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Analysis of electricity consumption in China (1990–2016) using index decomposition and decoupling approach

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ABSTRACT

Electricity consumption accounts for a significant portion of final energy consumption in countries worldwide and has a close relationship with economic growth. This paper explores the factors influencing electricity consumption in China during 1990–2016 using index decomposition analysis, and analyses the decoupling status between economic growth and electricity consumption, in addition to the influencing factors. These analyses are conducted at both national and sectoral levels. The results reveal that: (1) The economic activity effect was the main driving force increasing total electricity consumption in China, while the energy intensity effect hindered it. (2) Both diversity and aggregation existed at the sector level. The power generation, chemicals, and non-ferrous sectors were the top three contributors to increased electricity consumption. (3) The change of electricity consumption caused by GDP growth in China showed three decoupling states during 1990–2016: expansive negative decoupling, expansive coupling and weak decoupling. In particular, the energy intensity effect stimulated the occurrence of decoupling. (4) Industrial sectors played a significant role in decoupling in China, while service sectoral electricity consumption showed expansive coupling with its sectoral GDP in recent years.

1. Introduction

As the most common secondary energy, electric power is both clean and convenient to transmit, and it plays an important role in developing the national economy and improving people's living standards (Kim, 2015; Lin et al., 2016). In recent decades, China has become the largest energy consumer and electricity producer in the world (Chalvatzis and Rubel, 2015; Yuan et al., 2017). As an index of energy consumption, electricity consumption has a close relationship with economic growth (Lin and Liu, 2016; Wang et al., 2017). Either shortage or surplus of electric power will directly affect the coordinated development of the economy. Meanwhile, the coal-based electricity generation structure has led to serious environmental pollution (Lin and Ouyang, 2014b; Wei et al., 2015). Therefore, faced with the pressure of economic development requirements and resources' limitation, a profound understanding of the relationship between electricity consumption and economic growth can provide an important empirical basis not only for China's electricity construction but also for the formulation of effective energy-saving and economic policies.

Since Kraft and Kraft (1978) introduced the research issue of a nexus between energy consumption and economic growth, the related debate has been extended to numbers of items. The methods commonly used to study the interaction between energy resource consumption and economic development are regression analysis (Ge et al., 2017; Meng and Niu, 2011; Saidi and Hammami, 2015; Zhang et al., 2017a), the input–output model (Gao et al., 2018; Guevara and Domingos, 2017; Li et al., 2014; Su and Ang, 2012), and cointegration and the Granger causality test (Iyke, 2015; Kouakou, 2011; Shahbaz and Feridun, 2011). Li and Leung (2012) found that there is bidirectional causality between output and coal consumption in China's coastal and central regions. Lin and Chen (2018) studied the effect of economic variables on China's manufacturing sectoral energy consumption by establishing a VAR model. However, in general, the above models cannot fully reveal the different factors influencing energy consumption.

Index decomposition is a novel method to calculate the different factors influencing energy consumption. The existing literature has

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covered numerous index decomposition methods, but some of these methods have incompleteness of decomposition. Ang (2005) compared various index decomposition approaches, and he concluded that the Logarithmic Mean Divisia Index (LMDI) decomposition method is not only easy to use but also has good properties, such as polymerisation and reversibility of time and factors. Therefore, LMDI is a more applicable method in dealing with issues related to energy consumption decomposition.

Many scholars have applied LMDI and its deformation forms to investigate environmental pollution and energy consumption in some countries and regions and to analyse the structure effect and the efficiency effect levels. The research objects include CO_2 emissions' decomposition in Spain (Cansino et al., 2015, 2016), China's different sectors (Lin and Ouyang, 2014a; Ma et al., 2016; Ren et al., 2014), the electricity production sector (Ang and Goh, 2016; Ang and Su, 2016), the cement industry (Branger and Quirion, 2015), and the manufacturing sector (Jeong and Kim, 2013). Using the LMDI model, Qi et al. (2016) studied China's emission reduction factors, considering both energy and economic transformation. They concluded that improvement of energy efficiency is the most crucial driving factor to lower industrial CO_2 emissions. Regarding the national and provincial sides, Zhang and Tang (2015) studied the changes of carbon from export in China using a combination of a multi-regional input–output model and LMDI, and they determined the effect of predetermined driving factors influencing energy consumption. Ang and Wang (2015) used additive and multiplicative decomposition index analysis methods to study energy problems at different dimensions and levels. Fernández González and Moreno (2015) focused on decomposing the changes in Spain's electricity vulnerability, and they concluded that a significant increase in vulnerability arises from increasing energy prices. Using the LMDI method, Achour and Belloumi (2016) decomposed the driving factors of Tunisian's energy use in the traffic sector, and they concluded that the overall effect of energy intensity is negative. Moreover, some studies have applied decomposition analysis to other aspects of energy consumption, such as coal consumption (Chong et al., 2015), energy intensity (Baležentis et al., 2011; Tan and Lin, 2018), and overall energy consumption (Torrie et al., 2016; Wang et al., 2014). As for electricity consumption, Wang et al. (2010) used the LMDI method to conclude that technological and shift factors have an inverse-U-shaped and U-shaped effects on China's industrial electricity consumption. Besides, different industries have different energy saving potential. Inglesi-Lotz and Blignaut (2011) applied the same method, and they found that the increase in South Africa's electricity consumption is caused mainly by output factors and structural changes. Sectoral analysis also showed that only five out of fourteen sectors were influenced by efficiency improvements.

After examining the interrelationship between energy and economy, the question of whether either countries or sectors are becoming less reliant on energy is another important issue that remains to be answered. Decoupling analysis is a vital methodology to solve this problem. Introduced by Von (1989), the decoupling idea was first used by Zhang (2000) to examine environmental problems. Tapio (2005) proposed the concept of the decoupling index and used this indicator to assess the decoupling status in the European transport sector. Since then, the Tapio decoupling indicator has increasingly been adopted widely to further identify the interrelationship between economic development and energy and the related issues (Zhang et al., 2015, 2018). Zhou et al. (2017) adopted the Tapio index model to explore the decoupling relationship between China's economic growth and CO_2 emissions and expanded the research to eight different regions to compare various decoupling states. Meng et al. (2018) employed the same decoupling index to evaluate the synchronism between industrial value-added and fossil fuel consumption in China. Using the decoupling index and LMDI analysis, Zhang and Wang (2013) concluded that re-coupling (1999–2007) and weak decoupling (1991–1999 and 2007–2009) exist between China's national electricity consumption and GDP. However, they failed to conduct the decomposition and decoupling analysis at the sector level.

Up to now, many researchers have focused on the interrelationship between energy consumption and economic growth. Sectoral power consumption accounts for most of the electricity consumption in the whole society, and it indicates the characteristics and potential of national development (Zhang et al., 2017b). Nowadays, China's total GDP growth has deviated from power consumption growth in the short-term, especially for industry (Lin and Liu, 2016). Further, with the economic transformation and upgrading, this situation may become more apparent. It is necessary to study the characteristics and differences of electricity consumption in different sectors. However, few studies have conducted decomposition and decoupling analysis of China's electricity consumption at both national and sectoral levels in recent years. Furthermore, research aimed at exploring whether China' different sectors are becoming less dependent on sectoral electricity consumption is lacking. This paper aims to fill the above gaps.

The contributions of this study are as follows. (1) This is an integrated analysis of the status of electricity consumption and economy adjustment in China during 1990–2016. (2) Dividing China's economic sectors into 17 sub-sector groups, we analyse the changes of electricity consumption and its driving forces at multiple scales (i.e., the national and sectoral levels) based on index decomposition. (3) Combining index decomposition and decoupling analysis, we examine the decoupling status between total electricity consumption and economic output in China and analyse the change of each driving factor and its practical implications. (4) We calculate the decoupling index of 17 sectors and further discuss the decoupling relationship for some typical sectors during 1990–2016.

The remainder of this paper is organised as follows. Section 2 describes the related methods and the experimental data. In Section 3, we present the main results and discussions. Section 4 concludes this study and puts forward some policy implications.

2. Methodology and data source

2.1. Index decomposition model

According to Ang (2015), there are eight LMDI models considering different weights, decomposition approaches, and indicators. To decompose absolute electricity consumption change, which is quantity indicators, and discuss the results at the subcategory level, we apply additive decomposition analysis in this paper. The total electricity consumption in economic sectors in year t is Y^t, and it can be can be expressed as follows:

$$Y^t = \sum_i Y_i^t = \sum_i \frac{Y_i^t}{E_i^t} \cdot \frac{E_i^t}{G_i^t} \cdot \frac{G_i^t}{G^t} \cdot \frac{G^t}{P^t} \cdot P^t = \sum_i ES_i^t \cdot EI_i^t \cdot S_i^t \cdot PG^t \cdot P^t \quad (1)$$

where Y_i^t, E_i^t, and G_i^t represent the electricity consumption, energy consumption and GDP, respectively, of sector i in year t. G^t is the GDP in year t, and P^t is the total active population in year t. $ES_i^t = \frac{Y_i^t}{E_i^t}$ denotes the share of the sectoral electricity consumption to the total energy consumption of sector i in year t; $EI_i^t = \frac{E_i^t}{G_i^t}$ is the energy intensity of sector i in year t; $S_i^t = \frac{G_i^t}{G^t}$ is the economic structure of sector i in year t; and $PG^t = \frac{G^t}{P^t}$ is the per capita GDP output in year t.

The electricity consumption increase from a base year 0 to a target year t is represented by ΔY^t_{tot}. It can be resolved into five influencing drivers: (1) the change of electricity share effect (ΔY^t_{es}); (2) the change of energy intensity effect (ΔY^t_{ei}); (3) the change of economic structure effect (ΔY^t_s); (4) the change of economic activity effect (ΔY^t_{pg}); and (5) the change of population effect (ΔY^t_p). So, ΔY^t_{tot} can be calculated in the following formula.

$$\Delta Y^t_{tot} = \Delta Y^t_{es} + \Delta Y^t_{ei} + \Delta Y^t_s + \Delta Y^t_{pg} + \Delta Y^t_p \tag{2}$$

The influencing factor in Eq. (2) can be expressed as follows:

$$\Delta Y^t_{es} = \sum_i \frac{Y^t_i - Y^0_i}{lnY^t_i - lnY^0_i} \cdot \ln\left(\frac{ES^t_i}{ES^0_i}\right)$$

$$\Delta Y^t_{ei} = \sum_i \frac{Y^t_i - Y^0_i}{lnY^t_i - lnY^0_i} \cdot \ln\left(\frac{EI^t_i}{EI^0_i}\right)$$

$$\Delta Y^t_s = \sum_i \frac{Y^t_i - Y^0_i}{lnY^t_i - lnY^0_i} \cdot \ln\left(\frac{S^t_i}{S^0_i}\right)$$

$$\Delta Y^t_{pg} = \sum_i \frac{Y^t_i - Y^0_i}{lnY^t_i - lnY^0_i} \cdot \ln\left(\frac{PG^t}{PG^0}\right)$$

$$\Delta Y^t_p = \sum_i \frac{Y^t_i - Y^0_i}{lnY^t_i - lnY^0_i} \cdot \ln\left(\frac{P^t}{P^0}\right)$$

The electricity share indicates the effect of electricity consumption share in total energy consumption change. The energy intensity evaluates the effect of energy and technologies' efficiency improvement. The economic structure denotes the influence of sector structure adjustment on electricity consumption. The economic activity represents the effect of economic development in the whole society on electricity consumption. The population is the effect of population growth.

2.2. Decoupling model

The decoupling index is utilised to verify the interrelationship between related variables. When a state of decoupling shows, it implies that the growth rate of total sectoral electricity consumption is less than that of the GDP. According to Tapio (2005), from a benchmark year 0 to year t, the decoupling indicator of total electricity consumption (Y) and GDP (G) is defined as D^t. In this paper, we calculate the D^t as the following formula:

$$\begin{aligned} D^t &= \frac{\%\Delta Y}{\%\Delta G} = \frac{\frac{Y^t - Y^0}{Y^0}}{\frac{G^t - G^0}{G^0}} = \frac{G^0}{Y^0} \cdot \frac{\Delta Y^t_{es} + \Delta Y^t_{ei} + \Delta Y^t_s + \Delta Y^t_{pg} + \Delta Y^t_p}{\Delta G^t} \\ &= D^t_{es} + D^t_{ei} + D^t_s + D^t_{pg} + D^t_p \end{aligned} \tag{3}$$

where D^t is the total decoupling indicator, and D^t_{es}, D^t_{ei}, D^t_s, D^t_{pg}, and D^t_p denote the decoupling indicators of the five effects: electricity share sub-indicator (D^t_{es}), energy intensity sub-indicator (D^t_{ei}), economic structure sub-indicator (D^t_s), economic activity sub-indicator (D^t_{pg}), and population sub-indicator (D^t_p).

According to Tapio's definition (Tapio, 2005), there are eight decoupling states between electricity consumption and GDP; these are shown in Fig. 1.

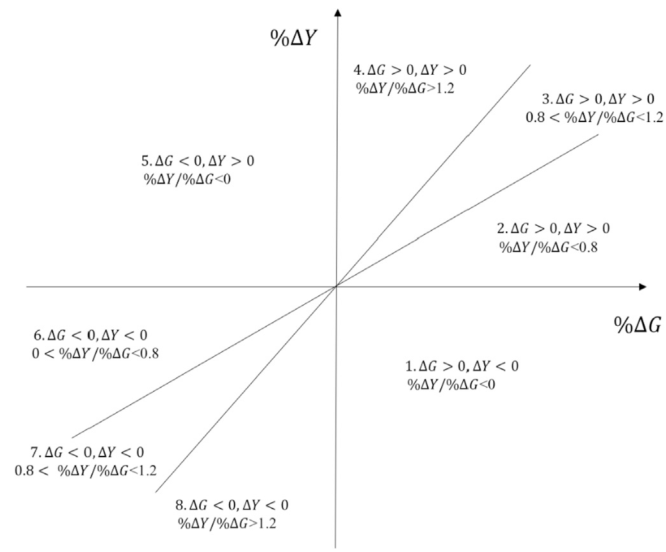

Fig. 1. The degree of coupling of electricity consumption from GDP. Notes: The decoupling state: 1. Strong decoupling; 2. Weak decoupling; 3. Expansive coupling; 4. Expansive negative decoupling; 5. Strong negative decoupling; 6. Weak negative decoupling; 7. Recessive coupling; 8. Recessive decoupling.

In terms of the correlation of economic development and energy pressure, the decoupling state can be separated into two main types: "relative decoupling" and "absolute decoupling". As shown in Fig. 1, during a period of time, when the rate of economic growth is much higher than is that of material consumption, they still have a certain coupling relationship; this is called relative decoupling, i.e. weak decoupling. When the material consumption decreases with the growth of the economy, the coupling relationship is dissolved; this is called absolute decoupling, i.e. strong decoupling. An expansive negative decoupling state indicates an irrational development mode, and the advancement of the economy comes at the expense of a large amount of energy consumption and environmental pollution. Expansive coupling is the most common mode in the current period, representing the close dependency and mutual promotion relationship between economy and energy. However, expansive coupling is detrimental for sustainable economic development in the long-run. As for the other four decoupling states, the economic growth is negative, and they are also undesirable.

2.3. Data description

Considering statistical consistency and data availability, this paper studies the period of 1990–2016 using the 17 sector classification shown in Table 1. The energy and economy data were all collected from the China Statistical Yearbook (NBSC, 1991–2017a,b) and the China Energy Statistical Yearbook (NBSC, 1991–2017a,b). Sectoral electricity consumption refers to the whole electricity generated by fossil fuel burning and clean power. The energy consumption refers to the sum of primary and secondary energy use measured by energy equivalency. The unit of electricity consumption is billion kilowatt hours (kWh), and the energy consumption is measured by standard coal consumption in ten thousand tons. The unit of GDP is billion yuan (BY) at a constant 2010 price. Furthermore, the population data came from the China Statistical Yearbook (NBSC, 2017a,b).

Table 1
Classification of sub-sectors in China's economic departments.

Classification	Specific departments
Agriculture	Agriculture, forestry, animal husbandry, fisheries, and water.
Mining	Mining and washing of coal
	Extraction of petroleum and natural gas
	Mining and processing of ferrous metal ores
	Mining and processing of non-ferrous metal ores
	Mining and processing of nonmetal ores and other ores
Foods and tobacco	Processing of food from agricultural products
	Foods
	Beverages
	Tobacco
Textile	Textile
	Textile wearing apparel, footwear, caps, leather, fur, feather and related products
Pulp and paper	Paper and paper products
Fuel processing	Processing of petroleum, coking, processing of nuclear Fuel
Chemicals	Raw chemical materials and chemical products
	Medicines
	Chemical Fibres
	Rubber and Plastics
Ceramics and cement	Non- metallic mineral products
Iron and steel	Smelting and pressing of ferrous metals
Non-ferrous	Smelting and pressing of non-ferrous metals
Metal and machinery	Metal products
	General purpose machinery
	Special purpose machinery
	Transport equipment
	Electrical machinery and equipment
	Communication equipment, computers, and other electronic equipment
	Measuring instruments and machinery for cultural activity and office work
Other manufacturing industries	Timber, manufacture of wood, bamboo, rattan, palm, and straw products
	Manufacture of furniture
	Printing, reproduction of recording media
	Manufacture of articles for culture, education, and sport activity
	Manufacture of artwork and other manufacturing
	Recycling and disposal of waste
Power generation	Production and distribution of electric power and heat power
	Production and distribution of gas
	Production and distribution of water
Construction	Construction
Transportation	Transport, storage, post and telecommunication services
Trade and catering	Wholesale, retail trade, and catering services
Service	Other service industry

3. Results and analysis

3.1. Analysis of electricity consumption and economic status in China

China has undergone a spectacular economic growth and a radical change in energy consumption in the past few decades. Its GDP increased from 5218.5 BY to 68911.6 BY during 1990–2016, indicating that the growth rate was 10.4% per year. The change of real GDP per capita and population in China over 1990–2016 are as shown in Fig. 2.

At the same time, China's reform and opening policies have also changed the country's economic structure and promoted industrial transformation. The economic structure of China is presented in Fig. 3. In the early 1990s, as the secondary and tertiary sectors were underdeveloped, the agricultural sector and its related sectors were still the engine that drove economic development. With the progress of mankind and the improvement of living standards, consumer demand for goods turns to increase the quality of life, which causes the proportion of the secondary and the tertiary sectors to increase year by year. Along with the advancement of industrialisation and informatisation, the manufacturing and emerging services have shown explosive expansion. They have replaced the agricultural sectors successfully and become the engine driving the expansion of China's economic scale and sustainable development. The economic importance of the agricultural sector was in decline.

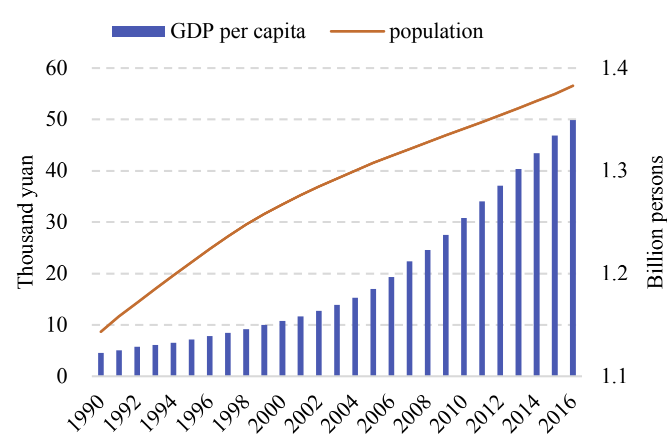

Fig. 2. The trends of real GDP per capita and population in China during 1990–2016.

Along with economic development, overall electricity consumption showed synchronous growth in the early years of opening up and reform. Electricity consumption in the economic sectors increased from 963.1 billion kWh in 1990–5287.7 billion

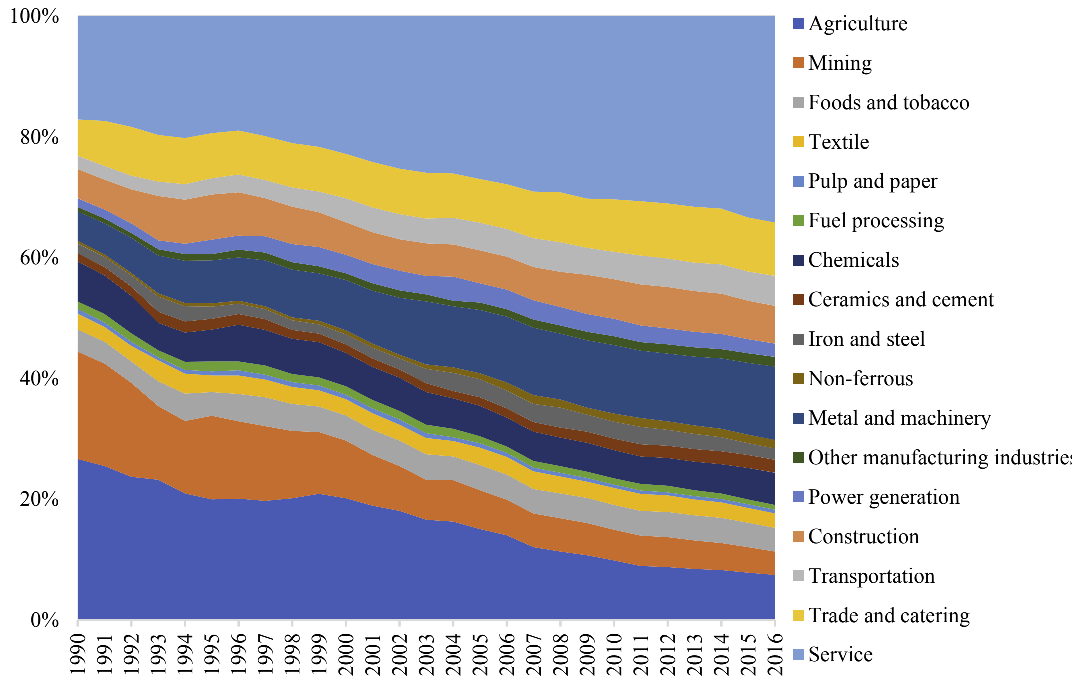

Fig. 3. The trends of economic structure in China during 1990–2016.

kWh in 2016. Considering time series, the correlation coefficient of electric power consumption growth rate and economic growth has reached 0.99 since 1990. However, within a specified period, a decoupling phenomenon existed between economic growth and electricity consumption. In the fourth quarter of 2008, the first and second quarter of 2009, the national electricity consumption growth equalled 7.1%, 4.0%, and 4.0%, respectively, all significantly lower than economic growth in the same period. Meanwhile, the ratio of electricity use to final energy consumption was increasing with each passing year (other energy consumption is relatively less, so it is not taken into account). The change of different energy consumption share is shown in Fig. 4. Also, as indicated in Fig. 4, coal consumption constituted more than 60% of total energy consumption; although this proportion was in decline, the figures mean that China is still a coal-based country.

The expansion of the economy and energy consumption have been followed by serious problems of environmental pollution and the greenhouse effect. Fortunately, people's consciousness of environmental protection and emissions' reduction has been strengthened constantly. As the progress of science and technology has brought upgrading of equipment and improved manufacturing techniques, energy efficiency showed an overall upward trend.

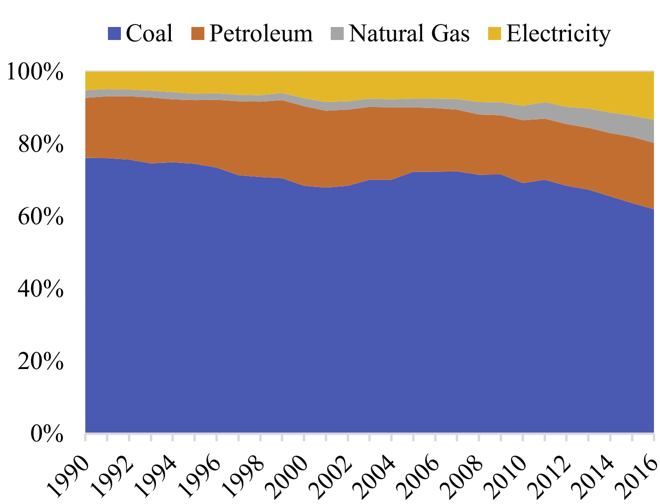

Fig. 4. The trends of energy consumption in China during 1990–2016.

The energy intensity tendency of 17 sectors is shown in Fig. 5; it has declined in a wave-pattern from 1990 to 2016. In general, the energy intensity of the agricultural sector and the tertiary sector has been lower than that of industries, indicating that the agricultural and tertiary sectors are less reliant on energy. Known as high energy-consuming industries, iron and steel, ceramics and cement, non-ferrous, and fuel processing were the top four sectors with high energy intensity. The energy intensity of the iron and steel and chemicals industries decreased by nearly 40% and 50%, respectively, during 1990–2016. The significant reduction of energy intensity of most secondary sectors can be due to a series of energy-saving polices, including the "*Top 1000 Priorities*" and "*Ten-Key Projects*" programs, and other strategies for banning low-efficiency production capacities (Liu et al., 2015). In 1993, China established a socialist market economy system, and the first iron and steel enterprise successfully went public. Structural adjustment of the steel industry required more energy support, resulting in a brief rise in energy intensity. Facing the new pressure of development with accession to the World Trade Organisation and the impact of the Asian financial crisis, China struggled to achieve the development targets, causing a decline in the energy efficiency of many sectors in early 21st century.

3.2. Decomposition analysis of electricity consumption in China

Using the index decomposition method presented in Section 2.1, the decomposition results of total electricity consumption in China can be seen in Fig. 6 and Table 2.

As implied from Table 2 and Fig. 6, the electricity share also led to the 26.2% increase of electricity consumption in China from 1990 to 2016, and the contribution of electricity share was positive

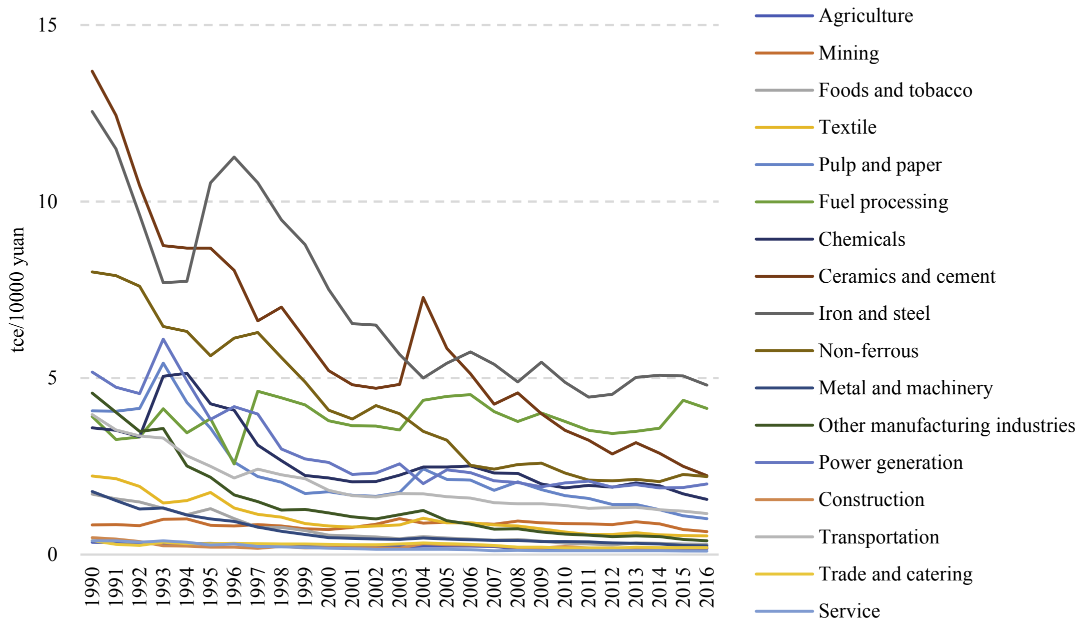

Fig. 5. The trends of energy intensity in China during 1990–2016.

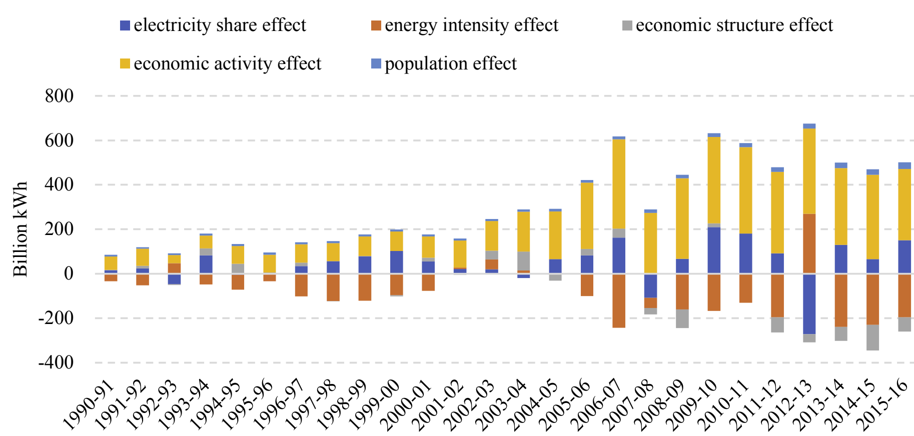

Fig. 6. Decomposition results of total electricity consumption in China, 1990–2016.

Table 2
Decomposition results of total electricity consumption in China, 1990–2016 (Unit: Billion kWh).

Year	ΔY^t_{es}	ΔY^t_{ei}	ΔY^t_{s}	ΔY^t_{pg}	ΔY^t_{p}	ΔY^t_{tot}
1990–1995	71.9	−151.6	85.8	311.0	40.2	357.4
1995–2000	266.3	−472.7	18.8	419.7	46.0	278.2
2000–2005	142.1	−14.3	110.2	744.2	49.5	1031.6
2005–2010	414.1	−716.7	−25.2	1724.0	73.2	1469.4
2010–2015	196.6	−524.9	−281.8	1862.8	111.8	1364.5
2015–2016	150.7	−196.0	−63.5	320.7	30.3	242.2
1990–2016	1241.7	−2080.0	−155.7	5382.4	351.1	4743.2

almost every year. During the 11th Five-Year Plan (FYP) period, there was a sudden boom in the electricity consumption share effect; the likely reason was that, given the implications of a differential electric power pricing policy, many enterprises were striving to adapt this measure, resulting in a lack of power conservation. The electricity consumption increased by 28.2% in the 11th FYP due to the electricity share change. In recent years, the expansion of power generation and supply has been the main reason for electricity consumption growth. As for 2012 to 2013, adjustment to the energy statistic standard has led to the abnormal change of electricity share. However, during 2015–2016, China's government emphasised the necessity to develop clean energy–based electricity consumption, and polices such as "*Renewable Energy Law*" and "*Renewable Portfolio Standard*" have stimulated explosion of the electricity share, causing a 150.7 billion kWh increase in electricity consumption.

According to Table 2, energy intensity played a dominating role in reducing electricity consumption by 43.9% at the aggregate level from 1990 to 2016. The energy intensity effect caused electricity consumption to reduce in all FYPs. Specifically, there was a short increase in the energy intensity effect during 2001–2004, as can be seen in Fig. 4. This is because, early in the accession to the WTO, China was facing the pressure of more high quality goods from foreign countries without paying attention to energy saving, resulting in a brief rise in energy intensity. During the 11th FYP period, China has completed the energy intensity reduction target of 20% through the requirements of programs such as exporting the tax rebate rate and shutting down low-efficiency production capacities. Furthermore, the aggregate electricity consumption reduced by 38.5% and 81.0% due to energy efficiency improvement during 2010–2015 and 2015–2016, respectively. It can be inferred that the energy intensity will continue to play a significant role in saving electricity in the future through application of energy-saving technologies and equipment.

It is worth mentioning that, judging only by the numbers, the economic structure effect was the most uncertain driver influencing electric power consumption each year. During the whole study period, the decline of electricity use caused by the economic structure effect was 155.7 billion kWh, accounting for only 3.3% of the total change. But, as seen from the perspective of FYPs, its hindering effect was becoming increasingly important. During the 8th, 9th, and 10th FYP periods, the structure effect remained positive, which indicates that the energy-intensive sectors still accounted for a non-negligible proportion before 2005, although the service sectors developed rapidly, as seen in Fig. 3. Since then, China has released series of policies aimed at optimising the economic structure, e.g., "*Distributing the Industrial Restructuring and Upgrading Plan*" and "*Decisions of Accelerating the Development of the Strategic Emerging Industries*"; these documents have had remarkable influence in promoting the upgrading of high energy-consuming industries and stimulating the establish of non-energy-intensive enterprises through both technical and financial support.

The economic activity effect was the main driving force increasing electricity consumption in China from 1990 to 2016. China has gone through a spectacular economic expansion since 1990, and its GDP reached 68911.6 BY in 2016, as shown in Fig. 2. With the vitality of the economy and the increase in GDP per capita, people with generous incomes pursued more comfortable living environments, and factories expanded production. Obviously, this led directly to soaring electricity consumption. In the meantime, as the total population increased, production activities became more active, and more electricity was needed. Fig. 1 indicates that China's population expanded by 20.9% in 26 years and reached one billion persons in 2016. However, the growth rate of the population was only 0.7% a year, which can explain why the contribution of the population effect to increasing electricity consumption was only 7.4%.

Aiming at analysing the characteristics and influencing factors of the electricity consumption in different sectors, the results of sectoral decomposition of electricity consumption are listed in Table 3.

From Table 3, we can conclude that high-energy-consuming industries, such as power generation (16.2%), chemicals (12.7%), non-ferrous (12.6%), metal and machinery (10.7%), and iron and steel (10.0%), mainly contributed to electricity consumption during 1990–2016. Known as energy-intensive sectors, chemicals, non-ferrous, iron and steel have high value-added. Moreover, most of equipment in these sectors is backward and inefficient, which does not help save electricity. Power generation is the pillar industry of China's development, and it has been expanding in recent years to satisfy the large demand for electricity. Metal and machinery is a strategic emerging industry that has received a huge amount of attention, along with investment and policy support. Continuous development has also caused electricity consumption to boom consistently. Meanwhile, pulp and paper has increased electricity consumption by only 1.2%, which is the lowest contribution to overall energy consumption by the industrial sectors. This can be explained by the drop in its value-added proportion from 1990 to 2016. With the rapid development of electronic information, it seems that the paper industry is declining.

From Table 3, we can conclude that the electricity share had a positive impact on electricity consumption for all sectors during 1990–2016, with the top three significant sectors being metal and machinery, power generation, and non-ferrous. These three sectors together accounted for 36.7% of the total change in electricity share. During the study period, the share of electricity in total energy use increased by 223.7%, 23.2%, and 89.7% in the metal and machinery, power generation, and non-ferrous sectors, respectively. The expansion of electricity consumption can be related to the increasing number of newly installed electric machines and equipment, such as motors, and pumps, in these sectors (Liu et al., 2015). Also, the continuous construction of large factories leads to more electricity consumption. In contrast, the fuel processing and construction sectors contribute only slightly to the increase of the electricity share, indicating that the impact of electricity-saving policies are remarkable in these two sectors.

As for the energy intensity effect, most sectors, except for fuel processing industry, have played a negative role. From 1990 to 2016, the contribution of the fuel processing industry to the energy intensity was 7.1 billion kWh, which might be due to less attention being paid to improving energy efficiency when merging enterprises. It is also possible that the fuel processing industry does not have great potential for energy conservation and that the relevant policies do not make sense. The sectors that have contributed most to the decrease in energy intensity are metal and machinery (15.8%), chemicals (14.3%) and ceramics and cement (13.2%). This is because many obligatory energy measures are implemented in these industries. For example, the popularisation and application of

Table 3
Decomposition results of sectoral electricity consumption in China, 1990–2016 (Unit: Billion kWh).

Sector	$\Delta Y^t_{es,\,i}$	$\Delta Y^t_{ei,i}$	$\Delta Y^t_{s,i}$	$\Delta Y^t_{pg,i}$	$\Delta Y^t_{p,i}$	$\Delta Y^t_{tot,i}$
Agriculture	23.3	−54.1	−105.3	188.9	13.7	66.5
Mining	68.7	−68.8	−199.8	337.9	23.6	161.6
Foods and tobacco	38.5	−74.5	−3.2	126.5	8.7	96.0
Textile	70.6	−109.9	−25.7	223.3	14.4	172.7
Pulp and paper	26.2	−50.3	−9.9	84.0	5.6	55.6
Fuel processing	5.7	7.1	−29.0	85.4	5.7	74.9
Chemicals	107.2	−297.1	30.8	712.3	47.2	600.4
Ceramics and cement	101.2	−274.5	86.0	350.4	22.7	285.7
Iron and steel	109.5	−128.9	−161.9	615.0	38.9	472.6
Non-ferrous	113.6	−134.3	123.5	420.1	26.5	549.4
Metal and machinery	190.3	−329.6	113.3	503.0	31.8	508.8
Other manufacturing industries	54.8	−102.5	30.9	115.2	7.4	105.8
Power generation	152.7	−215.2	−139.0	910.8	59.3	768.6
Construction	6.3	−17.9	2.4	70.4	4.7	66.1
Transportation	14.2	−45.1	25.6	112.4	7.5	114.6
Trade and catering	49.5	−42.3	17.3	188.4	11.9	224.8
Service	109.3	−138.2	88.3	338.5	21.4	419.2

energy saving technology and equipment in intelligent equipment, metal and machinery industries. Besides, large-scale group enterprises have been built to improve the efficiency of the ceramics and cement sector, and differential power prices are applied in the chemicals sector.

The results of the structure change effect of each sector are also presented in Table 3, which shows that they differ greatly. Mining, iron and steel, and power generation were the three main contributors to reducing the structure effect, indicating that the value-added proportion of these sectors dropped from 1990 to 2016. Actually, the mining industry still remains an important pillar of China's economy, but its value-added proportion decreased from 17.8% to 3.9% during the study period because, over the past few decades, the manufacturing and service sectors have developed more rapidly with industrialisation and informationisation. As for the iron and steel and the power generation industries, they are the main field of the upgrading and transformation of China's industrial structure. However, the non-ferrous, metal and machinery and service sectors have had a significant impact on the structure effect. The fast growth in the non-ferrous and the metal and machinery industries may result from the urbanisation in China since 1990. A huge amount of non-ferrous materials has been required to support the real estate industry and other infrastructure construction (Naughton, 2007). Meanwhile, more ownership of household electric appliances, such as air conditioners, washing machines, and refrigerators, has also stimulated the development of the metal and machinery industry.

3.3. Decoupling analysis of electricity consumption and economic growth in China

According to the above index decomposition analysis, we can draw the conclusion that economic activities were the dominating driver of sectoral electricity consumption growth. In this section, we use Tapio's decoupling index model to further explore the decoupling state between economic output and electricity consumption. The decoupling relationship between electricity consumption and GDP in China during 1990–2016 is shown in Table 4. The decoupling indicators of each effects are calculated, and the results are shown in Fig. 7.

Table 4
The decoupling state of total electricity consumption in economic sectors and GDP in China, 1990–2016.

	Year	$\%\Delta Y$	$\%\Delta G$	D	Decoupling state
8th FYP	1990–91	0.13	0.10	0.76	Weak decoupling
	1991–92	0.14	0.12	0.81	Expansive coupling
	1992–93	0.07	0.06	0.93	Expansive coupling
	1993–94	0.09	0.19	2.08	Expansive negative decoupling
	1994–95	0.11	0.07	0.69	Weak decoupling
9th FYP	1995–96	0.10	0.07	0.67	Weak decoupling
	1996–97	0.10	0.04	0.42	Weak decoupling
	1997–98	0.09	0.02	0.26	Weak decoupling
	1998–99	0.10	0.05	0.56	Weak decoupling
	1999–00	0.09	0.09	1.01	Expansive coupling
10th FYP	2000–01	0.09	0.08	0.95	Expansive coupling
	2001–02	0.10	0.12	1.19	Expansive coupling
	2002–03	0.10	0.17	1.78	Expansive negative decoupling
	2003–04	0.11	0.16	1.46	Expansive negative decoupling
	2004–05	0.12	0.13	1.16	Expansive coupling
11th FYP	2005–06	0.14	0.15	1.04	Expansive coupling
	2006–07	0.17	0.15	0.90	Expansive coupling
	2007–08	0.10	0.04	0.35	Weak decoupling
	2008–09	0.13	0.07	0.52	Weak decoupling
	2009–10	0.13	0.14	1.16	Expansive coupling
12th FYP	2010–11	0.11	0.12	1.13	Expansive coupling
	2011–12	0.10	0.05	0.55	Weak decoupling
	2012–13	0.09	0.08	0.90	Expansive coupling
	2013–14	0.08	0.04	0.53	Weak decoupling
	2014–15	0.08	0.03	0.30	Weak decoupling
	2015–16	0.07	0.05	0.68	Weak decoupling

From Table 4, we can see that only three decoupling states appeared during the study period. Expansive negative decoupling occurred in 1994 and 2002–2004. Expansive coupling occurred in 1991–1993, 1999–2002, 2004–2007, 2009–2011, and 2013. Electricity consumption exhibits a weak decoupling nexus with GDP growth, which indicates that electricity consumption rises as economic GDP grows; however, the power change rate is lower than is that of GDP. This phenomenon appeared in the remaining 12 years over the study period.

As can be seen from Fig. 7, the expansive negative decoupling that appeared in 1994 can be interpreted by the influence of the electricity share. Power generation was the most representative sector, and its electricity consumption increased from 76.0 billion kWh in 1993 to 140.1 billion kWh 1994. This boom may due to the industry transformation of coal-based and nuclear-based power plants in the early 1990s, which resulted in a large amount of electricity use in such sectors. In 2002–2004, this phenomenon is explained by increased energy intensity and the structure change effect. We can also see from Fig. 5 that the energy consumption intensity of most industries rose obviously in 2002–2004. Meanwhile, the sudden boom of production capacity and expansion of traditional industries since China entered the WTO without enough focus on energy saving and efficiency improvement, leading to a significant increase of electricity consumption.

The expansive coupling appeared in 11 of the study years, and this synchronism represents a close link between electricity and the economy. During 1991–1993, China experienced comprehensive reform and opening-up, and the rapid development of industrialisation and urbanisation has accelerated both economic growth and electricity consumption. After the Asian financial crisis, China entered a re-industrialisation period. The expansive coupling state in 1999–2002 might be due to the reliance of the economy on electricity. Moreover, the expansive negative decoupling in 2004–2007, 2007–2011, and 2013 also indicates that, in those years, the overall production scale expanded rapidly, leading to greater demand for electricity and that higher electricity consumption also stimulated GDP growth. Fig. 7 shows that the energy intensity effect played a significant role in the decoupling process.

For the remaining 12 years, the total electricity consumption showed weak decoupling with economic growth. The decoupling sub-indicator of the energy intensity was negative for the great majority of the years, which means that the improvement of energy efficiency stimulated the decoupling between electricity consumption and economic expansion. During 1994–1999, China's government paid much attention to shutting down energy-intensive and low-efficiency enterprises. As shown in Fig. 3, the value-added proportion of ceramics and cement and iron and steel decreased from 1.9% to 2.5%–1.4% and 1.5%, respectively. Taking into account that these two sectors are high-energy and electricity consuming sectors, optimisation of the structure improved energy efficiency and contributed to the decoupling. The Chinese government proposed “cutting down energy consumption per unit of GDP by 20% during 2005–2010” in the 11th FYP, and it succeeded. From 2007 to 2009, China's GDP had an annual growth rate of 11.6%, whereas electricity consumption grew relatively slowly (5.2%). In recent years, China has begun to implement more policies on saving energy and cutting down electricity. High-technology equipment and methods can reduce energy waste not only in the production process but also in selling process. Greater input of capital and personnel can also increase production efficiency. Fig. 6 indicates that, in 2012 and 2013–2016, the energy intensity effect and the structure effect index were both negative, reflecting a

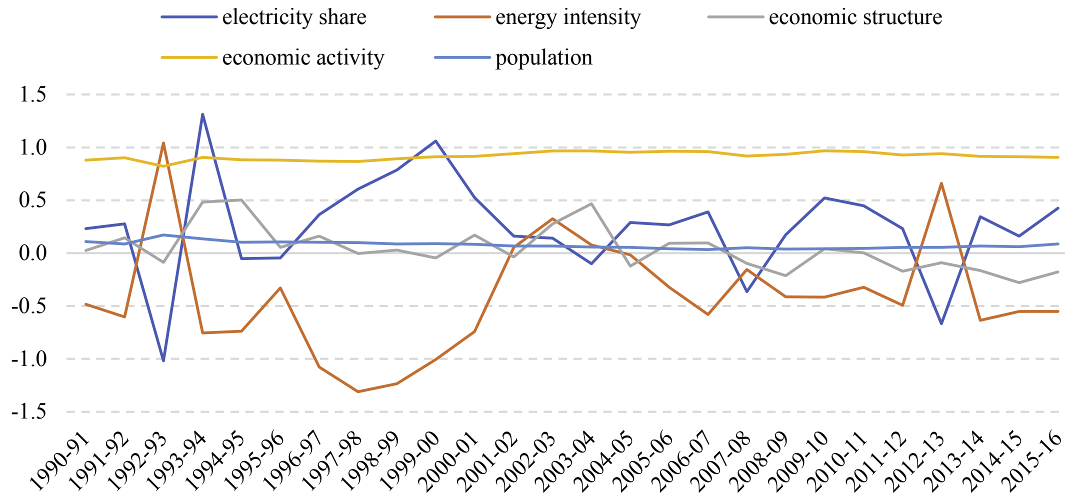

Fig. 7. Decoupling sub-indicator for electricity consumption in whole economic sectors, 1990–2016.

contribution of the decoupling relationship.

According to Fig. 7, it can be concluded that the electricity share effect and the energy intensity effect had strong volatility, and the fluctuations of the economic structure, economic activity, and population effect were relatively gentle. This leads to a basic synchronism of the tendency between the total decoupling indicator and the electricity share and energy intensity sub-indicators. At the same time, we can draw the conclusion that, in the next few years, electricity consumption and GDP growth will remain in a weak decoupling state in China.

Then, we calculate the decoupling index of electricity consumption from the added-value of all 17 sectors (the detailed results are presented in Table A1). We select some typical sectors—agriculture, power generation, chemicals, and service—to construct their decoupling index in Fig. 8. Power generation and chemicals are the top two contributors to increased industrial electricity consumption. To highlight most of the data and make sure that they can be shown clearly in the diagram, several data points with extreme values are deleted; this has no significant impact on either the overall characteristics or the comparison between sectors.

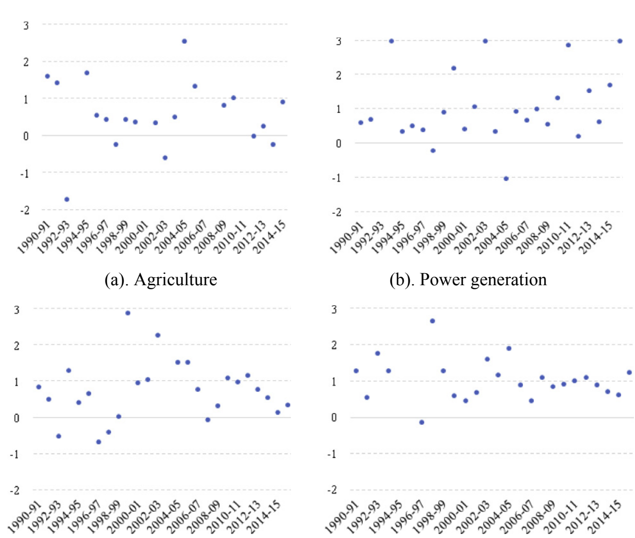

Fig. 8. Decoupling indicators for four typical sectors, 1990–2016.

From the comparison in Fig. 8, we can conclude that there were some obvious distinctions between the sectors. For the agriculture sector, the decoupling index had the widest range of values, representing four decoupling relationships, and the strong decoupling and weak decoupling states appeared in several years. In recent decades, China has experienced the phenomenon of “sacrificing agriculture to support the special period of industrial development” which may hinder the development of related industries. Besides, more efficient farm machinery can reduce the electricity consumption per unit of output. Meanwhile, resource saving agriculture has been strongly advocated, and this can develop ecological agriculture and reduce the overall land use (Zhao et al., 2017).

The power generation sector experienced a pattern from weak decoupling to strong decoupling, followed by expansive negative decoupling. Because early power generation industry development is not perfect and the scale of companies is generally small, this sector consumed less energy, most of which was fossil energy. Since then, China has significantly updated its industrial equipment and improved its energy efficiency to promote a more reasonable mode of development of the power generation sector, indicating a strong decoupling. In recent years, rapid development of industrialisation and urbanisation has required the full support of electricity. Thus, the expansion of power plants caused a boom in electricity consumption.

However, the chemicals sector went from weak decoupling to expansive negative decoupling, and then to strong decoupling. Before 2000, the chemicals sectors started to develop, accompanied by the need for chemical materials, medicines, rubber, and plastics, and many enterprises have since emerged, causing an increase of electricity consumption. However, most of these factories were small with no mass production. The sector flourished after 2000. Foreign trade and domestic demand stimulated the expansion of chemical factories, regardless of electricity saving. This may have led to the expansive negative decoupling of the chemicals sector from 2000 to 2005. Strong decoupling has appeared in recent years, indicating that electricity policies such as differential electric power pricing have had remarkable effects in terms of reducing electricity consumption in the chemicals sector. Moreover, improved technology and the use of energy saving equipment also contributed to decoupling.

The services sector also experience three main states. Expansive coupling occurred in approximately half of the study years, especially after 2005. From the decomposition results, we can see that the economic activity and the structure effect were the most significant factors influencing the decoupling in the services sector. As shown in Fig. 3, with the financial and technical support of related policies, the share of the services sector in China's total GDP increased from 17.3% to 34.2% during the study period. However, the decoupling effect of the services sector is marginal compared with that of industries; this may be because the services sector is more reliant on electricity than on fossil energy. During the 11th and 12th FYP periods, energy intensity was the main contributor to decoupling; this can be explained by advanced energy efficiency, such as more electricity-saving lighting, air-conditioners, and related electrical application systems. 2016 was the first year of the 13th FYP, and most sectors, including the services sector, suffered the pressures of sustainable development. Massive utilisation of electricity is the reason for the short-term increase in the decoupling index.

4. Discussion and policy implications

The main findings of this paper are summarised as follows.

(1) China's electricity consumption increased from 544.4 to 5287.7 billion kWh during 1990–2016. The power generation, chemicals, and non-ferrous sectors were the top three contributors to this increase. These conclusions are consistent with the studies of Wang et al. (2010), who used index decomposition to analyse China's industrial electricity consumption. At the same time, the energy intensity of the total economy and most sectors showed a declining tendency. The difference is that the change of energy intensity was relatively sharp in secondary industry sectors, whereas it was much gentler in the primary and tertiary sectors.

(2) Energy intensity improvement was the dominant contributor to reducing electricity consumption in whole study period and all FYP periods. Moreover, the metal and machinery, chemicals and ceramics, and cement sectors had the most significant effect on this drop. Conversely, the contributions from the construction, fuel processing, trade, and catering sectors to the decline of energy intensity were minor. The electricity share had a non-negligible effect on electricity consumption. The decomposition analysis indicates that metal and machinery and power generation were the top two contributors to electricity share increase. For all sectors, the share of electricity in total energy grew significantly from 1990 to 2016. Optimisation of economic structure had the smallest impact on decreasing electricity, and this hindering effect occurred only after the 9th FYP. The mining, iron and steel, and power generation sectors had a negative effect on this index, but the non-ferrous industry weakened the influence. Some of the results are similar to those of Inglesi-Lotz and Blignaut (2011), who analysed different factors of electricity consumption in South Africa.

(3) During 1990–2016, three decoupling states based on decoupling indexes occurred: expansive negative decoupling, expansive coupling, and weak decoupling. This result is consistent with Zhang and Wang (2013). The changes in the electricity share, energy intensity, and population effect demonstrated the occurrence of expansive negative decoupling. Decrease in energy intensity promoted weak decoupling between GDP growth and electricity consumption. In addition, an expansive negative decoupling state in the agricultural sector was transformed to a weak decoupling state in more recent years. There were differences among energy-intensive sectors, such as power generation and chemicals. However, electricity-saving in these sectors can lead to the decoupling state between electricity consumption and GDP growth in China. Electricity consumption in services sector may remain in the expansive coupling state with its value-added in the near future.

Based on the results, the following policy implications are put forward.

(1) Further deepening of electricity system reform is urgently required. Since the concept of "differential electric power pricing" was proposed in 1990s, the Chinese government has made much effort to optimise the power price system. "*Guiding Opinions on Implementing Multistep Electricity Price for Household Electricity Consumption*" was implemented in October 2010 to control residential power use. Moreover, in 2015, the National Development and Reform Commission of China released "*Some Opinions on Further Deepening the Reform of Electric Power System*", aimed at carrying out power side management and improving the electricity saving system in industries. A more reasonable electricity pricing strategy is essential, and the electricity use in energy-intensive industries should be restricted by stricter policies. Market transactions between power generation enterprises and users should be emphasised to reduce unnecessary waste.

(2) Efficient utilisation of energy and electricity should be promoted through modern technology. Many policies, such as "*Top 1000 Priorities*" and "*Ten-Key Projects*", target energy efficiency, and these programs have had a remarkable influence in reducing the energy intensity of some industries. For some sectors, e.g., fuel processing and other energy-intensive industries, which have performed badly in terms of energy efficiency improvement, specific innovation policies can be encouraged. Appropriate tax policies should be developed and subsidies should be given to encourage investment and R&D behaviour that enhances energy efficiency. For instance, equipment updating and waste recycling will be beneficial to electricity-saving. Moreover, it is essential to improve coal quality and exploit new and clean energy.

(3) Optimising the economic structure is fundamental. The advancement of industrialisation and urbanisation have significantly stimulated the need for energy-intensive products, such as iron, non-ferrous materials, and metal, which come from energy-intensive industries. Polices, such as, "*Made in China 2025*" and "*The* 13th *FYP for Economic and Social Development of China*", present the idea of eliminating backward production capacity and supporting strategic new industries. Hence, further electricity-saving can be achieved by encouraging imports of electricity-intensive products, guiding the industrial structure transformation and upgrading in the direction of low energy, and encouraging the advancement of high-tech enterprises with high added value. Further development of finance, science research, education, tourism, and entertainment can also reduce the overall electricity consumption.

5. Concluding remarks

China's GDP has reached a new stage since the country has experienced acceleration of industrialisation and modernisation, and a high growth rate is anticipated in the next few years. Along with the huge demand for energy resources to support its expanding economy, China's electricity consumption has grown rapidly.

In this paper, an LMDI model is introduced to conduct decomposition analysis of national and sectoral electricity consumption in China during 1990–2016. Specifically, the factors governing China's total electricity consumption and differential sectoral electricity consumption are investigated. Meanwhile, combining index decomposition and Tapio's decoupling indicator model, the decoupling state of electricity consumption and economic growth is explored, along with its sub-indicators. Finally, we discuss the decoupling interrelationship between electricity consumption and GDP in four typical sectors.

Overall, our combined decomposition and decoupling model provides a better understanding of the relationship between China's electricity consumption and economic growth. In order to realize the steady growth of electricity consumption and its decoupling relationship with GDP growth, more attention must be paid to improving energy efficiency and optimising the proportion of electricity, especially in some high energy-consuming industries, for example the power generation, chemicals, and non-ferrous sectors. Meanwhile, industrial structure upgrading has great potential in promoting more efficient electricity use.

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Appendix

Table A1
Decoupling index of electricity consumption from added value of all sectors (base = last year), 1990–2016.

Sector	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Agriculture	1.6	1.4	−1.7	−5.9	1.7	0.6	0.4	−0.2	0.4	0.4	5.5	0.4	−0.6
Mining	1.3	1.7	0.3	0.0	0.3	1.3	0.8	−1.6	−2.8	2.3	−2.3	−2.5	−6.7
Foods and tobacco	0.8	0.8	0.8	0.2	−5.9	−0.2	−0.1	6.2	−2.0	0.2	0.6	1.2	−1.3
Textile	0.9	0.4	0.6	2.4	−1.1	−0.4	0.6	−0.2	−0.9	1.8	0.8	2.6	1.5
Pulp and paper	2.2	1.4	0.0	0.0	0.7	0.0	0.0	1.6	0.6	11.3	0.8	0.9	5.0
Fuel processing	0.4	1.9	−0.3	1.6	−0.4	−5.5	1.1	−5.0	1.0	0.8	1.3	2.8	0.2
Chemicals	0.9	0.5	−0.5	1.3	0.4	0.7	−0.7	−0.4	0.0	2.9	1.0	1.0	2.3
Ceramics and cement	0.6	0.6	0.8	1.3	1.1	−0.1	0.3	−0.6	0.2	1.4	1.1	1.2	1.0
Iron and steel	0.4	0.4	0.4	1.6	−0.2	−0.2	0.3	0.1	0.9	0.5	0.5	1.0	0.6
Non-ferrous	0.8	0.6	0.3	1.0	0.6	−4.0	2.5	0.3	0.7	0.5	0.5	6.7	1.0
Metal and machinery	0.1	0.4	2.8	0.1	0.2	0.4	0.7	0.4	−0.1	0.9	0.9	1.1	1.1
Other manufacturing industries	19.2	4.1	3.6	−1.3	4.8	0.7	1.0	−15.2	6.0	1.4	0.5	0.4	7.1
Power generation	0.6	0.7	56.8	3.0	0.4	0.5	0.4	−0.2	0.9	2.2	0.4	1.1	3.0
Construction	1.0	0.4	1.4	2.0	0.5	2.5	13.0	10.0	−12.1	4.5	−1.0	1.5	1.2
Transportation	0.6	1.4	0.6	0.6	0.7	0.5	2.3	0.0	0.0	0.4	0.8	0.8	2.2
Trade and catering	0.5	1.0	10.4	4.0	1.4	1.4	1.9	1.0	1.7	1.8	1.2	1.2	2.4
Service	1.3	0.5	1.8	1.3	−6.3	7.3	−0.1	2.7	1.3	0.6	0.5	0.7	1.6

Sector	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Agriculture	0.5	2.6	1.4	6.8	−2.9	0.8	1.0	6.6	0.0	0.3	−0.2	0.9	3.5
Mining	0.7	1.7	0.0	0.9	0.5	0.4	1.5	1.6	0.9	1.9	0.3	−5.3	4.4
Foods and tobacco	3.0	1.1	1.0	1.1	0.6	0.4	0.9	0.9	0.9	0.9	0.4	0.6	1.1
Textile	5.3	0.6	1.6	0.7	−0.1	0.2	0.8	0.6	1.8	0.8	0.1	0.3	0.5
Pulp and paper	−2.6	0.6	1.6	−0.1	1.1	0.2	1.6	1.7	0.0	0.4	0.7	0.0	0.7
Fuel processing	2.4	5.1	5.2	0.9	0.2	2.4	1.3	0.7	−0.2	3.0	2.7	−1.4	2.1
Chemicals	6.6	1.5	1.5	0.8	−0.1	0.3	1.1	1.0	1.2	0.8	0.6	0.1	0.4
Ceramics and cement	−3.2	0.6	0.9	0.6	0.2	0.4	0.9	1.1	0.1	0.6	0.5	−0.8	0.4
Iron and steel	0.6	2.0	1.5	1.2	0.0	−3.7	1.1	1.1	1.3	2.2	−3.7	1.1	−0.4
Non-ferrous	0.5	0.8	0.5	1.1	8.5	−5.6	0.8	0.6	1.3	0.8	0.8	3.3	0.8
Metal and machinery	2.9	0.7	0.9	1.0	1.1	0.4	1.8	1.0	0.2	0.8	0.6	0.1	0.6
Other manufacturing industries	−0.1	0.5	0.5	0.4	0.8	0.4	0.8	0.9	0.5	0.0	0.7	0.1	0.5
Power generation	0.4	−1.0	0.9	0.7	1.0	0.6	1.3	2.9	0.2	1.5	0.6	1.7	3.0
Construction	1.6	0.4	1.1	0.8	1.2	0.6	1.0	1.2	0.7	1.4	0.9	−1.0	0.8
Transportation	0.7	−0.3	0.6	0.7	0.6	2.3	1.3	1.0	0.9	0.9	0.6	0.7	1.1
Trade and catering	2.5	0.2	0.8	0.5	0.5	1.0	0.7	1.1	1.1	1.1	0.7	1.4	1.7
Service	1.2	1.9	0.9	0.5	1.1	0.9	0.9	1.0	1.1	0.9	0.7	0.6	1.3

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