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Decoupling economic growth from carbon emissions growth in the United States: The role of research and development

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A B S T R A C T

The United States has achieved economic growth compatible with carbon reduction since 2007. This work is addressed to understand the eight effects, especially effects related to research & development (R&D) on the decoupling economic growth from carbon emission through a decomposition technique and a decoupling effort model. The results of sector analysis show that the changes of carbon emission in industry sector and transportation sector were dominant contributor and inhibitor to the drop of carbon emission, respectively. The decomposition results indicate that energy intensity was the leading contributor to the drop of carbon emission, followed by R&D intensity, sectoral carbon intensity, R&D efficiency; whereas economic scale was the primary inhibitor to the drop of carbon emission, followed by investment intensity, population size and sectoral energy structure. The results of decoupling efforts analysis uncover that energy intensity, R&D intensity, R&D efficiency and sectoral carbon intensity contributed to decoupling economic growth from carbon emission, whereas investment intensity, population size and sectoral energy structure did not contribute to the decoupling. Finally, some policy implications are proposed.

1. Introduction

In recent decades, global warming has received considerable attention and concerns, due to its negative impact on social and economic development. International community has been making great efforts to control climate change, from *United Nations Framework Convention on Climate Change, Kyoto Protocol* to *The Paris Agreement*. Carbon emission is one of main contributors to global warming. According to Global Carbon Project (GCP), total global carbon emission exceeded 30 billion tons, increased by1.6% in 2017. While in 2018, it is expected to increase by 2.7%, having possibility to hit a New High. Carbon emission from energy consumption accounts for nearly 80% of total global carbon emission. Therefore, controlling energy-related carbon emission will play a critical role in restraining global carbon emission and temperature rise. The United States announced to withdraw *Kyoto Protocol* in 2001. However, despite the government did not perform international responsibility of fighting against climate change together with international community, its energy-related carbon emission reached the peak of 6006 million tons in 2007, then progressively decreased, truly achieving decoupling. Hence, it is of great significance to figure out underlying reasons to decoupling energy-related carbon emission from economic growth in the United States.

The United States, as an important developed country, is featured by powerful technology. Regarding technology in environment field, on the one hand, it is expected to increase carbon emission, whereas advanced technology can be applied to expand production scale. While on the other hand, technology can be also applied to save energy consumption, to such an extent to reduce energy-related carbon emission. Figuring out the role of technology playing in carbon reduction while maintaining economy growing, is not only beneficial to low-carbon economy construction of the United States, but also can provide practical reference for the rest countries to make carbon-reduction policies. Technology is an abstract indicator, which is usually indirectly represented by energy intensity or carbon intensity (Feng et al., 2009; Wang and Jiang, 2019). Nevertheless, it is less accurate and can't completely reflect technology, due to the value of the two indicators depend on not only technological factor, but also other more important factors

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(Huang et al., 2018; Roca, 2002). Generally speaking, R&D expenditure is directly applied to technological innovation (Feng et al., 2009; Jiao et al., 2016; Lu et al., 2016). Therefore, in this paper, indicators of investment and R&D are applied to directly present the role of technology in carbon reduction of the United States.

The rest of paper is organized as follow. Section 2 presents a related and detailed literature review. Section 3 constructs decoupling effort model on the basis of extended kaya identity and LMDI decomposition method. Section 4 specifically discusses energy-related carbon emission situation and decomposition results in the United States. Section 5 comes to conclusions and proposes some policy implications.

2. Literature review

Global warming poses a great deal of pressure on social and economic development, and becomes an important concern globally. It is well appreciated that greenhouse gas, especially carbon emission makes a large contribution to global warming. Accordingly, in a world of rapid economic development, a large number of scholars have researched relationship between environmental pressure and economic growth. For the sake of easy application and reflection of real-time dynamic relationship between economic growth and environmental pressure, decoupling analysis has been extensively applied in relevant researches (Wang, Y. et al., 2017; Wang and Yang, 2015; Yang et al., 2018). Among various decoupling models, the OECD decoupling index model and Tapio decoupling model are widely used in environmental field (Chen, C. et al., 2018; Wu et al., 2018a; Xie et al., 2019). The former was proposed by Organization for Economic Co-operation and Development (Organization for Economic Co-operation and Development, 2002), the latter was proposed by Tapio (Tapio, 2005).

Regarding to the application of these two models, some scholars conducted decoupling analysis to a large extent. Wu et al. examined decoupling economic growth from carbon emission among developing and developed countries by comparatively applying OECD decoupling index, Tapio decoupling model and IGTX decoupling model (Wu et al., 2018b). The results indicated decoupling states of developed countries were better than those of developing countries. Shuai et al. (2019) applied Tapio decoupling model to investigate decoupling relationship between economic growth and total carbon emission, carbon emission per capita as well as carbon intensity among 133 countries worldwide. Wang et al. comparatively studied decoupling carbon emission from economic growth in China and India (Wang et al., 2018a). Wang et al. compared decoupling states between China and the United States and further explored factors influencing decoupling. The results indicated that decoupling states of the United States were more stable than China (Wang et al., 2018b). When narrowing down the research extent, some scholars put emphasis on signal country. Gray et al. explored whether decoupling economic growth from carbon emission will occur in Scotland (Gray et al., 2006). Freitas and Kaneko employed OECD decoupling index to investigate decoupling economic growth from carbon emission in Brazil (Freitas and Kaneko, 2011). Jiang et al. researched decoupling relationship between energy-related carbon emission and economic growth in the United States from 1990 to 2014 by Tapio decoupling model (Jiang et al., 2016). Roinioti and Koroneo conducted a decoupling analysis by OECD decoupling index after decomposition analysis in Greece(Roinioti and Koroneos, 2017). Zhou et al. (2017), Zhao et al. (2017), Wang and Jiang (Wang and Jiang, 2019) explored decoupling relationship between carbon emission and economic growth in China by Tapio decoupling model. More specifically, some scholars focused on provinces or cities, like Guangdong province by Wang et al. (2014), Jiangsu province by Wang et al. (2013) and Lu et al. (2015). Yu et al. (2017) selected Chongqing as research object and identified decoupling states from 1999 to 2010 by OECD decoupling index. They found absolute decoupling occurred between economic output and SO_2, waste water, soot. Wang et al. explored decoupling carbon emission from economic growth in Beijing and Shanghai from sectoral level. The results demonstrated that Beijing possessed a better decoupling states that Shanghai from the view of industry (Wang et al., 2019b). What's more, a large number of scholars highlighted the decoupling analysis from industrial level, such as tourism (Zi et al., 2014), nonferrous metals (Ren and Hu, 2012), agriculture (Han et al., 2018),transport (Loo and Banister, 2016; Sorrell et al., 2012).

Undoubtedly, there is a large body of literature about decoupling analysis, but most of them focused on identifying decoupling states between carbon emission and economic growth and further exploring factors influencing decoupling states (Chen, J. et al., 2018; Ma and Cai, 2019; Wu et al., 2019), quite a few have been performed to measure what efforts have been done to achieve decoupling and effectiveness of efforts. Evaluating decoupling effort can figure out effect of current carbon mitigation policies and further reflect the advantages and disadvantages of these policies, which facilitate the improvement of relevant policies and achievement of decoupling. Diakoulaki and Mandaraka (2007) comparatively assessed decoupling process among EU14 countries in manufacturing sector from 1990 to 2003, and found improvement of energy intensity and shift of energy structure contributed most to decoupling process. Climent and Pardo (Climent and Pardo, 2007), Mazzantia and Zoboli (Mazzanti and Zoboli, 2008) introduced econometrics into decoupling research to investigate decoupling effort of Spain and EU respectively. Freitas and Kaneko (Freitas and Kaneko, 2011) developed a method based on LMDI to explore decisive factors on carbon emission change in Brazil, after identifying decoupling of carbon emission from economic activity. Zhang and Da (Zhang, Y.J. and Da, Y.B., 2015), Yang et al. (2018) evaluated efforts made to achieve decoupling in China. The former found two-third of period studied appeared relative decoupling and improvement of energy intensity and energy structure significantly promote decoupling progress. The latter found all regions have exerted efforts and energy intensity was the main contributor to decoupling progress. Lou et al. (2018) examined whether typical carbon emission sector made enough efforts to construct low-carbon city from the view of global practice. Lin et al. (2018) quantified decoupling states and effort index of China's industrial carbon emission in the period of 1996–2015. The study demonstrated that manufacture and transportation emitted the most carbon dioxide, in addition energy intensity made the largest effort to carbon mitigation.

Through the above literature review, it can come to a conclusion that relevant decoupling effort studies are relatively rare, while decoupling effort studies aim at the United States are far rarer. As the greatest developed country, the United States effectively reduces carbon emission since 2007, gradually achieving decoupling. Further evaluate decoupling effort of the United States is seen to be demonstrative to low-carbon economy construction for both developed countries and developing countries. Hence, for the sake of assessing effectiveness of decoupling effort in the United States, this paper constructed a decoupling effort model through combining kaya identity and decomposition analysis.

With respect to decomposition analysis, it is seen to be an effective tool widely used in investigating drivers behind carbon emission (Han and Chatterjee, 1997; Lakshmanan and Han, 1997; Rhee and Chung, 2006) and energy consumption (Alcántara and Duarte, 2004; Garbaccio et al., 1999; Shahiduzzaman and Alam, 2013), for the reason of decomposing total change of a dependent variable as changes in terms of several independent variables (Ang, 1996; Ang and Choi, 1997). Generally, there are two main types of decomposition analysis: index decomposition analysis (IDA) and structure decomposition analysis (SDA) (Wang et al., 2019a). SDA heavily depends on input-output table, which cause its application limited (Wang and Wang, 2019). While IDA is intensively applied in the field of energy and environment (Bhattacharyya and Matsumura, 2010; Fujii et al., 2013; Kojima et al., 2010), in the light of its less requirement in data, and easy application in time series analysis and regional comparison (Ang, 2004). Among all IDA methods, because LMDI decomposition method can handle zero value perfectly and leave no residual (Ang, 2004; Mousavi et al., 2017), LMDI method has been widely applied by scholars (Hasanbeigi et al., 2013; Wang, Q. et al., 2017; Zhao, 2014).

As for application of LMDI in carbon emission research, Ouyang and Lin(Ouyang and Lin, 2015) applied the LMDI decomposition method to investigate influencing factors behind CO2 emissions in Chinese industrial sector. The study showed that industrial activity contributed the most to industrial carbon emissions increase, while energy intensity contributed the most to industrial carbon emissions decrease. Cansino et al. (2015) decomposed total carbon emission into carbon intensity, energy intensity, economic structure, economic scale and population size to analyze driving factors of Spain's carbon emission from 1995 to 2009. Timilsina and Shrestha (Timilsina and Shrestha, 2010) used the LMDI method to research responsible factors for the increase of carbon emission in transport sector among 20 countries of Latin American and Caribbean. The total carbon growth was divided into five influencing factors: fuel mix, modal shift, economic growth, emission coefficients, and energy intensity. The study turned out economic growth and energy intensity were main contributor to the increase of carbon emission of transport sector. Sumabat et al. (2016) decomposed carbon emission of Philippine into effect of population, economic scale, energy intensity, energy mix and carbon emission factor during 1990–2014. To our great extent of knowledge, previous studies mainly investigated conventional factors (e.g. energy intensity, economic activity). These factors can effectively illustrate macroeconomic impact of carbon emission, but fail to uncover deep microeconomic root of carbon emission changes (Shao et al., 2016). Without any doubt, enterprises' microeconomic behaviors, like investment and research and development (R&D) movement, play a significant role in energy-saving and carbon reduction (Shao et al., 2011; Xu and Lin, 2018). Recently, scholars attempted to extend LMDI decomposition method by introducing investment or R&D. Zhao et al. (2016) added three new investment factor (investment scale/share/efficiency) when exploring carbon emission in China. Shao et al. (2016), Zhang et al. (2017), Wang and Feng (Wang and Feng, 2018) all took R&D intensity/efficiency and investment intensity into consideration to respectively analyze changes of industrial carbon emission, the first one focused on Shanghai, the latter two focused on the whole China. Gao et al. (2019) considered carbon emission changes of Chinese pharmaceutical industry by combing R&D intensity/efficiency and investment intensity factors into LMDI method. Researches gradually noticed the impact of R&D and investment on carbon emission and took them into consideration, but relevant researches about R&D and investment are far ample.

Actually, the United States is tagged by powerful technology, but when it comes to factors influencing carbon emission, scholars usually concentrated on conventional factors (Shahiduzzaman and Layton, 2015). Feng et al. quantified the impact of consumption volume, population, fuel mix, energy intensity, consumption pattern and production structure on the Unites States carbon emission from 1997 to 2013 by SDA decomposition method, and found the carbon emission decrease during 2007–2013 was attributed to fuel mix shift from coal to natural gas (Feng et al., 2015). Jiang et al. decompsed carbon emission into population, economic scale, energy intensity, energy structure and carbon emission coefficient effect and furthur idnetified decoupling relationship between carbon emission and economic growth in the United States (Jiang et al., 2016). Shahiduzzaman and Layton decomposed carbon emission into energy structure, energy intensity, economic structure, economic scale and population to assess the challenge of fulfillment of 2025 carbon emission target (Shahiduzzaman and Layton, 2017). The U.S. Energy Information Administration (EIA) investigation energy-related carbon emission in the U.S. by decomposing it into population effect, economic production effect, energy intensity effect and carbon intensity effect (EIA, 2018). Besides, Fernández Fernández et al. explored the influence of aggregate R&D expenditure on carbon reduction during 1990–2013, not only in the United States, also EU-15 and China (Fernández et al., 2018). Jiang et al. introduced technology state, labor input and investment effect into three conventional factors (carbon coefficient, energy intensity and energy structure) though combining C-D function and LMDI method to figure out the United States carbon emission changes in 2000–2016 (Jiang et al., 2019). Though some scholars began to consider microeconomic factors, the considered factors ae not comprehensive in existing researches about the United States. Given that R&D expenditure and fixed asset investment are closely relevant to technological innovation and economic production, playing an important role in energy-saving and carbon-reduction. Incorporating them into course of decomposition is of importance (Ang, 2004; Kojima et al., 2010; Lin et al., 2018). Moreover, the United States ranks top with respect to technology. Exploring the impact of technological factors (e.g. R&D intensity, R&D efficiency, investment intensity) on carbon emission will conducive to carbon reduction and low-carbon economy construction. Hence, this paper took a step forward to explore factors driving energy-related carbon emission of the United States with incorporation of R&D expenditure and fixed asset investment.

This study has made contributions to the relevant research of relationship between carbon emission and economic growth in major two aspects. Firstly, this paper constructed a comprehensive and systematical framework by combining Kaya identity, Tapio decoupling model and LMDI method, so as to investigate relationship between carbon emission and economic growth in the United States, which is the second largest carbon emitter. Surprisingly, the carbon emission in the United States began to decrease since 2007, hence, LMDI method was applied to explore factors influencing the decrease. In addition, when identifying the decoupling states, the Tapio decoupling model was chosen, then we went a step forward to assess effectiveness of efforts made to achieve decoupling by decoupling effort method. Secondly, different from previous studies, this paper took R&D expenditure and fixed asset investment into consideration, for directly investigating technological factors on carbon emission and decoupling status. To our great extent of knowledge, our study became the first try to comprehensively consider technological factors in decomposition and decoupling analysis in the United States featured by powerful technology, which accelerate low-carbon economy in the United States, also conductive to formulation scientific and practical policies of carbon mitigation in other countries.

3. Methods and data source

3.1. Tapio decoupling model

It is greatly appreciate that the OECD decoupling index and Tapio decoupling model are two mainstream decoupling models in environmental field. However, the OECD decoupling index model is too sensitive to the choice of base year, thus the calculated results are not stable trustworthy enough (Zhao et al., 2016; Zhou et al., 2017). By contrast, Tapio decoupling model gets over the problem of high sensitivity to base year and possesses a refined decoupling states category (Zhao et al., 2016). As a result, in order to identify relationship between carbon emission and economic growth in the United States, the Tapio decoupling model is illustrated in our study. The decoupling index e is described as follow:

$$e = \frac{\left(C^t - C^0\right)/C^0}{\left(GDP^t - GDP^0\right)/GDP^0} = \frac{\Delta C/C^0}{\Delta GDP/GDP^0} = \frac{\%C}{\%GDP} \quad (1)$$

Where C^t and GDP^t represents total carbon emission and gross domestic product in target year t, respectively; C^0 and GDP^0 represents total carbon emission and gross domestic product in base year 0, respectively; $\%C$ and $\%GDP$ represents growth rate of total carbon emission and gross domestic product.

According to Tapio, decoupling state is concretely defined as eight categories as Fig. 1. The strong negative decoupling is the worst decoupling state, where economy declining while carbon emission increasing; strong decoupling is opposite to it, which is the best decoupling state with economy increasing while carbon emission decreasing. In addition, when $\%C > 0$ and $\%GDP > 0$, from expansive negative decoupling $(e > 1.2)$ to expansive coupling $(0.8 \le e \le 1.2)$ to weak decoupling $(0 \le e < 0.8)$, decoupling state is improving. On the contrary, when $\%C < 0$ and $\%GDP < 0$, from recessive decoupling $(e > 1.2)$ to recessive coupling$(0.8 \le e \le 1.2)$ to weak negative decoupling $(0 \le e < 0.8)$, decoupling state is deteriorating.

3.2. Decomposition technique

Based on kaya identity (Kaya, 1990), the energy-related carbon emission of the United States is described as follows:

$$\boldsymbol{C} = \sum_i \frac{\boldsymbol{C_i}}{\boldsymbol{E_i}} \times \frac{\boldsymbol{E_i}}{\boldsymbol{E}} \times \frac{\boldsymbol{E}}{\boldsymbol{G}} \times \frac{\boldsymbol{G}}{\boldsymbol{R}} \times \frac{\boldsymbol{R}}{\boldsymbol{I}} \times \frac{\boldsymbol{I}}{\boldsymbol{G}} \times \frac{\boldsymbol{G}}{\boldsymbol{P}} \times \boldsymbol{P} \quad (2)$$

while definitions of variables in Eq. (1) are summarized in the following Table 1.

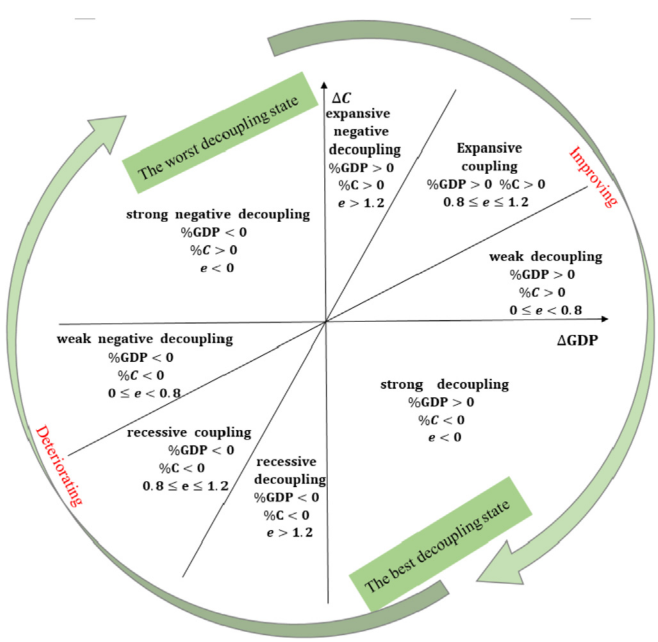

Fig. 1. Decoupling States of carbon emission and economic growth in the United States.

Where SCI_i (calculated as C_i/E_i) denotes carbon emission per Btu of energy consumption, that is to say the sectoral carbon intensity in sector i; SES_i (calculated as E_i/E) denotes the share of Btu of energy consumption in sector i to total Btu of energy consumption, that is sectoral energy structure; EI (calculated as E/G) represent energy intensity; RE (calculated as G/R) and RI (calculated as R/I) are, respectively, R&D efficiency and R&D intensity; II are investment intensity. AE and P denotes economic scale and population size respectively. Therefore, Eq. (1) can be further expressed as follows:

$$C = \sum_i SCI_i \times SES_i \times EI \times RE \times RI \times II \times AE \times P \quad (3)$$

Among decomposition method, LMDI method is widely used in the field of environmental researches, in the light of its ease of use, without residuals, perfectly handling zero and negative value, and other desirable properties (Ang, 2004; Ang and Liu, 2001; Ang and Zhang, 2000; Ang et al., 1998; Liu and Ang, 2007). In this paper, in order to explore the influence of different factors on total energy-related carbon emission, we use LMDI decomposition method to decompose total energy-related carbon emission. The specific processes are shown in the following flow chart(see Fig. 2).

Where ΔC stands for the change of total energy-related carbon emission; while C^t and C^0 represent carbon emission in target year t and base year 0 respectively. ΔC_{SCI}, ΔC_{SES}, ΔC_{EI}, ΔC_{RE}, ΔC_{RI}, ΔC_{II}, ΔC_{AE}, ΔC_P are, respectively, carbon emission change caused by sectoral carbon intensity effect, sectoral energy structure effect, energy intensity effect, R&D efficiency effect, R&D intensity effect, investment intensity effect, economic scale effect and population size effect[1].

3.3. Decoupling effort model

Decoupling effort refers to all direct or indirect actions that reduce carbon emission, without hurting economic development. In the research of carbon emission, taking out carbon emission caused by economic scale effect can further assess the effectiveness of decoupling effort. Therefore, in this paper, we try to measure the actual effectiveness of effort all the above factors have done to achieve decoupling (except economic scale effect) by applying decoupling effort model.

When decoupling effort results in carbon emission increase, in the case of $\alpha \le 0$ denoting no decoupling effort. While decoupling effort results in carbon emission decrease, in the case of $0 < \alpha < 1$ denoting weak decoupling effort, $\alpha \ge 1$ denoting strong decoupling effort (see Fig. 3).

Table 1
Definitions of variables in Eq. (2).

Variable	Definition
i	Type of sector
E	Total Btu (British thermal unit) of energy consumption
R	R&D expenditure
G	GDP (gross domestic product)
I	Fixed asset investment
P	Population size

[1] carbon emission change caused by sectoral carbon intensity effect, sectoral energy structure effect, energy intensity effect, economic scale effect and population size effect belong to conventional factor. R&D efficiency effect, R&D intensity effect, investment intensity effect belong to technological factor.

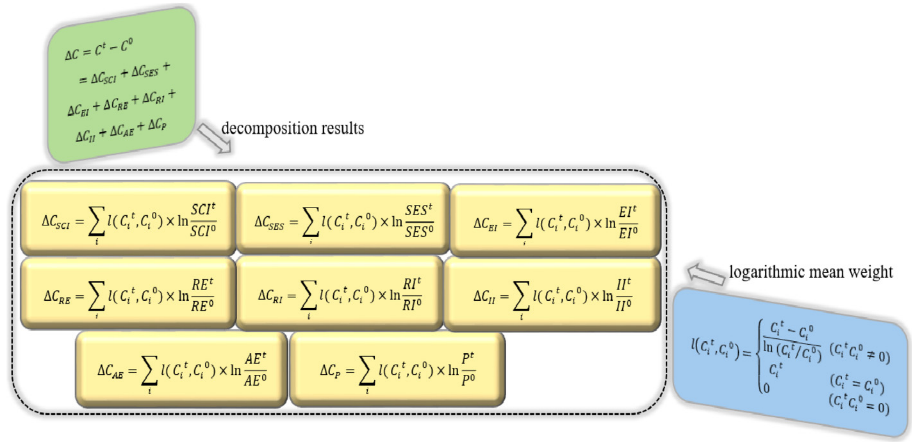

Fig. 2. The flow chart of LMDI additive decomposition method.

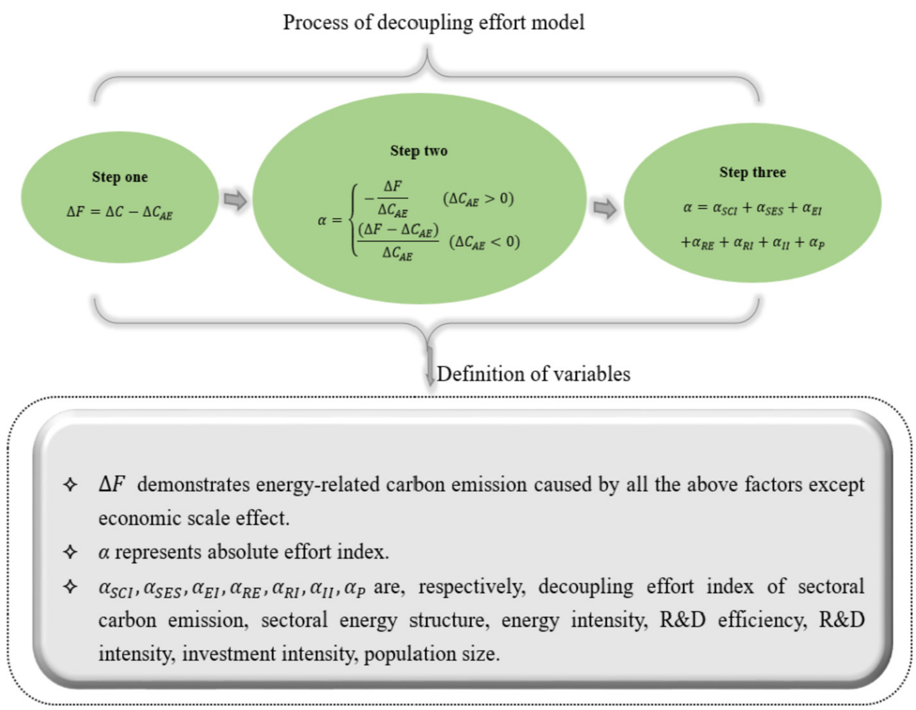

Fig. 3. The flow chart of decoupling effort model.

3.4. Data source

The data set spans from 1997 to 2015, in the light of data limit in R&D expenditure, and refers to four sectors (residence, industry, transportation and commerce). The GDP and fixed asset investment data are collected from Bureau of Economic Analysis (BEA, 2019). Btu of energy consumption and energy-related carbon emission data are collected from Energy Information Administration (EIA, 2019). Data of population comes from US Census Bureau (US Census Bureau, 2019). And data of R&D expenditure comes from World Bank (World Bank, 2019). Among them, data of GDP, fixed asset investment and R&D are converted to 2010 constant dollars.

4. Results and analysis

4.1. Analysis of energy-related carbon emission

4.1.1. Analysis of total energy-related carbon emission

Fig. 4 clearly presents changes of total energy-related carbon emission in the United States. According to Fig. 4, the carbon emission process can be subdivided into two stages: 1997–2007 and 2008–2015. The former stage demonstrated an upward trend with an average annual growth rate of 0.73%. The total energy-related carbon emission reached a peak of 6006 Mt (million ton) in 2007. As for the latter stage, it demonstrated a sharp downward trend with an average annual growth rate of-1.39%. The decline was especially remarkable in 2008–2009, with a decrease of 419 Mt. As

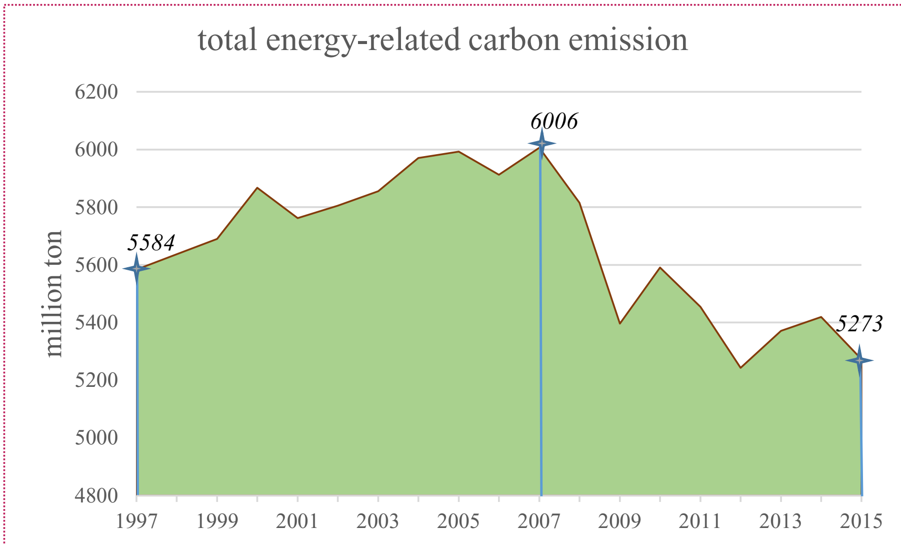

Fig. 4. Total energy-related carbon emission of the United States.

a whole, the total energy-related carbon emission decreased from 5584 Mt in 1997 to 5273 Mt in 2015, decreasing by 5.57%. Total energy-related carbon emission has been virtually controlled, at the same time maintaining economy growing. As an important developed country, achieving carbon reduction is with enormous significance for global environment protection (See. Fig. 4).

4.1.2. Analysis of sectoral energy-related carbon emission

In addition, how does energy-related carbon emission change in specific sector? Deeply investigating changes in sector level will do a favor for specific carbon-reduction policy-making. Sectoral energy-related carbon emission can be also divided into two stages: 1997–2007 and 2008–2015. From 1997 to 2007, energy-related carbon emission in residence, transportation and commerce sector all increased for almost years, with an average annual growth rate of 1.31%, 1.49% and 1.53% respectively. As for industry, it usually decreased with an average annual growth rate of -0.9%. From 2008 to 2015, energy-related carbon emission in residence, transportation and commerce sector started to decrease. Regarding to average annual growth rate of these three sectors, residence sector took the lead, which was -2.45%, followed by commerce sector of -2.02% and transportation sector of -0.38%. Industry continued to decrease, but the average annual growth rate was -1.41%, which was larger than that of 1997–2007 stage (see Fig. 5).

Overall, residence and industry sector contributed to an decrease of energy-related carbon emission, while transportation and commerce sector contributed to a increase. Commerce and residence sector haven't changed a lot from 1997 to 2015 regarding to energy-related carbon emission, the former increased by 6 Mt, the latter decreased by 53 Mt. More importantly, industry sector was primary carbon reducer, with continuing decrease trend during study period. The energy-related carbon emission decreased by 368 Mt overall, dropping by 20.18%. Especially, due to global economic crisis, the energy-related carbon emission dropped drastically during 2008–2009, decreasing by 208 Mt. In addition, as the most dominant sector to the decrease of energy-related carbon emission, industry sector contributed 118.33% to total energy-related carbon emission decrease. Transportation sector was primary carbon increaser, with a contribution of 104 Mt and contributing −33.44% to total energy-related carbon emission decrease. The glowing fossil energy demand may account for the contribution of transportation sector. With living standard improving day by day, private car ownership and driving distance also increase, which may cause energy-related carbon emission from transportation sector drastically increase. As a result, transportation sector gradually became the largest carbon emitter among the four studied sectors.

4.2. Analysis of factors driving energy-related carbon emission

As shown in Fig. 6, overall, R&D efficiency, R&D intensity, energy intensity and sectoral carbon emission contributed to a decrease of energy-related carbon emission, while economic scale, investment intensity, population size and sectoral energy structure contributed to an increase of energy-related carbon emission.

Energy intensity was seen to be the largest inhibitor of energy-related carbon emission, with a contribution rate of 1310% to total energy-related carbon emission decrease. Energy intensity caused energy-related carbon emission decrease during the whole study period, especially from 1997 to 2006, decreasing by 275 Mt per year. Through the speed of energy-related carbon emission decrease has been slowed down since 2007, it still caused energy-related carbon emission decrease by average 177 Mt per year. It resulted in a decrease of 4075 Mt overall. The above indicated that energy intensity has improved a lot, causing energy-related carbon emission obviously decrease from 1997 to 2015. Increasing R&D expenditure will partly conductive to evolve energy-saving technologies and cleaner development pattern, which will lead to less energy use per unit of economic out, signifying constant energy efficiency improvement, which confirming the study of Shao et al. (2016). Consequently, energy intensity also continuously change and has different influence to carbon emission. However, energy intensity is not fully and effectively drive carbon emission decrease and the influence is not stable yet, which indicating energy intensity has great potential to carbon reduction. Therefore, priority still shall be given to improving energy intensity.

This was followed by R&D intensity and R&D efficiency, which contributed to a decrease of energy-related carbon emission by 289% and 231%, respectively. Actually, the effect of R&D really takes a few months or even a couple of years to appear, so the influence of R&D on carbon emission is quite difficult to quantify. R&D intensity was represented by the share of R&D in investment and R&D efficiency was transformation of economic output per unit of R&D

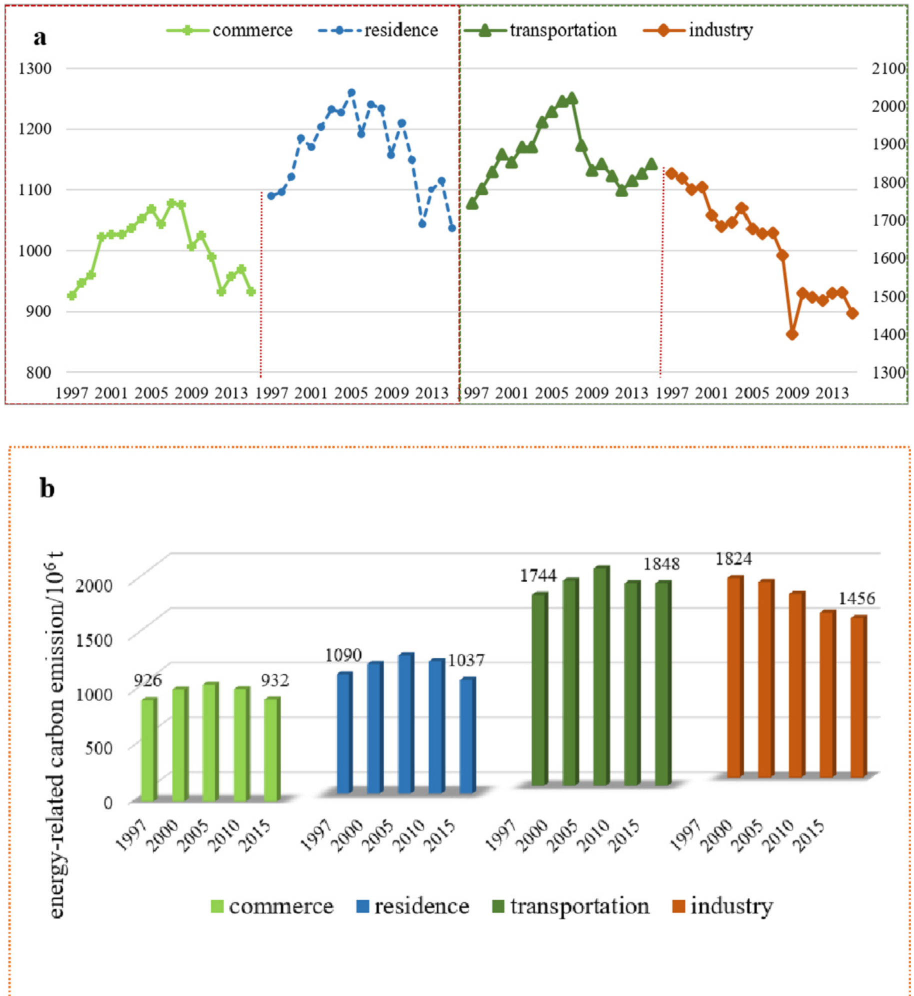

Fig. 5. Sectoral energy-related carbon emission of the United States.

expenditure. As shown in Fig. 6, R&D intensity led energy-related carbon emission decrease in most of years, decreasing by 899 Mt over the whole study period. R&D efficiency also drove energy-related carbon emission decrease, with a reduction of 719 Mt overall. Particularly, R&D intensity increased energy-related carbon emission by 1437 Mt in 2006–2009, R&D efficiency decreased in 2009–2010 and 2011–2012. The global economic crisis in 2008 may be responsible. Before and after economic crisis, in order to strengthen economy, more R&D expenditure was used to expand production scale during 2006–2009. The impact of R&D efficiency confirmed our explanation, which increased by 614 Mt then the R&D expenditure may gradually change to develop carbon-reduction policies. It was clear that allocation of R&D expenditure was gradually improved, which was more spent on innovation and application of energy-saving and carbon-reduction technologies, rather than expansion of production scale. In the future, efforts shall be made to continue optimize R&D expenditure allocation.

After the above three factors, sectoral carbon intensity also promoted energy-related carbon emission decrease. It totally decreased by 731.63 Mt, but it was sped up to decrease energy-related carbon emission since 2007, with a speed of 67 Mt per year.

Economic scale was the main contributor to energy-related carbon emission, which is in line with Vinuya's work (Vinuya et al., 2010). It drove energy-related carbon emission increase by 3317 Mt overall in 1997–2015 (except 2008–2009 due to the influence of economic crisis), with an average speed of 184 Mt per year and a contribution rate of -1066%. However, the energy-related carbon emission drove by economic scale was progressively decreasing since 2007. It exhibited that economic production was still primary contributor to energy-related carbon emission, but economic production gradually got rid of heavy dependence on energy consumption and energy-related carbon emission drove by economic scale gradually slowed down.

Investment intensity was the second largest contributor to energy-related carbon emission, increased by 1618 Mt overall. Investment intensity drove energy-related carbon emission decrease in 2000–2002 and 2006–2009. For the rest years, it drove energy-related carbon emission increase by 2695 Mt overall. Investment intensity obviously drove energy-related carbon emission drastically increase, reflecting that allocation of investment expenditure was not reasonable enough, more spent on expansion of economic scale, Hence, in the future construction of low-carbon economy, allocation of investment expenditure needs to be further optimized.

Population size positively drove energy-related carbon emission increase in 1997–2015, increasing by 931 Mt. It denoted that energy consumption increased with population size increasing, therefore energy-related carbon emission increased with population size increasing. Consequently, measures on controlling population size or energy consumption per capita shall be effective to

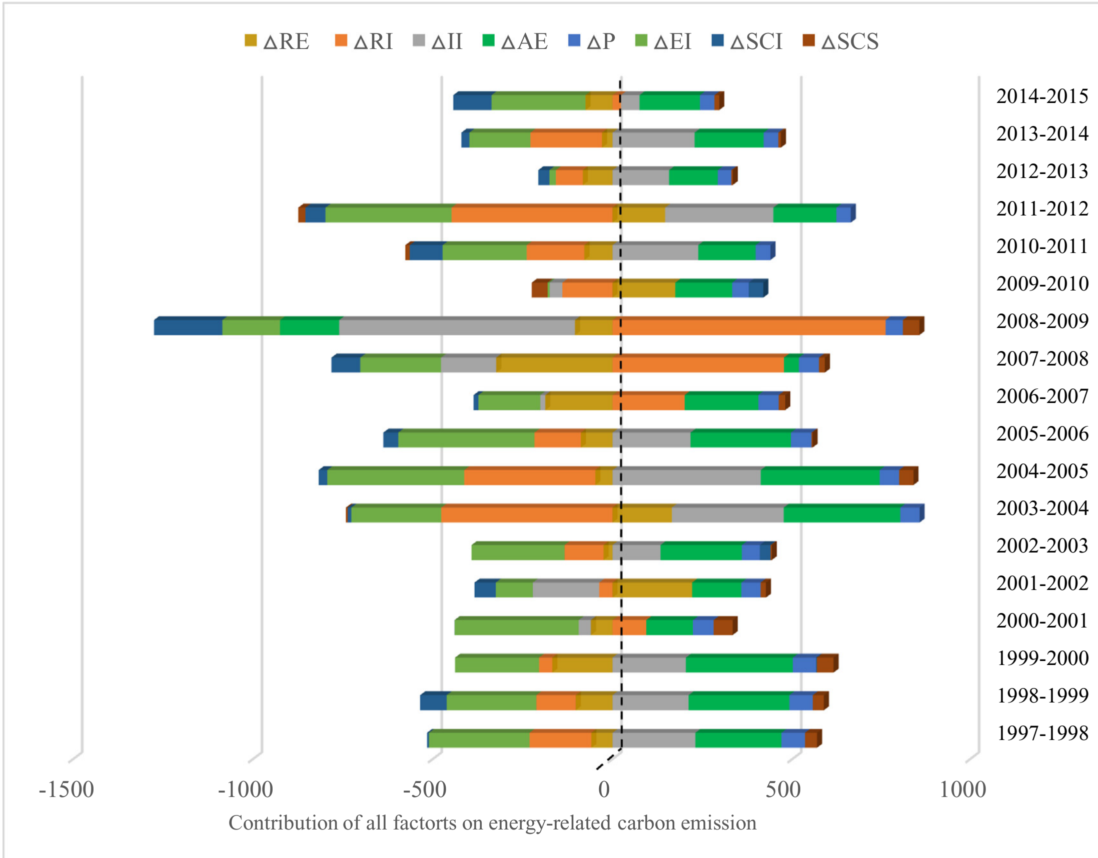

Fig. 6. Figure of all decomposed factors' impact on energy-related carbon emission.

curb energy-related carbon emission drove by population size. As for sectoral energy structure, it only had minor impact on energy-related carbon emission, contributed to an increase of 248 Mt.

4.3. Analysis of decoupling effort

4.3.1. Identifying decoupling states

As clearly depicted in Fig. 7, the decoupling index can be subdivided into two time period: 1997–2007 and 2008–2015. In the first time period, decoupling index usually between 0 and 0.8, in a weak decoupling state. Before 2007, only decoupling index in 2000–2001 and 2005–2006 appeared as negative value. It indicated that when economy growing, so did carbon emission. While during 2008–2015, decoupling index drastically changed. Carbon emission started to decline since 2007, therefore, the year 2008 immediately presented strong decoupling. Due to the global economic crisis, decoupling state was not ideal enough, in recessive decoupling in 2008–2009 and expansive coupling in 2009–2010. For the following years, decoupling state gradually improved and appeared a trend of strong decoupling (See. Fig. 7).

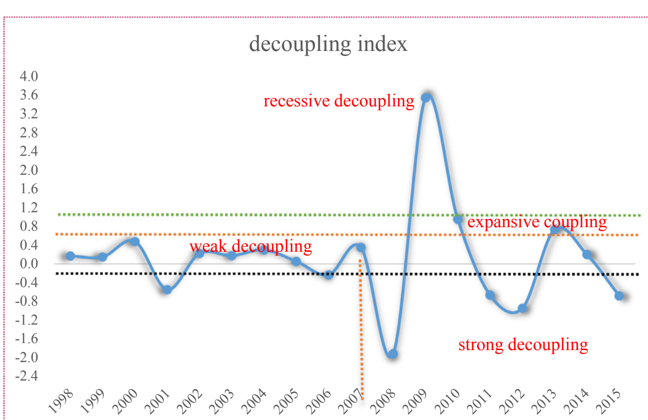

Fig. 7. Decoupling index of the United States.

4.3.2. Analysis of decoupling effort

Due to the economic crisis, the decoupling effort index in 2007–2009 was significantly larger or smaller than the rest year, causing the peak of decoupling effort index appearing in 2007–2008.

As highlighted in Table 2, during 2009–2010, the absolute decoupling index was −0.2323, less than 0, in a no decoupling effort state, the rest years has always made efforts for achieving decoupling, presenting a strong effort state overall. Obviously, the absolute decoupling effort index reached the peak in 2007–2008, which was 5.5863, in a strong decoupling effort state, indicating that decoupling effort policies has made significant influence on achieving decoupling.

From the table, the decoupling effort index of energy intensity had all greater than 0, and the number of year in strong decoupling effort state is larger than the number of year in weak decoupling effort state. The decoupling effort index of energy intensity nearly maintained stable around 1.01, except 2007–2008 (which reached the high value of 5.39). Overall, it can be seen that energy intensity presented a strong decoupling effort state.

As for R&D intensity, the decoupling effort index was worst in

Table 2
Decupling effort index of all influencing factors.

year	αRE	αRI	αII	αP	αEI	αSCI	αSES
1997–1998	0.2456	0.7168	−0.9624	−0.2732	1.1693	0.0215	−0.1390
1998–1999	0.3640	0.3909	−0.7549	−0.2320	0.8896	0.2630	−0.1097
1999–2000	0.5629	0.1228	−0.6857	−0.2162	0.7855	−0.0085	−0.1560
2000–2001	0.4614	−0.7214	0.2600	−0.4429	2.6547	0.0024	−0.4061
2001–2002	−1.6179	0.2678	1.3501	−0.3921	0.7530	0.4326	−0.1077
2002–2003	0.1088	0.4797	−0.5884	−0.2213	1.1424	−0.1317	−0.0146
2003–2004	−0.5073	1.4630	−0.9556	−0.1682	0.7681	0.0310	0.0157
2004–2005	0.1442	1.1001	−1.2443	−0.1665	1.1504	0.0723	−0.1226
2005–2006	0.3136	0.4625	−0.7761	−0.2054	1.3556	0.1489	−0.0090
2006–2007	0.9116	−0.9794	0.0677	−0.2766	0.8393	0.0662	−0.0877
2007–2008	7.7617	−11.4452	3.6835	−1.3422	5.3920	1.9261	−0.3897
2008–2009	0.6328	−4.6219	3.9891	−0.2987	0.9757	1.1565	−0.2851
2009–2010	−1.1034	0.8800	0.2235	−0.2892	0.0360	−0.2567	0.2777
2010–2011	0.4889	1.0048	−1.4937	−0.2570	1.4650	0.5733	0.0772
2011–2012	−0.8355	2.5551	−1.7196	−0.2294	2.0023	0.3178	0.1144
2012–2013	0.6070	0.5525	−1.1596	−0.2785	0.1334	0.2275	−0.0268
2013–2014	0.1506	1.0363	−1.1868	−0.2111	0.8825	0.1162	−0.0373
2014–2015	0.4462	−0.1402	−0.3060	−0.2404	1.5543	0.6329	−0.0780

2007–2008, which was −11.45 in a no decoupling effort state. As a whole, the decoupling effort state switched from weak decoupling effort state (1997–2006) to no decoupling effort state (2007–2009), then switched to strong decoupling effort state (2010–2015), indicating R&D intensity has gradually made effective effort for achieving decoupling. The decoupling effort index of R&D efficiency presented an “inversed V-shape”, the highest point appeared in 2007–2008, which was the value of 7.76, in a no decoupling effort state. Overall, it still made effort to achieve decoupling, though the effectiveness was not significant enough.

The decoupling effort index of sectoral carbon intensity was less than 0, in a no decoupling effort state in 1999–2000, 2002–2003 and 2009–2010, greater than 1, in a strong decoupling effort stated in 2007–2009, for the rest year, the decoupling effort index was greater than 0 and less than 1, in a weak decoupling state. In general, it was in a weak decoupling effort state, making effort to achieving decoupling. From the effectiveness of decoupling effort, it can rank the third, just after energy intensity and R&D intensity.

The decoupling effort indexes of investment intensity, population size and sectoral energy structure were less than 0 in almost year, in a no decoupling effort state. Among the three factors, investment intensity was smallest, with average value of −0.62 (except 2007–2009), followed by population size and sectoral energy structure. For population size, the decoupling effort index was stable at −0.32 (except the smallest value of −1.34 in 2007–2008). It indicated that population size stably did not promote decoupling, causing energy-related carbon emission increase. Though sectoral energy structure was in a no decoupling effort state, the decoupling effort index was relatively small, with an average value of −0.08. Properly adjust sectoral structure in energy will effectively curb energy-related carbon emission, so as to positively promote decoupling.

4.4. Discussion

When it comes to energy-related carbon emission, it is easy to see that industry sector has effectively curb energy-related carbon emission, residence sector was gradually switching to carbon-reduction sector. However, transportation and commerce sector still resulted in considerable energy-related carbon emission, especially transportation sector. Consequently, the United States should make it a priority to curb considerable energy-related carbon emission in transportation and commerce sector, especially transportation sector.

With respect to three technological factors, from the perspective of cumulative effect, energy-related carbon emission increased by investment intensity was roughly offset by R&D intensity and R&D efficiency. It uncovered that R&D intensity and R&D efficiency effect, and investment intensity effect reached a dynamic equilibrium, where technology roughly neither increases nor decreases energy-related carbon emission. In order to break the dynamic equilibrium and promote carbon-reduction, the investment expenditure should be better allocated by reducing expenditure on economic scale expansion. As for decoupling efforts, though effectiveness of R&D efficiency was not significant yet, R&D intensity gradually made efforts to promote decoupling. While investment intensity did not make efforts at all. Therefore, in the future development of low-carbon economy, considerable efforts should be made to mitigate the impact of investment intensity on energy-related carbon emission and decoupling.

No surprisingly, energy intensity contributes the most to the decrease of energy-related carbon emission and economic scale contributes the most to an increase, which in line with some previous studies (Ren et al., 2014; Wang et al., 2018b; Zhang, Y.-J. and Da, Y.-B., 2015). In addition, energy intensity was roughly in a strong decoupling effort state, demonstrating that energy intensity was the main effort-maker for achieving decoupling energy-related carbon emission from economic decoupling in the United States. Population size and sectoral energy structure were in a no decoupling effort state.

5. Conclusion and policy implications

To better understanding driving factors behind energy-related carbon emission and effectiveness of decoupling effort of the United States, this work developed a decomposition analysis to investigate driving factors behind energy-related carbon emission, with the use of extended kaya identity and LMDI decomposition method. Then, we went a step forward to assess effectiveness of decoupling effort on achieving decoupling through decoupling effort model. The main results were listed as follow:

(i) The total energy-related carbon emission decreased since 2007 in the United States, achieving real decoupling, which is different from most countries in the world. The energy-related carbon emission in residence and industry decreased with time going by, but increased in transport and commerce. To our surprise, since 1999, energy-related carbon emission in transport exceeded industry, becoming the largest energy-related carbon emitter.

(ii) Economic scale was seen to be the main inhibitor, while energy intensity was the main contributor to energy-related carbon emission decrease. R&D intensity, R&D efficiency and sectoral carbon intensity all played a positive role in reducing energy-related carbon emission. Investment intensity ranked after economic scale, which was the second largest inhibitor to energy-related carbon emission decrease. Population size ranked after investment intensity, also had a significant negative impact on energy-related carbon emission decrease. Sectoral energy structure played a minor but negative role in decrease of energy-related carbon emission.

(iii) Generally, the decoupling effort index of the United States was roughly greater than 1, in a strong decoupling effort state. It indicated that the Unites States have made considerable effort and carbon-reduction policies well functioned. Among all effects, energy intensity was primary effort-maker to achieving decoupling. It was in a strong decoupling effort state in most years. While energy intensity still had potential to be improved, more efforts should be made. R&D intensity, R&D efficiency and sectoral carbon intensity also undertook effort to achieve decoupling, but they were in a weak decoupling state overall, their effectiveness was seen to be not significant yet.

(iv) The energy-related carbon emission caused by R&D intensity and R&D efficiency effect, and by investment intensity effect were mutually offset. In the following carbon-reduction work, priority shall be given to optimize investment allocation, at the same time, try to further optimize R&D expenditure. In this way, technological factors will make positive impacts on energy-related carbon emission reduction.

Based on the above conclusions, the following policy implications were put forward to further reduce energy-related carbon emission and promote decoupling energy-related carbon emission from economic development.

(a) Differentiated policies and measures shall be formulated and enacted for the four sectors. As the largest carbon emitter, considerable efforts should be made to reduce carbon emission in transportation sector, promoting the use of new-energy vehicle, which will result in less carbon emission, improving transportation infrastructure and or so. As for industry and residence sector, energy-related carbon reduced during study period, indicating policies of carbon-reducing was effective. Hence, it is necessary to carry on the previous policies and encourage new effective policies to be applied.

(b) The way of economic development shall be shifted to less dependence on energy consumption. Economic scale was the primary inhibitor to carbon emission reduction, indicating that economic development of the United States was still heavily depended on energy consumption. Thus, one of effective way to reduce carbon emission was reducing its dependence on energy consumption, continuously improving energy intensity, switching to clean and renewable energy, e.g, solar, wind, nuclear and so on.

(c) More attention shall be paid to rational allocation of investment and R&D expenditure. Through above discussion, it can be seen that R&D expenditure was more spent on innovation and application on energy-saving and carbon-reduction technologies, whereas, investment expenditure was more spent on expansion of production scale. For the purpose of carbon emission reduction, it was urgent to turn investment expenditure into developing energy-saving and carbon-reduction technologies. Meanwhile, continuing to improve R&D efficiency and R&D intensity should also be put on agenda.

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