991–2012. Though the share of the tertiary industry increased to 44.59% in 2012 from 33.68% in 1991, the share of the secondary industry has accounted for more than 45% since 2003. In the recent years, the share of the primary industry only accounted for about 10%. Figure 2 also shows that the gap between the secondary industry and tertiary industry gradually narrowed. Because the secondary industry is energy-intensive sector, over 75% of energy is consumed in the secondary industry. The fluctuation of the secondary industry can explain why the economic structure effect only played a positive role in 1994, 1998–1999, 2001–2002, 2007, 2009, and 2011–2012.

3.2 Decoupling analysis

According to the ZM decoupling indicator defined in Sect. 2.1, the ZM decoupling state for the China is listed in Table 3. As shown in Table 2, the change of the economic growth effect (ΔE_g^t) is over zero. Thus, only four decoupling statuses occurred over the study period: weak decoupling, expansive coupling, strong decoupling, and expansive negative decoupling. The development in 1996, 2002, 2005, 2006, and 2011 presented expansive coupling. Expansive negative decoupling only appeared in three years: 2003, 2004, and 2008, and the decoupling indicator was 0.62, 0.88, and 0.24, respectively. Strong decoupling only appeared in 1997, 1998, and 1999, and the decoupling indicator was -1.60 , -1.30 , and -1.03 , respectively. The energy consumption presented weak decoupling with economic growth in the rest 10 years.

Strong decoupling only occurred in 1997, 1998, and 1999, which can be explained by the change of the energy intensity effect (ΔE_{ei}^t), as listed in Table 2. Figure 2 also shows that the energy intensity for the secondary and tertiary industry presents a quickly decline

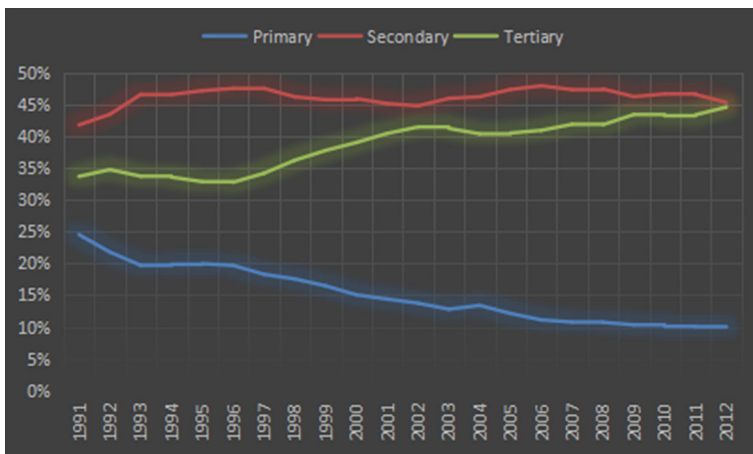


Fig. 2 Changes of economic structure in China

Table 3 ZM decoupling state and Tapio decoupling state for China over 1991–2012

	ZM— indicator	Decoupling state	Tapio indicator	Decoupling state
1991–1992	−0.54	Weak decoupling	0.45	Weak decoupling
1992–1993	−0.58	Weak decoupling	0.40	Weak decoupling
1993–1994	−0.44	Weak decoupling	0.54	Weak decoupling
1994–1995	−0.46	Weak decoupling	0.53	Weak decoupling
1995–1996	−0.28	Expansive coupling	0.71	Weak decoupling
1996–1997	−1.60	Strong decoupling	−0.55	Strong decoupling
1997–1998	−1.30	Strong decoupling	−0.29	Strong decoupling
1998–1999	−1.03	Strong decoupling	−0.02	Strong decoupling
1999–2000	−0.80	Weak decoupling	0.19	Weak decoupling
2000–2001	−0.76	Weak decoupling	0.23	Weak decoupling
2001–2002	−0.38	Expansive coupling	0.61	Weak decoupling
2002–2003	0.62	Expansive negative decoupling	1.67	Expansive negative decoupling
2003–2004	0.88	Expansive negative decoupling	1.97	Expansive negative decoupling
2004–2005	−0.11	Expansive coupling	0.89	Expansive coupling
2005–2006	−0.31	Expansive coupling	0.67	Weak decoupling
2006–2007	−0.47	Weak decoupling	0.51	Weak decoupling
2007–2008	0.24	Expansive negative decoupling	1.26	Expansive negative decoupling
2008–2009	−0.41	Weak decoupling	0.58	Weak decoupling
2009–2010	−0.58	Weak decoupling	0.38	Weak decoupling
2010–2011	−0.07	Expansive coupling	0.93	Expansive coupling
2011–2012	−0.58	Weak decoupling	0.41	Weak decoupling

tendency in the three years, especially the secondary industry. In 2003, 2004, and 2008, the occurrence of expansive negative decoupling was also attributable to the change of the energy intensity effect (ΔE_{ci}^t). The energy intensity for the secondary industry increased in those three years. The slowly decline of the energy intensity was the reason that expansive coupling occurred in those five years.

Table 3 also lists the Tapio decoupling state for China over 1992–2012. The Tapio decoupling indicator is defined as the ratio of the percentage change of energy use to the percentage change of GDP. The detailed Tapio formula can be referred to the results presented by Tapio (2005). Due to the percentage change of GDP is positive, only four decoupling status appeared during the study period: strong decoupling, weak decoupling, expansive coupling, and expansive negative decoupling. Table 3 lists the difference between the Tapio decoupling indicator and the ZM decoupling indicator. The development in 1996, 2002, and 2006 presented expansive coupling under the ZM decoupling indicator. However, weak negative decoupling appeared in the three years under the Tapio decoupling indicator. Compared with the Tapio decoupling indicator, the ZM decoupling indicator can reflect which factors lead to the decoupling.

4 Conclusions

Decoupling theory is a useful tool to study the relation between economic growth (GDP) and energy consumption or environment issue. Based on the LMDI method, this paper defined a new decoupling indicator (ZM decoupling indicator). China was selected as a case study. The ZM decoupling indicator was also utilized to explore the state of decoupling between the economic growth and energy consumption in China. The main conclusions drawn from the present study are as follows:

- (1) Along with the rapid economic growth, the final energy consumption in China rose to 2275.02 Mtce in 2012. Over the study period, all the energy intensity presented a decline tendency except for several years. The gap of economic structure between the secondary industry and tertiary industry gradually narrowed during the study period 1991–2012.
- (2) The economic growth effect (ΔE_g^t) was the critical factor in the growth of the final energy consumption in China. However, the energy intensity effect (ΔE_{ei}^t) played an important role in decreasing the final energy consumption, followed by the economic structure effect (ΔE_s^t).
- (3) Using the definition of the ZM decoupling indicator and Tapio decoupling indicator, only four decoupling statuses occurred in China over the study period: weak decoupling, expansive coupling, strong decoupling, and expansive negative decoupling. The difference between the Tapio decoupling indicator and the ZM decoupling indicator only appeared in 1996, 2002, and 2006.

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