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Investigating effect of R&D investment on decoupling environmental pressure from economic growth in the global top six carbon dioxide emitters

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HIGHLIGHTS

• The effects of R&D on reduce in environmental pressures were analyzed.
• Effects of R&D efficiency and per capita R&D expenditure were investigated.
• Combination method was used to uncover the impact mechanism of the decoupling.
• Improving technological progress should be priority.

GRAPHICAL ABSTRACT

ABSTRACT

This work is aimed to investigate the effect of research and development (R&D) on reduce in environmental pressures through an empirical analysis of the top six global carbon emitters (the C6: China, USA, India, Russia, Japan, and Germany). This work is valuable toward carbon reduction within C6 countries and the world (C6 emit roughly 60% of the global carbon emissions). Moreover, it is also meaningful for exploring the decoupling of economic development from carbon emissions in other areas (both developing and developed countries). The main findings displayed that the decoupling status in developed countries (i.e., USA, Japan, and Germany) were better and more stable than in developing countries (i.e., China, India, and Russia). Germany performed best among the developed countries, and China performed most stable among the developing countries. The effect of the per capita R&D expenditure was main resistance to decoupling carbon emissions from economic development in C6 countries. However, the energy intensity effect and R&D efficiency effect related to technological progress were the main driving forces for the decoupling process. Consequently, this study proposes that the improvement of technological progress should be prioritized.

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1. Introduction

In recent years, the greenhouse effect mainly caused by greenhouse gas emissions has continued to accumulate (Wang and Su, 2020), further leading to rising temperatures and global warming, which has caused widespread concern in the international community (Mora et al., 2018; Steiner et al., 2018). The 2015 Paris Agreement clearly stated a globally pursued goal, i.e., all parties will strengthen their capacity to address climate change challenges, command the increase of energy demand is caused by economic growth (Wang et al., 2019b). Therefore, the current global dilemma of emissions reduction originates from the desire of global countries to achieve economic development.

The coordinated development of both economic increase and carbon emissions has become an important prerequisite for the successful realization of the stipulated global carbon emission reduction goals. The reason for this is that no country will perform its emission reduction responsibilities as scheduled if this requires the undermining of economic growth (Wang et al., 2019a). Therefore, decoupling both has received worldwide attention and is typically referred to as an important theory that enables the coordination between economic development and environmental damage reduction (OECD, 2002). Furthermore, decoupling has been proposed as policy objective by many countries and international organizations (OECD, 2002; UNEP, 2011). The top six CO₂ emitters (C6) China, USA, India, Russia, Japan, and Germany cause 60.42% of the global CO₂ emissions (BP, 2019). Moreover, C6 countries achieve 52.44% of the global economic output (The World Bank, 2017).

Due to the important status of C6 countries within the global economy and with regard to global carbon emissions in particular, exploring the trends for the decoupling of economic development from CO₂ emissions, and the understanding of the driving forces behind this decoupling have significant implications not only for C6 countries but also for other countries in the world. The contribution of this study mainly lies in the following three aspects:

• In view of the important status of top six CO₂ emitters in the global economy and global carbon emissions, but lack of research, this paper utilizes the series of decoupling analysis to explore the decoupling states and driving forces behind the decoupling to make up for this vacancy.
• As for exploring the driving factors of decoupling elasticity, this paper combines the extended factor decomposition method and the Tapio decoupling model to find out the mechanism by which the driving factors act on the decoupling states.
• In view of the important role of research and development in reducing carbon emissions and further achieving decoupling, this paper incorporates R&D efficiency effect and per capita R&D expenditure effect into the drivers of carbon emissions, and quantifies the extent of their impact on decoupling of carbon emissions from economy by extending the Kaya formula.

The organization of the rest of this paper is below: Section 2 reviews the literature related to decoupling theory. Section 3 presents data source and model approach which includes decoupling index and decomposition model. Section 4 introduces the main decoupling and decomposition results. Conclusions and policy recommendations are presented in Section 5.

2. Literature review

2.1. Literature review on the development of decoupling method

2.1.1. Literature review on the development of decoupling method

Decoupling can expose the relationship between global or individual environmental pollution and economic development, can be used to indicate asynchronous changes in environmental pollution and economic growth. Such decoupling can achieve low-carbon development at a quantitative level, and was first utilized in the environmental field by Zhang in 2000 (Zhang, 2000). In 2002, the OECD first proposed the concept of decoupling indicators and began a quantitative analysis of decoupling (OECD, 2002). Immediately thereafter, Juknys expanded the decoupling indicators in the OECD decoupling model (Juknys, 2003), and Vehmas et al. established a comprehensive decoupling framework in 2003 (Vehmas et al., 2003a; Vehmas et al., 2003b). Based on this development of decoupling research, Tapio first proposed decoupling elasticity and expanded the decoupling index to 8 categories in 2005 (Tapio, 2005). In 2007, Diakoulaki and Mandaraka established a decoupling effort model, which is based on the Tapio decoupling model and refined Laspeyres model (Diakoulaki and Mandaraka, 2007). The continuous improvement of decoupling by many scholars has promoted its application at an unprecedented level.

2.1.2. Literature review on the application of decoupling method

Most decoupling studies focused on a single region, including the national level (García-Gusano et al., 2018; Martinico-Perez et al., 2018; Román-Collado et al., 2018; Wang et al., 2019a), the provincial level (Hu et al., 2019; Siping et al., 2019; Zhao and Li, 2018), and the level of a specific city (Rao and Yang, 2018; Su et al., 2019; Wang and Zhou, 2019). Zhao et al. (2017) investigated the decoupling of the economic development from China’s CO₂ emissions by applying Tapio’s decoupling model. The findings showed that China achieved only weak decoupling from 1992 to 2012. The effects of energy intensity and economic output played the most significant role for decoupling process. Román-Collado et al. (2018) developed a two-level decomposition analysis to investigate Colombia’s decoupling between economy and energy consumption during 2000–2015. The results identified strong decoupling between 2000 and 2007 (but not after 2008, due to the intensity effect). Chen et al. (2017) employed the Tapio decoupling method to assess the connection between Macau’s greenhouse gas emissions and its economy, and showed that Macau’s economy has a clear decoupling trend and can be characterized by weak decoupling. Roinioti and Koroneos (2017) applied the decoupling effort method to assess the progress of decoupling carbon emissions from economy in Greece. The main findings displayed that a weak decoupling effect was achieved frequently, and only a few years had no decoupling effect. Yang et al. (2018) employed Tapio decoupling model to investigate the decoupling index of China’s industrial output and carbon emissions. Their findings displayed that the decoupling of the manufacturing sector was best within the industrial sectors. Engo (2018) evaluated the decoupling status between Cameroon’s economy and its carbon emissions from 1990 to 2015 by applying Tapio decoupling model. Engo found that Cameroon experienced weak decoupling during the entire research time. Wang and Jiang (2019) found that the decoupling between China’s economy and carbon emissions is mainly characterized by expansive negative decoupling and weak decoupling. Given that Australia is among the top ten greenhouse gas emitters, Leal et al. (2019) used the Tapio decoupling method to study the connection between carbon emissions and economy in various Australian sectors between 1990 and 2015. They found that agricultural and commercial
services showed strong decoupling, while other sectors showed weak decoupling. Yu et al. (2017) used Chongqing as an example to explore the decoupling between economic development and six environmental pollution indicators by using the OECD decoupling model. The reported results showed that SO2 emissions, soot, and waste water showed absolute decoupling, while energy consumption, carbon emissions, and solid waste showed relative decoupling during 1999–2010. Technological changes played the greatest role to cause decoupling of all environmental pollution indicators while the economic structure played only a very small positive or negative decoupling effect.

Decoupling studies on specific regions are typically very detailed, while comparative decoupling studies that investigate multiple regions are rare (Shuai et al., 2019; Wu et al., 2019). Wang et al. (2018b) compared the decoupling of carbon emissions and economy between the United States and China between 2000 and 2014. The main findings revealed that the United States mainly experienced weak decoupling and strong decoupling, and China was mainly characterized by expansive coupling and weak decoupling. Vavrek and Chovancova (2016) found that V4 countries generally experienced strong decoupling, indicating that greenhouse gas emissions have decreased while economic growth has been retained. Luo et al. (2017) studied the decoupling of CO2 emissions of 30 Chinese provinces using their agricultural output during 1997–2014. The results indicated that East China had strong decoupling states. Madalenbo and Moutinho (2018) used countries of the EU-15 group as research object, and utilized both the Tapio decoupling method and the LMDI method. They developed a decoupling effort index to estimate the impact of specific drivers on the decoupling index between carbon emissions and economic growth. Zhou et al. (2017) compared the decoupling of economic development and industrial carbon emissions of 8 regions in China during 1996–2012. The reported results identified weak decoupling in most regions. Wu et al. (2018) discussed the decoupling between economic development and CO2 emissions of representative developed and developing countries. Their results identified strong decoupling in developed countries, while developing countries demonstrated weak decoupling. By comparing the relationship between India and China's carbon emissions and economic growth, Wang et al. (2018a) found that China's decoupling status is dominated by weak decoupling, while India's volatility is large.

The existing research shows that whether a single region or multiple regions are investigated, the Tapio decoupling model is the best choice for many scholars (Karakaya et al., 2019; Wenbo and Yan, 2018). When the connection between carbon emissions and economy is investigated, scholars generally focus on a single region, and comparative analysis of multiple regions is rare. Moreover, when analyzing multiple regions, many scholars conduct comparative analysis mainly based on location or economic relationships, while few scholars focus on a country's carbon emissions rank in the world. However, the top six countries with regard to carbon emissions are the major contributors to the global carbon emissions; therefore, the realization of low-carbon economic development in the C6 countries is critical toward achieving global carbon emissions targets.

2.2. Literature review on factor decomposition

2.2.1. Literature review on the development of factor decomposition

Decoupling analysis can determine the connection between carbon emissions and economy in these C6 countries. However, decoupling carbon emissions from the economy requires a further exploration of the mechanisms underlying decoupling. In general, the drivers for environmental changes are identified using decomposition analysis. Structural decomposition analysis (SDA) and index decomposition analysis (IDA) are the main components of the decomposition method. (De Oliveira-De Jesus, 2019; Yu et al., 2019). SDA has developed into a mainstream economic analysis tool in the field of input-output technology, but the application of this method needs to be built on the input-output table (Wang and Wang, 2020). Therefore, the lack of input-output table hinders the further promotion of the SDA method (Wang and Jiang, 2020).

On the contrary, the IDA method is widely used, and there are many derivative methods (Hoekstra and van den Bergh, 2003). Among the derivative methods of IDA method, the most common methods can be divided into Laspeyres decomposition method and the Divisia decomposition method (Lyu et al., 2016). The Laspeyres decomposition method can explore the percentage change of various factors during the study period. Because this method is easy to explain the results, it has been applied by institutions and scholars (Mason and Burney, 2017). However, the decomposition results of the Laspeyres decomposition method have residual errors, and complex formulas are needed to solve the residual errors (Ang, 2004). The Divisia decomposition method is based on the logarithmic change to study the change of the weight of each factor in the total amount, which was applied to the energy decomposition by Boyd in 1987 (Boyd et al., 1987). Then, the Divisia decomposition method has been extended and improved by other scholars (Ang, 2005; Ang and Choi, 1997; Ang and Zhang, 2000). Among them, because the LMDI decomposition method is simple to calculate and has no residual error, it has become the factor decomposition method preferred by many scholars (Li et al., 2019; Ma et al., 2019).

2.2.2. Literature review on the application of factor decomposition

Based on the LMDI decomposition method, many scholars have focused on the driving forces that under carbon emissions (Inglesi-Lotz, 2018; Román-Colgado and Morales-Carrión, 2018; Moutinho et al., 2018) studied the top 23 countries, ranked by their renewable energy consumption, and explored the drivers affecting carbon emissions using LMDI method. These were financial development, fossil fuels intensity, renewable source productivity, trading of fossil fuels, carbon trade intensity, and electricity financial power. Chong et al. (2019) decomposed Malaysia’s carbon emissions into six major drivers with a specific focus on measuring the role of technology drivers. The results showed that the effects of technology drivers on carbon emission increased. Li et al. (2018) utilized the LMDI method to decompose Kazakhstan’s energy-related carbon emissions into the following effects: economic active, population, energy intensity, and energy CO2 structure. They found economic and population growth promoted the growth of carbon emissions, while energy intensity and energy CO2 structure effect suppressed carbon emission growth. Fatima et al. (2019) studied the main influencing factors industrial carbon emissions in China by applying the LMDI method. Income effect and labor effect were identified as the two largest contributors to promoting carbon emissions. Energy intensity and carbon emission coefficient were identified as two major factors that suppress carbon emissions. Pourebadorlavan Covich et al. (2018) quantified the effects of activity, structure, energy intensity, fuel mix, and emission factors for carbon emissions of the manufacturing sector in East Azerbaijan. The results showed that activity levels and emission factors exerted an active role for carbon emission growth. Gu et al. (2019) employed LMDI method and the system dynamics method to estimate the impact of several new drivers on Shanghai’s carbon emissions. They found that the promotion of public transportation and the optimization of the power generation structure would help to reduce Shanghai’s carbon emissions. Daldoul and Dakhlouai (2018) assessed the impact of energy efficiency, as well as the structure and development level of the transport sector on the carbon emissions in the Tunisian transport industry. The findings displayed that the rapid increase in carbon emissions was caused by the improvement of the level of transport development. Applying the LMDI method, Chontanawat et al. (2019) showed that changes in the economic structure are conducive to reducing carbon emissions and carbon intensity in the Thai industrial sector; however, energy intensity has led to an increase in both. Akbostanci et al. (2018) investigated the impact drivers of carbon emissions for Turkey’s five major sectors, and identified economic activity and energy intensity as decisive factors for carbon emissions. Reviewing the above literature indicates that scholars from
various countries have used the LMDI model to decompose and analyze the carbon emissions of different research objects. In general, economic activity and energy intensity were identified as key drivers.

Carbon emission reduction is a common global goal, which has led scholars to extensively study the mechanism underlying the growth of carbon emissions (Mousavi et al., 2017; Moutinho et al., 2015). However, due to the special connection between carbon emissions and economic growth, we cannot blindly trigger an economic downturn just to reduce carbon emissions. However, due to the special connection between carbon emissions and economy, economic decline cannot be blindly triggered simply to achieve carbon emission reduction. Therefore, it is even more important to achieve between decoupling carbon emissions and economy by exploring the mechanism that impact the relationship between both (Meng et al., 2018). Zhao et al. (2016) introduced the decomposition results of the LMDI method to Tapio decoupling model, and focused on measuring the impacts of investment scale, investment share, and investment efficiency on decoupling of industrial carbon emissions in China. They identified investment scale as an important factor that inhibited the decoupling process. Wang et al. (2018b) employed the LMDI method and the Tapio decoupling model to compare the decoupling state and driving factors of decoupling state between China and the United States. They found that both the economy and population limited the decoupling process. Zhao et al. (2017) identified the influencing factors of carbon emissions in China, and measured the effect of every driver on the decoupling of economic growth from carbon emissions in China. The main findings identified energy intensity and economy as the most significant drivers that affect economic decoupling in China. Investigations of the influencing factors of decoupling indicators are fewer than investigations of the influencing factors of carbon emissions. In addition, the influencing factors of decoupling indicators are not much different from the influencing factors of carbon emissions, since they are usually carbon intensity, energy structure, energy intensity, economic growth, and population.

Many scholars have explored the determinants of carbon emissions and reported that technological progress reduced environmental degradation (Petrović and Lobanov, 2019). Therefore, many countries often seek to curb their carbon emissions by improving technological progress, which results in increasing R&D expenditures in various countries. Fernández et al. (2018) and Awaworyi Churchill et al. (2019) analyzed the impact of R&D expenditures on carbon emissions; however, the impact of R&D expenditures on the decoupling of carbon emissions from economy has rarely been investigated. With regard to the importance of R&D expenditure toward carbon emission reduction, this paper focused on the impact of both the efficiency and scale of R&D on the decoupling process of carbon emissions and economic growth in C6 countries.

To realize the global carbon emission reduction target, this paper targets the C6 countries, which occupy an important position with regard to economy and carbon emissions. The decoupling process and its driving factors are explored in the C6 countries. First, the Tapio decoupling model was used to analyze the decoupling state of carbon emissions and economic growth in C6 countries, and to further clarify the connection between carbon emissions and economy; secondly, the Kaya formula is extended, mainly considering the R&D efficiency and R&D scale as driving factors of carbon emissions; finally, the Tapio decoupling method and the LMDI model were combined to quantify the specific impact of drivers on decoupling carbon emissions from economy.

3. Methodology and data

The methodological flow diagram in this paper is shown in Fig. 1, and the specific method description and derivation are shown in Sections 3.1 and 3.2.

3.1. Decoupling index

According to the study of Tapio (2005), the decoupling index of CO2 emissions from economic output is shown in Eq. (1):

\[ \varepsilon = \frac{\% \Delta C}{% \Delta G} = \frac{\Delta C/C^0}{\Delta G/G^0} \]

Here, \( \% \Delta C \) represents the percentage of CO2 emission changes, \( % \Delta G \) represents the percentage of GDP changes, and \( \Delta \) represents the period between the initial year \( 0 \) and the tail year \( t \). Based on \( \varepsilon \), the Tapio decoupling elasticity provides more detailed decoupling possibilities, which are presented in Table 2.

Three categories of decoupling were identified: decoupling, negative decoupling, and coupling. The decoupling stage can be subdivided into weak decoupling, strong decoupling, and recessive decoupling. The negative decoupling stage can be subdivided into expansive negative decoupling, weak negative decoupling, and strong negative decoupling. The coupling stage is subdivided into expansive coupling and recessive coupling. Under the premise that both economic output and CO2 emissions increase, weak decoupling occurs when the economic output grows faster than CO2 emissions. Under the premise that economic output and weak negative decoupling occurs when CO2 emissions grow faster than economic output. Under the premise that economic output and weak negative decoupling occurs when economic output declines faster than CO2 emissions. Coupling occurs when both economic and CO2 emission change toward the same direction at almost equal rates. Strong decoupling represents the ideal state in a low-carbon economy, where economic growth can be achieved by decreasing CO2 emissions. Strong negative decoupling has the least desirable trait, where CO2 emissions increase despite decreasing economic growth.

3.2. Decomposition model

The CO2 emissions can be decomposed via Eq. (2), following (Kaya, 1990):

\[ C = \sum_{i=1}^{3} C_i = \sum_{i=1}^{3} \left( C_i - C_{i-1} \right) = \sum_{i=1}^{3} \left( \frac{C_i}{E_i} \times \frac{E_i}{G_i} \times \frac{G_i}{R_i} \times \frac{R_i}{P} \right) \times P = EC_i \times EM_i \times EI \times RE \times PR \times P \]

Here, \( i \) represents the energy type \( i = 1 \) represents coal, \( i = 2 \) represents oil and \( i = 3 \) represents natural gas. Table 3 shows the meaning of the symbols in Eq. (2).

According to the additive LMDI model (Ang, 2005), the aggregated CO2 emissions changes, are decomposed into six driving forces as shown in Eq. (3): emission coefficient effect, energy structure effect, energy intensity effect, R&D efficiency effect, per capita R&D expenditure effect, and population effect.

\[ \Delta C = C_t - C_0 = \Delta C_{EC} + \Delta C_{EM} + \Delta C_{EI} + \Delta C_{RE} + \Delta C_{PR} + \Delta C_P \]

The effects of driving forces of CO2 emission changes from period 0 to \( t \) are calculated using Eqs. (4)–(10).

\[ \Delta C_{EC} = \sum_{i=1}^{3} I\left( C_i, C^0 \right) \ln \frac{EC_i}{EC^0} \]

\[ \Delta C_{EM} = \sum_{i=1}^{3} I\left( C_i, C^0 \right) \ln \frac{EM_i}{EM^0} \]

\[ \Delta C_{EI} = \sum_{i=1}^{3} I\left( C_i, C^0 \right) \ln \frac{EI_i}{EI^0} \]
Table 2
The states of Tapio decoupling (Tapio, 2005).

| Decoupling state       | ΔC | ΔG | ε          |
|------------------------|----|----|------------|
| Decoupling             | ≤0 | >0 | 0 < ε < 0.8 |
| Strong decoupling      | >0 | >0 | ε < 0      |
| Negative decoupling    | >0 | <0 | ε > 1.2    |
| Expansive negative decoupling | >0 | <0 | 0 < ε < 0.8 |
| Strong negative decoupling | >0 | <0 | ε < 0     |
| Expansive coupling     | >0 | >0 | 0.8 < ε < 1.2 |
| Recessive coupling     | >0 | >0 | ε < 0.8    |

Table 3
Definitions of variables in Eq. (2).

| Variable | Definition                                      |
|----------|------------------------------------------------|
| C_i      | CO2 emissions arising from the ith energy      |
| E_i      | The ith energy consumption                     |
| E        | Total Energy consumption                       |
| G        | GDP in constant 2010 US$                       |
| R        | R&D expenditure                                |
| EC_i     | Carbon emission coefficient of the ith energy type |
| EM_i     | Energy mix, measured by the ratio of ith energy use to total energy use |
| EI_i     | Energy intensity, measured by the ratio of total energy use to GDP |
| RE       | R&D efficiency                                 |
| PR_i     | Per capita R&D expenditure                     |
| P_i      | Population                                     |

\[
\Delta C = \sum_{i=1}^{3} L(C_i, C_i^0) \ln \frac{P_{i}}{P_{i0}}
\]

\[
\Delta C_{RE} = \sum_{i=1}^{3} L(C_i, C_i^0) \ln \frac{R_{i}}{R_{i0}}
\]

\[
\Delta C_{PR} = \sum_{i=1}^{3} L(C_i, C_i^0) \ln \frac{PR_{i}}{PR_{i0}}
\]

\[
\Delta C_{P} = \sum_{i=1}^{3} L(C_i, C_i^0) \ln \frac{P_{i}}{P_{i0}}
\]

\[
L(C_i, C_i^0) = \frac{C_i - C_i^0}{\ln C_i - \ln C_i^0} \quad \text{or} \quad C_i^0, C_i = C_i^0
\]

Inputting Eq. (3) into Eq. (1) yields the decoupling index ε as expressed in Eq. (11). Six factors affect the decoupling elasticity: ε_{ec} for carbon emission coefficient, ε_{em} for energy mix, ε_{pr} for energy intensity, ε_{pr} for R&D efficiency, ε_{pr} per capita R&D expenditure, and ε_{pr} for population.

\[
\varepsilon = \frac{\Delta C / C^0}{\Delta G / G^0} = \left( \frac{\Delta C_{EC} + \Delta C_{EM} + \Delta C_{EI} + \Delta C_{RE} + \Delta C_{PR} + \Delta C_{P}}{\Delta G / G^0} \right)
\]

\[
= \frac{\Delta C_{EC} / C^0}{\Delta G / G^0} + \frac{\Delta C_{EM} / C^0}{\Delta G / G^0} + \frac{\Delta C_{EI} / C^0}{\Delta G / G^0} + \frac{\Delta C_{RE} / C^0}{\Delta G / G^0} + \frac{\Delta C_{PR} / C^0}{\Delta G / G^0} + \frac{\Delta C_{P} / C^0}{\Delta G / G^0}
\]

\[
= \varepsilon_{ec} + \varepsilon_{em} + \varepsilon_{pr} + \varepsilon_{re} + \varepsilon_{pr} + \varepsilon_{p}
\]

3.3. Data source

This study investigated the period from 1996 to 2014. The data for energy-related CO2 emissions, GDP, R&D expenditure, and population data originate from The World Bank (2017) (https://data.worldbank.org/). Energy consumptions were derived via the BP (2019) (https://www.bp.com/). To eliminate the impact of price volatility, both GDP and R&D expenditures were converted to 2010 constant $.

4. Results

4.1. Overview of economic development and CO2 emissions in C6 countries

As illustrated in Fig. 2, all C6 countries had different economic growth rates, during the study period. The GDPs of China, USA, India, Russia, Japan, and Germany in 2014 were 5.13 times, 1.53 times, 3.04 times, 2.00 times, 1.13 times, and 1.28 times of those of the base year, respectively. The USA has the largest economy, with an annual economic growth rate of 2.40%. A significant slowdown of USA’s GDP was only found for 2007–2008, which was caused by a severe financial crisis. China’s economic output exceeded that of Japan in 2009. China enjoyed
a spectacular economic growth especially since the reform and opening-up in the late 1970s, and retained an annual growth rate of 9.51% throughout the study phase. Although Japan’s economic output is among the top three in the world, it is in a state of weak economic growth, which is characterized by the lowest annual growth rate (0.70%) among the other C6 states. As an emerging economy, India has a smaller economic base; however, in recent years, it has experienced rapid economic growth with an average annual increase rate of 6.37%, which is second only to that of China. Russia’s economic output has been higher than that of India in 1996–2008; however, it has declined in 2008–2009 due to an economic crisis and has since then remained lower than India’s economic output. Germany’s economic growth trend was very similar to that of Japan, with an average annual increase rate of only 1.36%. According to this analysis, with regard to the average annual growth rate of economy, China, India, and Russia (all developing countries) outperform the developed countries of USA, Japan, and Germany.

In general, the CO2 emissions showed similar trends to the economic performances (Fig. 3). In 2014, the CO2 emissions of China, USA, India, Russia, Japan, and Germany were 2.81 times, 1.00 times, 2.50 times, 1.04 times, 1.02 times, and 0.81 times of those of the base year, respectively. The annual CO2 emission growth rates of all C6 countries were slightly lower than that of the GDP. Although the USA has retained a large carbon emissions base, China exceeded the USA and became the largest emitter since 2006. CO2 emissions experienced an enormous growth in China, which accelerated particularly since the early 2000s. The amount of CO2 emissions in the other four countries was relatively small. India’s CO2 emissions exceeded that of Russia in 2009, and became the third CO2 emitter in the world. The developed countries Japan and Germany emitted less carbon emissions than the developing countries.
countries India and Russia. It is worth noting that carbon emissions in Russia, Japan, and USA showed a significant decreasing trend during the study period.

4.2. Decoupling trend

To further clarify the results, the long study period was divided into four sub-periods to investigate the overall decoupling trend.

4.2.1. Phase I (1996–2000)

Fig. 4 shows that the decoupling status between CO₂ emissions and economy in C6 countries during Phase I concentrated on weak and strong decoupling. This is a very positive signal, since both states indicate the best development direction during the decoupling process. From the perspective of each country, China and Germany have optative decoupling statuses, which were strongly decoupled, and both occurred between 1996 and 1999. The economic output of the USA and India grew faster than their carbon emissions during Phase I; therefore, both countries have mainly experienced weak decoupling and expansive coupling. Japan experienced strong decoupling during 1996–1997 and weak decoupling during 1998–2000. The variation span of the decoupling state of Russia was large, and the decoupling state differed each year. Russia undergone the most favorable decoupling status (strong decoupling) in 1996–1997, but also experienced the most detrimental decoupling status (strong negative decoupling) in 1998–1999.

4.2.2. Phase II (2000–2005)

Fig. 5 clearly indicates that the decoupling states of C6 countries in Phase II are more concentrated during the first quadrant and the fourth quadrant than during Phase I. Furthermore, no negative expansion decoupling was found, and the third quadrant only appeared once, i.e., recessive coupling appeared affected Germany in 2002–2003. India experienced a single state of decoupling, and weak decoupling occupied the entire Phase II. Both the USA and Russia have only experienced the two decoupling states of weak decoupling and strong decoupling; the key difference is that the USA is characterized by weak decoupling, while Russia is characterized by strong decoupling. China's carbon emissions increased faster than its GDP in 2001–2005, and experienced both negative expansion decoupling and expansive coupling. Strong decoupling occurred in Japan both during 2000–2001 and 2004–2005, indicating that carbon emissions have declined in the state of economic growth.

4.2.3. Phase III (2005–2010)

As shown in Fig. 6, the decoupling states that appeared during Phase III were expanding compared to Phase II. This is based on the premise of simultaneous decline of economy and carbon emissions. The decoupling status that appeared in the third quadrant was concentrated during 2007–2009, which was mainly affected by a financial crisis. However, the decoupling between China and India was spread throughout the first and fourth quadrants, and economic output has not declined as a result of the economic crisis. Recessive decoupling occurred in the USA, Japan, and Germany during 2007–2009, 2007–2009, and 2008–2009, respectively, indicating that carbon emissions decreased faster than economic output. Recessive coupling occurred in Russia during 2008–2009, indicating that CO₂ emission decline was roughly identical to that of the economy. China experienced expansive coupling and weak decoupling in this period. India's carbon emissions increased faster than its economic output, with expansive negative decoupling during 2007–2009.

4.2.4. Phase IV (2010–2014)

Similar to Phase II, the decoupling states in 2010–2014 were concentrated in the first quadrant and the fourth quadrant, and strong decoupling was more prevalent (Fig. 7). During Phase IV, China's decoupling has gradually improved, from expansive coupling in 2010–2011 to weak decoupling in 2011–2013. China’s decoupling then experienced the most beneficial strong decoupling in 2013–2014. In the USA, carbon emissions declined in 2010–2012, showing strong decoupling, and increased in 2012–2014, showing weak decoupling. During Phase IV, India was characterized by expansive negative decoupling, showing the carbon emission increase rate exceeded the economic increase rate. Russia and Germany mainly experienced strong decoupling and expansive negative decoupling. In Japan, the decoupling status gradually improved during Phase IV, but experienced strong negative decoupling in 2010–2011, when carbon emissions increased, while the economy declined. During 2011–2012, Japan's decoupling status first became weak decoupling, and then became strong decoupling.

4.3. Analysis of decomposition results of decoupling indicators

Corresponding to the above decoupling analysis, the driving forces of C6 countries' decoupling were further quantified for the four phases defined in Section 4.2 (see Fig. 8).
During the first phase of 1996–2000: The per capita R&D expenditure effect was the main obstacle for the decoupling process in the C6 countries. Among them, the per capita R&D expenditure effect promotes the decoupling index of China, USA and India increased by >1, indicating that the growth rate of carbon emissions caused by this factor is greater than the economic growth rate. The effect of the energy intensity effect and R&D efficiency effect on the decoupling index of C6 countries is <1, which indicate that energy intensity effect and R&D efficiency effect are the two main determinants that promote the decoupling process of C6 countries. The former was the main favorable factor for the USA, Russia, and Germany, while the latter was the main favorable factor for China, India, and Japan. China and Germany could be characterized by strong decoupling, mainly because of the effect values of energy intensity, R&D efficiency and carbon emission coefficients are all negative, indicating that these three factors have caused the suppressive action in carbon emissions and have inhibited the growth of the decoupling index. Population effect only promoted the decoupling process in Russia with a value <0, and inhibited the decoupling process in other countries. Energy intensity, R&D efficiency and per capita R&D expenditure effect followed a consistent direction in the decoupling process of the C6 countries. However, the action directions of carbon emission coefficient effect and energy mix effect differed strongly.

During the second phase of 2000–2005: Compared with Phase I, the R&D efficiency effect of the USA replaced the per capita R&D expenditure effect and became the largest inhibitor with the effect value of 0.3264. However, the per capita R&D expenditure was also the major obstacle for the decoupling process of carbon emissions and economy in China, India, Russia, Japan, and Germany. With regard to China, the energy mix and energy intensity effect converted the action direction, and together with the effect of per capita R&D expenditure and population, these became the major inhibitors of decoupling process. Only the impact of carbon emission coefficient and R&D efficiency is <0, which promoted the decoupling process. The R&D efficiency effect, per capita R&D expenditure effect, and population effect have caused significant obstacles for the decoupling process in the USA, which promoted decoupling index growth by 0.3264, 0.2718 and 0.3399, respectively. However, due to the positive roles of the energy intensity effect and carbon emission coefficient effect with the effect value of −0.8278 and
−0.0010, the USA mainly experienced weak decoupling. The promotion effect of the energy intensity effect on decoupling process exceeded the R&D efficiency effect, thus becoming the largest promoter of the decoupling process in India. Similar to Phase I, the per capita R&D expenditure effect was still the main obstacle for Japan’s decoupling process with the effect value of 0.3943. Coupled with the weakening promotion effect of R&D efficiency effect, this suggests a pessimistic decoupling state for Japan.

During the third phase of 2005–2010: Great differences were found in the role of each effect in the decoupling process of C6 countries compared with the first two stages. The only commonality is that the energy intensity effect is a very important influencing factor whose effect is far <0, which is beneficial to the realization of the decoupling process of C6 countries. The per capita R&D expenditure effect, as the main inhibitory force with the effect value of 1.3486, far exceeds the promotion effect of energy mix, energy intensity, and R&D efficiency, thus characterizing China as following weak decoupling. For the USA, the promotion effect of energy intensity and R&D efficiency on the decoupling process is almost twice as high as the inhibitory effect of per capita R&D expenditure effect on the decoupling process. Moreover, the population effect also plays an important role for inhibiting the decoupling process. The emergence of strong decoupling in Japan and Germany mainly originated from the promoting effect that the energy intensity effect exerts on the decoupling process. With regard to Russia, the energy intensity...
effect and the per capita R&D expenditure effect were the biggest promoter and suppressor of the decoupling process with the effect value of $-0.3320$ and $0.5975$, respectively.

During the fourth phase of 2010–2014: The emergence of strong decoupling in the USA was mainly the result of the contribution of the energy intensity effect to the decoupling process with the effect value of $-1.0297$. This shows that the carbon emission reduction rate caused by the energy intensity effect is greater than the economic growth rate, which is very important for the coordinated development of carbon emissions and economic growth in the USA. In addition, carbon emission coefficient effect and energy mix effect also play an important role in the decoupling process in the United States with the effect value of $-0.0222$ and $-0.2241$, respectively. Unlike in the USA, in Germany, the emergence of strong decoupling was mainly the result of the promotion of energy intensity effect, carbon emission coefficient effect, R&D efficiency effect, and population effect on the decoupling process. However, none of the three contributing factors had a lower effect than $-1$, indicating that the carbon emission reduction rate caused by these three factors was less than the economic growth rate. India had the worst decoupling status among all C6 countries, which is mainly because only the energy intensity effect promoted the decoupling process, while other effects inhibited the decoupling process with the effect value is $>0$. China, Russia, and Japan were all characterized by weak decoupling; however, for different reasons. For China, the per capita R&D expenditure effect had a strong inhibitory effect on the decoupling process with the effect value of $1.3955$. However, due to the positive impact of the energy intensity effect with the effect value of $-0.5180$ and the R&D efficiency effect with the effect value of $-0.5079$, China stabilized at the weak decoupling state. The energy intensity effect had played the major driving force in Russia’s decoupling process; however, it suppressed Japan’s decoupling process. R&D efficiency effect was the main promoter of Japan’s decoupling process but was the biggest obstacle for Russia’s decoupling process.

5. Conclusions and policy recommendations

This paper compared the decoupling of economy from CO$_2$ emissions of the top six CO$_2$ emitting countries (China, USA, India, Russia, Japan, and Germany) during the period from 1996 to 2014. The extended LMDI model was employed to decompose the decoupling index into six drivers: carbon emission coefficient, energy mix, energy intensity, R&D efficiency, per capita R&D expenditure, and population.

The obtained results indicate that the decoupling states of C6 countries during Phase II and Phase IV were more concentrated in the first quadrant and the fourth quadrant than during Phase I and Phase III. This indicates that the connection between CO$_2$ emissions and economic growth was more satisfactory during 2000–2005 and 2010–2014. In Phase III, due to the impact of the financial crisis, the decoupling states of C6 countries began to expand toward the third quadrant, under the premise that carbon emissions and economic output decreased simultaneously. Furthermore, the decoupling states in developed countries (USA, Japan, and Germany) were superior and more stable than those of developing countries (China, India, and Russia). Germany performed best among the developed countries, and China was most stable among the developing countries.

The per capita R&D expenditure effect played the major resistance for the decoupling between carbon emissions and economy in C6 countries. The effect of energy intensity and R&D efficiency related to technological progress were the main driving forces of the decoupling process. Per capita R&D expenditure effect, energy intensity effect, and R&D efficiency effect dominated the decoupling of developing countries, thus leading to a difference in decoupling performance. Population effect played an important role for suppressing the decoupling process between the USA and India. However, it only had a relatively small impact on other countries and has even promoted the decoupling process between Russia and Japan. The effects of carbon emission coefficient effect and energy mix effect on the decoupling process were relatively weak and thus did not exert a decisive role in the decoupling states.

CO$_2$ emissions from China and USA far exceeded those of the other C6 countries. Therefore, China and the USA should actively assume the responsibility for emission reduction and increase their efforts to promote the decoupling process. To further promote the coordinate development of economic growth and environment, energy efficiency and R&D efficiency are supposed to improve as the basis of future decoupling efforts. Aggregate energy efficiency and R&D efficiency improved mainly as a result of technological progress (Voigt et al., 2014). The overall technological levels of developed countries were better than those of developing countries. Developing countries can thus learn from developed countries (especially from Germany) how to promote technological advancement. In addition, the energy structure should be further optimized to fully utilize its emission reduction potential by prioritizing cleaner energy sources. It is essential to transform the development pattern of domestic economy and maintain stable economic growth. The promotion of low-carbon awareness through publicity and education is also important in daily life.

CRediT authorship contribution statement

**Rongrong Li**: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Supervision, Writing - review & editing.

**Rui Jiang**: Methodology, Software, Data curation, Investigation, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1

| Year | CO$_2$ emissions in C6 countries (Mt) | USA | India | Russia | Japan | Germany |
|------|--------------------------------------|-----|-------|--------|-------|---------|
| 1996 | 3218.13                              | 5197.14 | 841.21 | 1587.94 | 1157.57 | 871.35 |
| 1997 | 3214.31                              | 5312.88 | 874.22 | 1502.72 | 1154.94 | 841.81 |
| 1998 | 3057.03                              | 5352.80 | 890.52 | 1470.25 | 1117.27 | 834.25 |
| 1999 | 3032.30                              | 5454.95 | 947.88 | 1503.49 | 1156.56 | 801.60 |
| 2000 | 3107.45                              | 5644.13 | 981.36 | 1528.45 | 1180.08 | 809.51 |
| 2001 | 3157.90                              | 5545.46 | 985.55 | 1526.24 | 1165.20 | 834.86 |
| 2002 | 3488.70                              | 5590.45 | 994.16 | 1517.82 | 1184.22 | 811.52 |
| 2003 | 4110.49                              | 5623.37 | 1036.22 | 1563.82 | 1207.80 | 806.43 |
### Table A1 (continued)

| Year | China | USA | India | Russia | Japan | Germany |
|------|-------|-----|-------|--------|-------|---------|
| 2004 | 4749.79 | 5701.50 | 1087.59 | 1558.97 | 1232.41 | 800.88 |
| 2005 | 5363.91 | 5732.98 | 1148.56 | 1566.15 | 1204.53 | 781.68 |
| 2006 | 5912.50 | 5640.58 | 1222.08 | 1617.29 | 1196.62 | 799.67 |
| 2007 | 6351.97 | 5733.00 | 1320.41 | 1606.55 | 1218.47 | 763.87 |
| 2008 | 6854.87 | 5561.42 | 1530.01 | 1662.90 | 1178.81 | 764.35 |
| 2009 | 7181.13 | 5222.25 | 1634.50 | 1617.29 | 1145.93 | 744.27 |
| 2010 | 7867.39 | 5353.08 | 1608.11 | 1617.29 | 1145.93 | 744.27 |
| 2011 | 8686.74 | 5244.16 | 1720.01 | 1704.63 | 1165.49 | 715.74 |
| 2012 | 8926.42 | 5070.59 | 1881.77 | 1768.40 | 1202.87 | 723.66 |
| 2013 | 9055.61 | 5106.52 | 1892.99 | 1712.93 | 1217.61 | 741.68 |
| 2014 | 9049.13 | 5197.23 | 2099.56 | 1650.06 | 1185.17 | 703.85 |

### Table A2

Energy consumption in C6 countries (unit: million tonnes oil equivalent).

| Year | China | USA | India | Russia | Japan | Germany |
|------|-------|-----|-------|--------|-------|---------|
| 2004 | 4749.79 | 5701.50 | 1087.59 | 1558.97 | 1232.41 | 800.88 |
| 2005 | 5363.91 | 5732.98 | 1148.56 | 1566.15 | 1204.53 | 781.68 |
| 2006 | 5912.50 | 5640.58 | 1222.08 | 1617.29 | 1196.62 | 799.67 |
| 2007 | 6351.97 | 5733.00 | 1320.41 | 1606.55 | 1218.47 | 763.87 |
| 2008 | 6854.87 | 5561.42 | 1530.01 | 1662.90 | 1178.81 | 764.35 |
| 2009 | 7181.13 | 5222.25 | 1634.50 | 1617.29 | 1145.93 | 744.27 |
| 2010 | 7867.39 | 5353.08 | 1608.11 | 1617.29 | 1145.93 | 744.27 |
| 2011 | 8686.74 | 5244.16 | 1720.01 | 1704.63 | 1165.49 | 715.74 |
| 2012 | 8926.42 | 5070.59 | 1881.77 | 1768.40 | 1202.87 | 723.66 |
| 2013 | 9055.61 | 5106.52 | 1892.99 | 1712.93 | 1217.61 | 741.68 |
| 2014 | 9049.13 | 5197.23 | 2099.56 | 1650.06 | 1185.17 | 703.85 |

### Table A3

GDP in constant 2010 US$ in C6 countries (unit: billion).

| Year | China | USA | India | Russia | Japan | Germany |
|------|-------|-----|-------|--------|-------|---------|
| 2004 | 4749.79 | 5701.50 | 1087.59 | 1558.97 | 1232.41 | 800.88 |
| 2005 | 5363.91 | 5732.98 | 1148.56 | 1566.15 | 1204.53 | 781.68 |
| 2006 | 5912.50 | 5640.58 | 1222.08 | 1617.29 | 1196.62 | 799.67 |
| 2007 | 6351.97 | 5733.00 | 1320.41 | 1606.55 | 1218.47 | 763.87 |
| 2008 | 6854.87 | 5561.42 | 1530.01 | 1662.90 | 1178.81 | 764.35 |
| 2009 | 7181.13 | 5222.25 | 1634.50 | 1617.29 | 1145.93 | 744.27 |
| 2010 | 7867.39 | 5353.08 | 1608.11 | 1617.29 | 1145.93 | 744.27 |
| 2011 | 8686.74 | 5244.16 | 1720.01 | 1704.63 | 1165.49 | 715.74 |
| 2012 | 8926.42 | 5070.59 | 1881.77 | 1768.40 | 1202.87 | 723.66 |
| 2013 | 9055.61 | 5106.52 | 1892.99 | 1712.93 | 1217.61 | 741.68 |
| 2014 | 9049.13 | 5197.23 | 2099.56 | 1650.06 | 1185.17 | 703.85 |

### Table A4

Population in C6 countries (unit: million person).

| Year | China | USA | India | Russia | Japan | Germany |
|------|-------|-----|-------|--------|-------|---------|
| 2004 | 5701.50 | 1087.59 | 1558.97 | 1232.41 | 800.88 |
| 2005 | 5732.98 | 1148.56 | 1566.15 | 1204.53 | 781.68 |
| 2006 | 5640.58 | 1222.08 | 1617.29 | 1196.62 | 799.67 |
| 2007 | 5733.00 | 1320.41 | 1606.55 | 1218.47 | 763.87 |
| 2008 | 5561.42 | 1474.00 | 1662.90 | 1178.81 | 764.35 |
| 2009 | 5222.25 | 1634.50 | 1530.01 | 1076.54 | 707.29 |
| 2010 | 5353.08 | 1608.11 | 1617.29 | 1145.93 | 744.27 |
| 2011 | 5244.16 | 1720.01 | 1704.63 | 1165.49 | 715.74 |
| 2012 | 5070.59 | 1881.77 | 1768.40 | 1202.87 | 723.66 |
| 2013 | 5106.52 | 1892.99 | 1712.93 | 1217.61 | 741.68 |
| 2014 | 5197.23 | 2099.56 | 1650.06 | 1185.17 | 703.85 |

(continued on next page)
References

Aklobostance, E., Tunc, G.J., Turut-Aşık, S., 2018. Drivers of fuel based carbon dioxide emissions: the case of Turkey. Renew. Sust. Energ. Rev. 81, 2599–2608.

Ang, B.W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy 32, 1131–1139.

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33, 867–871.

Ang, B.W., Choi, K.H., 1997. Decomposition of aggregate energy and gas emission intensities for industry: a refined Divisia index method. Energy J. 18, 59–73.

Ang, B.W., Zhang, F.Q., 2000. A survey of index decomposition analysis in energy and environmental studies. Energy 25, 1149–1176.

Awaworyi Churchill, S., Inekwe, J., Smyth, R., Zhang, X., 2019. R&D intensity and carbon emissions in the G7: 1870–2014. Energy Econ. 80, 30–37.

Boyd, G., McDonald, J.F., Ross, M., Hanson, D.A., 1987. Separating the changing compositions of U.S. manufacturing production from energy efficiency improvements: a Divisia index approach. Energy J. 8, 77–96.

BP, 2019. Statistical review of world energy. https://www.bp.com/zh_cn/china/reports-and-publications/_bp_2017-_.html.

Chen, B., Yang, Q., Li, J.S., Chen, G.Q., 2017. Decoupling analysis on energy consumption, embodied GHG emissions and economic growth— the case study of Macao. Renew. Sust. Energ. Rev. 67, 662–672.

Chong, C.H., Tan, W.X., Ting, Z.J., Liu, P., Ma, L., Li, Z., et al., 2019. The driving factors of energy-related CO2 emission growth in Malaysia: the LMDI decomposition method based on energy allocation analysis. Renew. Sust. Energ. Rev. 115, 109556.

Chompratwat, J., Wiboonchutchuala, P., Buddhavanich, A., 2019. An LMDI decomposition of carbon emissions in the Thai manufacturing sector. Energy Rep. 6, 705–710.

Daldout, M., Dhalbou, A., 2018. Using the LMDI decomposition approach to analyze the influencing factors of carbon emissions in Tunisian transportation sector. Int. J. Energy Econ. Policy 8, 22–28.

De Oliveira-De Jesus, P.M., 2019. Effect of generation capacity factors on carbon emission intensity of electricity of Latin America & the Caribbean, a temporal IDA-LMDI analysis. Renew. Sust. Energ. Rev. 101, 516–526.

Diakoulaki, D., Mandarakis, M., 2007. Decomposition analysis for assessing the progress in decoupling industrial growth from CO2 emissions in the EU manufacturing sector. Energy Econ. 29, 636–644.

Engo, J., 2018. Decomposing the decoupling of CO2 emissions from economic growth in Cameroon. Environ. Sci. Polit. Res. 25, 3545–35463.

Fatima, T., Xia, E., Cao, Z., Khan, D., Fan, J.-L., 2019. Decomposition analysis of energy-related CO2 emission in the industrial sector of China: evidence from the LMDI approach. Environ. Sci. Polit. Res. 26, 21735–21748.

Fernández, Y., Fernández López, M.A., Olmedillas Blanco, B., 2018. Innovation for sustainability: the impact of R&D spending on CO2 emissions. J. Clean. Prod. 172, 3459–3467.

García-Gusano, D., Suárez-Botero, J., Dufour, J., 2018. Long-term modelling and assessment of the economy-energy decoupling in Spain. Energy 151, 455–466.

Gu, S., Fu, B., Thrienevi, T., Fujita, T., Ahn, J.W., 2019. Coupled LMDI and system dynamics model for estimating urban CO2 emission mitigation potential in Shanghai, China. J. Clean. Prod. 240, 118034.

Hoekstra, R., van den Bergh, J.C.M., 2003. Comparing structural decomposition analysis and index. Energy Econ. 25, 79–94.

Hu, M., Hu, Y., Yuan, J., Lu, F., 2019. Decomposing the decoupling of water consumption and economic growth in Jiangxi, China. J. Water Reuse Desal. 9, 104–116.

Inglesi-Lotz, R., 2018. Decomposing the south African CO2 emissions within a BRICS countries context: signaling potential energy rebounds effects. Energy 147, 648–654.

Jabur, R., 2003. Transition period in Lithuania–do we move to sustainability? Energy 4, 4–9.

Karakeya, E., Bostan, A., Özçağ, M., 2019. Decomposition and decoupling analysis of energy-related carbon emissions in Turkey. Environ. Sci. Polit. Res. 26, 32080–32091.

Kaya, Y., 1990. Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios IPCC Energy and Industry Subgroup, Response Strategies Working Group.

King, A.D., Karyló, D.J., Henley, B.J., 2017. Australian climate extremes at 1.5°C and 2°C of global warming. Nat. Clim. Chang. 7, 412.

Leal, P.A., Marques, A.C., Fuinhas, J.A., 2019. Decomposing the decoupling of CO2 emissions from economic growth in China USA India Russia Japan Germany.

Table A5

Research and development expenditure in C6 countries (Unit: % of GDP).

|        | China | United States | India | Russian | Japan | Germany |
|--------|-------|---------------|-------|---------|-------|---------|
| 1996   | 56.32 | 244.18        | 64.77 | 96.59   | 269.21 | 213.72  |
| 1997   | 63.87 | 247.09        | 69.60 | 104.37  | 276.97 | 217.88  |
| 1998   | 64.69 | 249.68        | 71.33 | 95.38   | 287.36 | 221.23  |
| 1999   | 74.96 | 254.17        | 73.39 | 99.62   | 289.28 | 233.38  |
| 2000   | 89.32 | 262.05        | 76.72 | 104.98  | 290.57 | 239.17  |
| 2001   | 94.03 | 263.83        | 74.59 | 117.69  | 297.18 | 238.56  |
| 2002   | 105.79| 254.97        | 73.55 | 124.78  | 301.39 | 241.54  |
| 2003   | 112.04| 255.29        | 72.90 | 128.60  | 304.30 | 245.66  |
| 2004   | 121.50| 249.00        | 76.71 | 115.13  | 302.95 | 242.08  |
| 2005   | 130.79| 250.60        | 83.58 | 106.80  | 318.10 | 242.25  |
| 2006   | 136.85| 255.00        | 82.22 | 107.29  | 327.84 | 245.60  |
| 2007   | 137.30| 262.69        | 81.55 | 111.61  | 333.96 | 244.63  |
| 2008   | 144.47| 276.68        | 86.74 | 104.44  | 333.72 | 259.71  |
| 2009   | 166.21| 281.86        | 84.44 | 125.19  | 323.14 | 272.64  |
| 2010   | 170.99| 274.05        | 82.21 | 113.02  | 313.71 | 271.37  |
| 2011   | 177.54| 276.97        | 83.13 | 101.26  | 324.48 | 279.56  |
| 2012   | 190.58| 268.86        | 154.40| 102.68  | 320.91 | 286.81  |
| 2013   | 199.02| 272.49        | 162.40| 102.52  | 331.50 | 282.11  |
| 2014   | 202.11| 273.39        | 170.91| 107.01  | 340.02 | 287.29  |
Rao, G., Yang, F., 2018. Decoupling measurement of regional CO2 emissions growth: a Ma, X., Wang, C., Dong, B., Gu, G., Chen, R., Li, Y., et al., 2019. Carbon emissions from en-
Lyu, W., Li, Y., Guan, D., Zhao, H., Zhang, Q., Liu, Z., 2016. Driving forces of Chinese primary air pollution emissions: an index decomposition analysis. J. Clean. Prod. 133, 136–144.
Ma, X., Wang, C., Dong, B., Gu, G., Chen, R., Li, Y., et al., 2019. Carbon emissions from energy consumption in China: its measurement and driving factors. Sci. Total Environ. 648, 1411–1420.
Madelano, M., Moutinho, V., 2019. Effects decomposition: separation of carbon emissions decoupling and decoupling effort in aggregated EU-15, Environ. Dev. Sustain. 20, 181–198.
Maswood, A., Burney, S.A., 2017. Standard errors for the Laspeyres index number with autocorrelated error models. Commun. Statistic Theory Methods 46, 10807–10816.
Martinico-Perez, M.F.G., Schandl, H., Fishman, T., Tanikawa, H., 2018. The socio-economic autocorrelated error models. Commun. Statistic Theory Methods 46, 10607–10616.
Meng, M., Fu, Y., Wang, X., 2018. Decoupling, decomposition and forecasting analysis of China’s fossil energy consumption from industrial output. J. Clean. Prod. 177, 752–759.
Mora, C., Spiriandelli, D., Franklin, E.C., Lynham, J., Kantar, M.B., Miles, W., et al., 2018. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. Nat. Clim. Chang. 8, 1062–1067.
Mousavi, B., Lopez, N.S.A., Biona, J.R.M., Chiu, A.S., Blesi, M., 2017. Driving forces of Iran’s CO2 emissions from energy consumption: an LMDI decomposition approach. Appl. Energy 204, 804–811.
Moutinho, V., Moreira, A.C., Silva, P.M., 2015. The driving forces of change in energy-related CO2 emissions in eastern, western, northern and southern Europe: the LMDI approach to decomposition analysis. Renew. Sust. Energ. Rev. 50, 1485–1499.
Moutinho, V., Madelano, M., Inglesi-Lotz, R., 2018. Factors affecting CO2 emissions in top countries on renewable energies: a LMDI decomposition application. Renew. Sust. Energ. Rev. 90, 605–622.
OECD, 2002. Sustainable Development: Indicators to Measure Decoupling of Environmental Pressure From Economic Growth. OECD, Paris, France.
Olthof, A., Christensen, J.M., 2018. Emissions Gap Report 2018.
Petron, V., Lobanov, M.M., 2019. The impact of R&D expenditures on CO2 emissions: evi-

dence from sixteen OECD countries. J. Clean. Prod. 248, 119187–119197.
Pourrebaldadlorni, Covich, M., Fallahi, F., Alizadeh, E., Salehi Abar, K., 2018. Decomposing the influencing factors of CO2 emissions in east Azarbayjan province manufacturing industries using the LMDI approach. Q. J. Appl. Theories Econ. 5, 199–222.
Rao, G., Yang, F., 2018. Decoupling measurement of regional CO2 emissions growth: a case study of Chongqing, China. DEStech Transactions on Environment, Energy and Earth Sciences.
Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., et al., 2016. Paris agreement climate proposals need a boost to keep warming well below 2°C. Nature 534, 631–639.
Roinioti, A., Koroneos, C., 2017. The decomposition of CO2 emissions from energy use in Greece before and during the economic crisis and their decoupling from economic growth. Renew. Sust. Energ. Rev. 75, 448–459.
Román-Collado, R., Morales-Carrillo, A.V., 2018. Towards a sustainable growth in Latin America: a multiregional spatial decomposition analysis of the driving forces behind CO2 emissions changes. Energy Policy 115, 273–280.
Román-Collado, R., Cansino, J.M., Botia, C., 2018. How far is Colombia from decoupling? Two-level decomposition analysis of energy consumption changes. Energy 148, 687–700.
Shuai, C., Chen, X., Wu, Y., Zhang, Y., Tan, Y., 2019. A three-step strategy for decoupling economic growth from carbon emission: empirical evidences from 133 countries. Sci. Total Environ. 646, 524–543.
Siping, J., Wendai, L., Liu, M., Xiangjun, Y., Hongjuan, Y., Yongming, C., et al., 2019. Decoupling environmental pressures from economic growth based on emissions monetization: case in Yunnan, China. J. Clean. Prod. 208, 1563–1576.
Steininger, K.W., Munoz, P., Karstensen, J., Peters, G.P., Strohmaier, R., Velázquez, E., 2018. Austria’s consumption-based greenhouse gas emissions: identifying sectoral sources and destinations. Glob. Environ. Chang. 48, 226–242.