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Decomposition and decoupling analysis of carbon dioxide emissions from economic growth in the context of China and the ASEAN countries

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Abstract: China and the Association of Southeast Asian Nations (ASEAN), as the engine of world economic development, are facing tremendous challenges concerning the balance between economic growth and low-carbon development. Nevertheless, previous studies on the relationship between economic growth and carbon emissions have seldom been contextualized in this region. The paper analyses the decoupling elasticity between carbon dioxide (CO_2), the gross domestic product (GDP) and energy consumption in China and the ASEAN countries over the period 1990–2014. Based on the Log-Mean Divisia Index (LMDI), it explores the effect of four factors on the total changes in CO_2 emissions, namely the carbon density effect, energy intensity effect, economic effect in terms of per capita GDP and population effect. The study shows that the economic effect in terms of per capita GDP is the dominant driving force for the increase in CO_2 emissions. The carbon density and population effects also play a role in this regard. Energy intensity has contributed significantly to the decrease in CO_2 emissions in most of the examined countries. To decouple economic growth from environmental pressure, energy policies in China and the ASEAN countries need to scale up the share of renewable energy, increase the efficiency of energy use and implement green development as long-term targets in the region.

Key words: Decoupling elasticity, decomposition, LMDI model, CO_2 emission, China, ASEAN countries

1. Introduction

China and the Association of Southeast Asian Nations (ASEAN), as the engine of world economic development, are facing tremendous challenges regarding the balance between economic growth and sustainable development. According to the International Energy Agency's (IEA) database, the gross domestic product (GDP) of China in 2014 accounted for 13.25% of the world's economy, which is nearly 33 times the figure in 1990, while its carbon dioxide (CO_2) emissions constituted 28.48% of the world's total CO_2 emissions, more than three times the figure in 1990. The GDP in the ASEAN, China's second-largest trading partner, accounted for 3.2% of the world's economy in 2014, which is 6.7 times the number in 1990, while its CO_2 emissions in 2014 constituted 3.85% of the world's total CO_2 emissions, 2.3 times the percentage in 1990. According to the Global Climate Risk Index compiled by Germanwatch, Myanmar, the Philippines, Vietnam, Thailand and Cambodia are ranked in the top 20 countries in the world that have been most affected by climate change in the past 20 years (Germanwatch 2019). The increasing GDP and CO_2 emissions in the region have excessively outpaced the world averages. To achieve the goal of CO_2 emission reduction in the Paris Agreement, of which both China and the ASEAN countries are members, it is paramount to understand the relationship between economic development and CO_2 emissions and the impacts of the influential factors on CO_2 emissions.

Recent decades have seen vast literature focusing on the relationship between economic growth and CO_2 emissions. decoupling analysis has been widely employed in this research area (OECD 2002; Tapio 2005). The rationale of decoupling research is to dissociate economic growth from environmental degradation to achieve sustainable development. The extent of decoupling is measured through a decoupling indicator based on the elasticity concept. The Tapio Decoupling Index has been widely used by many researchers (Shuai et al. 2019). It presents eight possible combinations of decoupling status, namely strong decoupling, weak decoupling, recessive decoupling, strong negative decoupling, weak negative decoupling, expansive negative decoupling, expansive coupling and recessive coupling (Tapio 2005). Decoupling analysis has been undertaken in various contexts, at the global level (Chen et al. 2018; Shuai et al. 2019), the country level (Aldy 2005; Lu et al. 2007; Lin et al. 2015; Roinioti and Koroneos 2017; Wang et al. 2017b, 2018) and at the provincial or city level (Wang et al. 2017a, 2017c), and in carbon-intensive industrial sectors, such as the building sector (Ma and Cai 2018; Ma et al. 2018; Ma and Cai 2019), the agriculture sector (Han et al. 2018), the transportation sector (Tapio 2005), the construction industry (Wu et al. 2018) and sectors in general (Zhao et al. 2017; Zhou et al. 2017; Yang et al. 2018). Decoupling analysis is easier to calculate and understand and presents the real-time dynamic relationship between economic development and environmental degradation.

Decoupling research has often been combined with decomposition analysis to investigate the driving forces of different degrees of decoupling relationship. There are three decomposition techniques, namely structural decomposition analysis (SDA), based on the input–output model, production decomposition analysis (PDA), based on production theory and the distance function, and index decomposition analysis (IDA), among which IDA has been the most widely used (Zhou et al. 2017). Index decomposition analysis aims to decompose the aggregation with a governing function into a number of predefined factors of interest (Ang 2004). The Divisia Index and Laspeyres Index are the most commonly used methods in either the multiplicative or the additive form of index decomposition analysis. Among the different sub-categories of the methods for index decomposition analysis, Ang argued that the Logarithmic Mean Divisia Index (LMDI) presents perfect decomposition due to its zero residual, easy handling of zero values in the data set, theoretical foundation, adaptability, consistency in aggregation, ease of use and result interpretation (Ang 2004). A growing number of studies have set the changes in the CO_2 emissions as the governing function to understand the factors influencing emissions. The predefined factors of interest that affect CO_2 emissions have often been set as, for example, the economic growth, energy intensity, energy structure, industry structure and so on (Khuong et al. 2019).

Nevertheless, the decoupling between economic growth and environmental pressure at the regional level, especially in the ASEAN countries, is far from clear. China, as the ASEAN's biggest trade partner for the past ten consecutive years, plays a crucial role in regional economic growth and sustainable development. Determining how to decouple economic growth from environmental pressure is fundamental for the region's green growth. Thus, the decoupling of CO_2 emissions from economic growth in the context of China and the ASEAN countries and its influencing factors deserve more careful study. This study employs decoupling analysis to examine the decoupling status in China and the ASEAN countries and further explores the reasons for the decoupling status presented and the driving forces based on decomposition analysis through the LMDI method. The paper is organized as follows. Section 1 presents the literature review and research questions of the study. Section 2 summarizes the methodology and data source. The research results are discussed and analysed in section 3. Finally, section 4 presents the main conclusion.

2. Methods and data source

2.1 Decoupling model

Tapio defined the decoupling elasticity of CO_2 emissions from the GDP (DE(C, G)) in a given period from base year 0 to target year t as follows:

$$\mathrm{DE}(\mathrm{C},\mathrm{G})^t = \frac{\frac{C^t - C^0}{C^0}}{\frac{G^t - G^0}{G^0}} \tag{1}$$

where G^t and G^0 are the total GDP in year t and base year 0 and C^t and C^0 are the total CO_2 emissions in year t and base year 0.

Formula (1) can also be expressed as follows:

$$\mathrm{DE}(\mathrm{C},\mathrm{G})^t = \frac{\frac{C^t - C^0}{C^0}}{\frac{E^t - E^0}{E^0}} \times \frac{\frac{E^t - E^0}{E^0}}{\frac{G^t - G^0}{G^0}} = DE(C,E)^t \times DE(E,G)^t \tag{2}$$

where E^t and E^0 are the total energy consumption in year t and base year 0. DE(C, G) is the decoupling elasticity of CO_2 emissions from the GDP between base year 0 and target year t; $\mathrm{DE}(\mathrm{C},\mathrm{E})^t = \frac{\frac{C^t - C^0}{C^0}}{\frac{E^t - E^0}{E^0}}$ is the decoupling elasticity of energy consumption from CO_2 between base year 0 and target year t; and $\mathrm{DE}(\mathrm{E},\mathrm{G})^t = \frac{\frac{E^t - E^0}{E^0}}{\frac{G^t - G^0}{G^0}}$ is the decoupling elasticity of the GDP from energy consumption between base year 0 and target year t.

Tapio defined eight kinds of decoupling status, namely strong decoupling, weak decoupling, expansive coupling, expansive negative decoupling, strong negative decoupling, weak negative decoupling, recessive coupling and recessive decoupling, as listed in Table 1.

Table 1 The criteria of decoupling elasticity

State	Degree of coupling/decoupling	$\frac{C^t - C^0}{C^0}$	$\frac{G^t - G^0}{G^0}$	$DE(C,G)^t$
Decoupling	Strong decoupling (SD)	<0	>0	(-∞,0)
	Weak decoupling (WD)	>0	>0	(0,0.8]
	Recessive decoupling (RD)	<0	<0	(1.2, +∞)
Coupling	Recessive coupling (RC)	<0	<0	(0.8,1.2]
	Expansive coupling (EC)	>0	>0	(0.8,1.2]
Negative decoupling	Expansive negative decoupling (END)	>0	>0	(1.2, +∞)
	Strong negative decoupling (SND)	>0	<0	(-∞,0)
	Weak negative decoupling (WND)	<0	<0	(0,0.8]

2.2 Kaya identity and the LMDI-I decomposition model

The Kaya identity presents the connection between CO_2 emissions and their influencing factors (i.e. the carbon intensity of the energy mix (CE), the energy intensity of the economy (EG), the per capita GDP (GP) and the population (P)) (Kaya 1989). The CO_2 emissions in year t (C^t) can be expressed as:

$$C^t = \frac{C^t}{E^t} \times \frac{E^t}{G^t} \times \frac{G^t}{P^t} \times p^t = CE^t \times EG^t \times GP^t \times P^t \quad (3)$$

where C^t stands for the total CO_2 emissions in year t, E^t for the total energy consumption in year t, G^t for the total GDP in year t and P^t for the total population in year t; $\mathrm{CE}^t = \frac{C^t}{E^t}$ is the carbon intensity of the energy mix in year t; $EG^t = \frac{E^t}{G^t}$ is the energy intensity of the economy in year t; and $GP^t = \frac{G^t}{P^t}$ is the per capita GDP in year t.

The LMDI-I decomposition model has been widely approved in a large body of literature due to its strong theoretical foundation, perfect decomposition and consistency in aggregation (Ang and Liu 2001). According to the LMDI model, the change in CO_2 emissions between base year 0 and target year t ΔC ($\Delta C = C^t - C^0$) can be decomposed into four factors in additive form:

$$\Delta C^t = \Delta C_{ce}^t + \Delta C_{eg}^t + \Delta C_{gp}^t + \Delta C_p^t \quad (4)$$

among which

$$\Delta C_{ce}^{t} = \frac{C^{t}-C^{0}}{\ln(C^{t})-\ln(C^{0})}\ln\left(\frac{CE^{t}}{CE^{0}}\right) \tag{5}$$

$$\Delta C_{eg}^{t} = \frac{C^{t}-C^{0}}{\ln(C^{t})-\ln(C^{0})}\ln\left(\frac{EG^{t}}{EG^{0}}\right) \tag{6}$$

$$\Delta C_{gp}^{t} = \frac{C^{t}-C^{0}}{\ln(C^{t})-\ln(C^{0})}\ln\left(\frac{GP^{t}}{GP^{0}}\right) \tag{7}$$

$$\Delta C_{p}^{t} = \frac{C^{t}-C^{0}}{\ln(C^{t})-\ln(C^{0})}\ln\left(\frac{P^{t}}{P^{0}}\right) \tag{8}$$

where ΔC_{ce}^{t} is the carbon density effect in changes in CO_2 emissions; ΔC_{eg}^{t} is the energy intensity effect; ΔC_{gp}^{t} is the economic intensity effect in terms of per capita GDP; and ΔC_{p}^{t} is the population effect.

2.3 Data source

The research period in this paper is from 1990 to 2014. All the energy data used in this paper are collected from the IEA's database. Due to missing data for Laos, it is not included in this research. Therefore, the ASEAN countries in this paper refer to nine countries, namely Brunei, Cambodia (data missing from 1990 to 1994), Indonesia, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam. The unit of GDP is billion USD in 2010 prices.

3. Results and discussion

3.1 Regional comparison of key factors

China has experienced rapid economic growth during the last two decades. Its GDP rose from USD 928.23 billion in 1990 to USD 8487.61 billion in 2014, with an annual average growth rate of 9.66% (Figure 2). Comparatively, the GDP of the nine ASEAN countries rose from USD 732.88 billion in 1990 to USD 2407.70 billion in 2014, with an annual average growth rate of 5.08%. It brought intense pressure for environmental sustainability concerning the high demand for energy consumption and the resulting huge increase in CO_2 emissions in the region (Figures 1 and 3). The total energy consumption of the nine ASEAN countries increased from 173.13 Million Tons of Oil Equivalent (Mtoe) in 1990 to 438.26 Mtoe in 2014, representing an annual average growth rate of 3.95%. Consequently, the amount of fuel combustion-related CO_2 emissions rose from 355.92 Mt in 1990 to 1217.27 Mt in 2014, accounting for an annual average growth rate of 5.26%. In respect of China, the total energy consumption increased from 654.31 Mtoe in 1990 to 1987.83 Mtoe in 2014, representing an annual average growth rate of 4.74%, whereas the amount of fuel combustion-related CO_2 emissions rose from 2109.24 Mt in 1990 to 9134.90 Mt in 2014, accounting for an annual average growth rate of 6.30%. Meanwhile, the 2000s witnessed a sharp increase in energy consumption and CO_2 emissions in China, with an annual average growth rate of 7.85% and 9.50%, respectively.

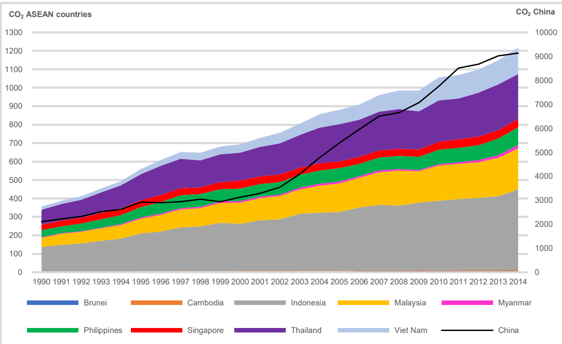

Figure 1 The CO_2 emissions from 1990 to 2014 in China and the ASEAN countries (Mt)

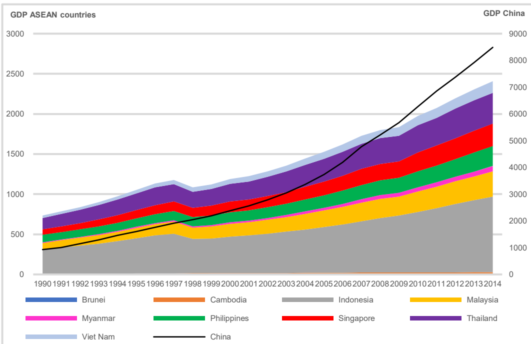

Figure 2 The GDP growth from 1990 to 2014 in China and the ASEAN countries (billion 2010 USD)

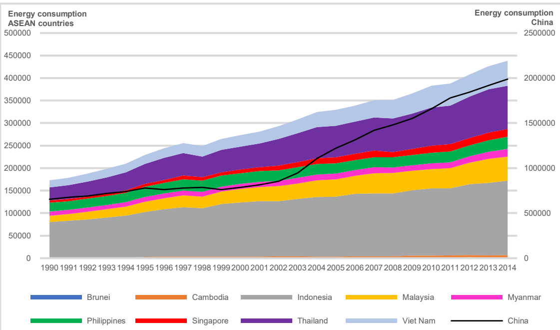

Figure 3 The total energy consumption from 1990 to 2014 in China and the ASEAN countries (ktoe)

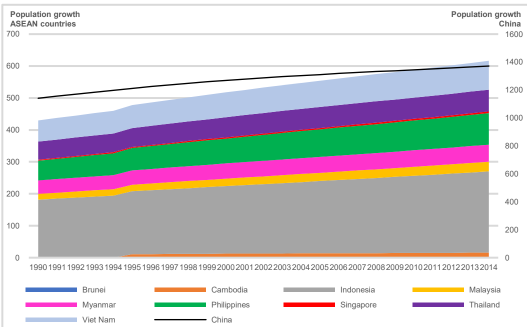

Figure 4 The population growth from 1990 to 2014 in China and the ASEAN countries (millions)

The population growth, in contrast, followed a different pattern in China (Figure 4). It presented an annual average growth rate of 0.77% between 1990 and 2014; especially in the 2000s, the annual average increase rate fell to 0.59%. The population of the nine ASEAN countries showed an annual average growth rate of 1.52% between 1990 and 2014.

The change tendency of energy intensity from 1990 to 2014 in China and the ASEAN countries is presented in Figure 5. In China, the energy intensity decreased significantly from 704.90 ktoe/billion USD in 1990 to 234.20 ktoe/billion USD in 2014, showing an annual average decrease rate of 4.49%. A rapid decrease occurred in the 1990s, with an annual average decrease rate of 7.57%. Among the ASEAN countries, Myanmar presented the most obvious rapid decrease, with an annual average rate of 6.71% from 1990 to 2009. The energy intensity of Cambodia also decreased significantly from 694.72 ktoe/billion USD in 1995 to 280.94 ktoe/billion USD in 2008.

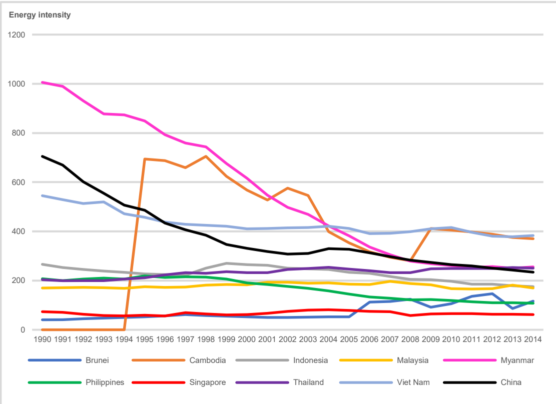

Figure 5 The energy intensity from 1990 to 2014 in China and the ASEAN countries (ktoe/billion USD)

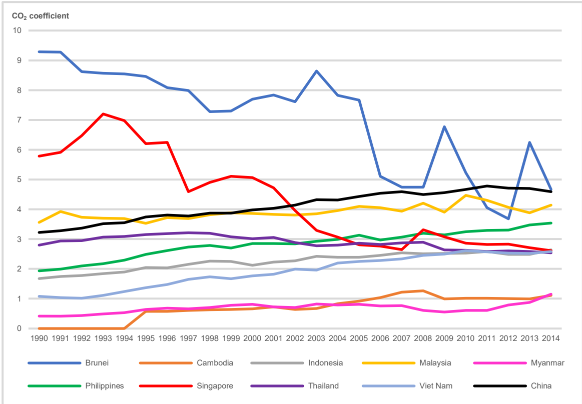

Figure 6 The CO_2 coefficient from 1990 to 2014 in China and the ASEAN countries (kt/ktoe)

The CO_2 coefficient is defined here as the ratio of total CO_2 emissions to total energy consumption, reflecting the change in energy structures. The change tendency of the CO_2 coefficient varied in China and the ASEAN countries. Brunei and Singapore presented a fluctuating change from 1990 to 2014. The CO_2 coefficient of Brunei decreased from 9.29 kt/ktoe in 1990 to 4.66 kt/ktoe in 2014. For Singapore, it decreased from 5.78 kt/ktoe in 1990 to 2.61 kt/ktoe in 2014, while China presented a steady increase from 3.22 kt/ktoe in 1990 to 4.60 kt/toe in 2014, showing a similar trend to most ASEAN countries.

3.2 Decoupling analysis

The GDP decoupling elasticity of CO_2 emissions from 1990 to 2014 in China and the ASEAN countries is presented in Table 2 and depicted in Figure 7. Strong decoupling occurred in Brunei in the second half of the 1990s and the first half of the 2010s, in Myanmar and the Philippines in the second half of the 2000s and in Singapore in the first half of the 2000s, indicating that positive GDP growth accompanied a carbon emission decrease. Weak decoupling occurred in nine countries, namely Cambodia, Myanmar and the Philippines in the first half of the 2000s, Indonesia, Malaysia, Singapore, Thailand and China from 2005 to 2014 and Singapore and China in the 1990s; that is, the GDP growth rate increased more than the carbon emission rate. Vietnam also experienced weak decoupling of the GDP from CO_2 from 2010 to 2014. The CO_2 emissions were expansively coupled to the GDP in Indonesia, Malaysia and Vietnam between 1990 and 1994, Cambodia and Myanmar between 1995 and 1999, Brunei and Thailand between 2000 and 2004 and Cambodia and the Philippines between 2010 and 2014. Expansive negative decoupling was apparent in almost all ten countries during different stages, with a much faster growth rate of carbon emissions than the GDP except in Singapore. The Philippines experienced expansive negative decoupling in the 1990s, as did Vietnam in the 2000s. Strong negative decoupling only occurred in Malaysia and Thailand from 1995 to 1999, meaning negative GDP growth accompanied by a carbon emission increase with unhealthy development.

Over the study period, only three decoupling statuses occurred in the GDP decoupling elasticity of CO_2: namely weak decoupling, expansive coupling and expansive negative decoupling. China, Singapore and Myanmar performed weak decoupling during the period 1990–2014. Thailand, the Philippines and Indonesia presented expansive coupling, while Vietnam, Malaysia and Brunei performed expansive negative decoupling.

Table 2 The GDP decoupling elasticity of CO_2 from 1990 to 2014 in China and the ASEAN countries

	1990–1994		1995–1999		2000–2004		2005–2009		2010–2014		1990–2014	
Brunei	2.2840	END	-1.7986	SD	1.0772	EC	75.3439	END	-13.5022	SD	2.4435	END
Cambodia	-	-	0.9614	EC	0.5560	WD	2.1213	END	0.9945	EC	-	-
Indonesia	0.9637	EC	-21.6530	SND	1.2370	END	0.5965	WD	0.6392	WD	1.0548	EC
Malaysia	1.0928	EC	2.0903	END	1.3926	END	0.5646	WD	0.6950	WD	1.2126	END
Myanmar	1.6308	END	0.8746	EC	0.1268	WD	-0.8831	SD	4.4043	END	0.6568	WD
Philippines	3.8603	END	1.2192	END	0.1808	WD	-0.0026	SD	0.9404	EC	0.9171	EC
Singapore	0.7520	WD	0.0298	WD	-0.3276	SD	0.3246	WD	0.1311	WD	0.1806	WD
Thailand	1.4180	END	-11.0635	SND	1.0862	EC	0.2976	WD	0.7368	WD	1.1815	EC
Vietnam	0.9796	EC	1.5036	END	2.2178	END	1.4876	END	0.5477	WD	1.8497	END
China	0.4265	WD	0.0195	WD	1.2710	END	0.5954	WD	0.5051	WD	0.4090	WD

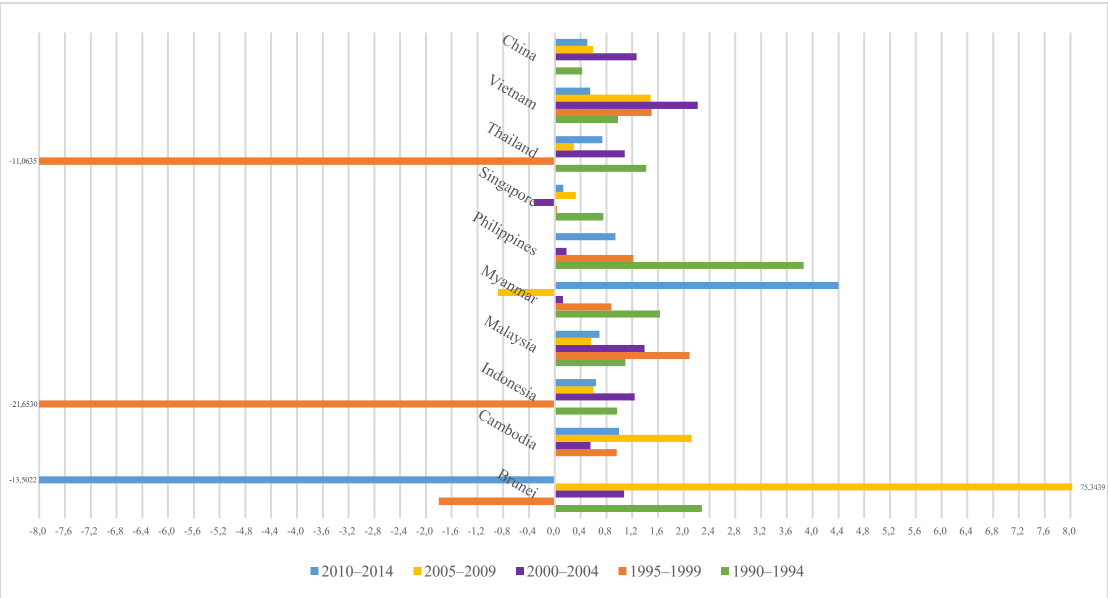

Figure 7 The decoupling of CO_2 from the GDP from 1990 to 2014 in China and the ASEAN countries

The energy consumption decoupling elasticity of CO_2 from 1990 to 2014 is presented in Table 3 and depicted in Figure 8. Most countries entered an era of expansive negative decoupling that lasted for decades, indicating that the growth rate of carbon emissions was much faster than that of energy consumption. Indonesia experienced expansive negative decoupling for the whole period from 1990 to 2014. Expansive negative decoupling was also present in Cambodia from 2005 to 2014, in Myanmar and the Philippines in the 1990s and in Vietnam in both the 1990s and the 2000s. Brunei experienced an alternative change of weak decoupling and strong decoupling during the last two decades, as did Singapore from 1995 to 2004. Thailand performed weak decoupling for 20 years from 1995 to 2014, and for Malaysia it lasted for 10 years from 2005 to 2014. This demonstrates a tendency towards an obviously ameliorated energy structure. China experienced expansive negative decoupling and strong negative decoupling in the 1990s and 2000s and expansive coupling from 2005 onwards, mainly due to its coal-dominated energy structure. Recessive decoupling occurred in Myanmar from 2005 to 2009 and weak negative decoupling in the Philippines in the same period, signifying that deceased energy consumption failed to reduce the level of CO_2 emissions with a similar ratio due to the pollution-centred energy structure.

Table 3 The energy consumption decoupling elasticity of CO_2 from 1990 to 2014 in China and the ASEAN countries

	1990–1994		1995–1999		2000–2004		2005–2009		2010–2014		1990–2014	
Brunei	0.7108	WD	-0.8808	SD	1.1901	EC	0.7259	WD	-0.2541	SD	0.3410	WD
Cambodia	-	-	1.6831	END	-7.2578	SND	1.2367	END	1.5468	END	-	-
Indonesia	1.8371	END	1.6493	END	2.3470	END	1.6588	END	1.4655	END	2.1148	END
Malaysia	1.1136	EC	1.5546	END	1.1258	EC	0.6257	WD	0.6351	WD	1.2176	END
Myanmar	4.9848	END	5.5615	END	0.7273	WD	11.4346	RD	4.7914	END	4.9675	END
Philippines	4.7558	END	2.2561	END	-2.6520	SND	0.5328	WND	1.7157	END	4.0278	END
Singapore	3.5961	END	0.0279	WD	-0.1068	SD	-2.5696	SND	0.1930	WD	0.2293	WD
Thailand	1.3699	END	0.7602	WD	0.7427	WD	0.2846	WD	0.6963	WD	0.8663	EC
Vietnam	2.0082	END	2.2579	END	1.9823	END	1.5170	END	0.9052	EC	2.9474	END
China	1.8809	END	-0.2811	SND	1.2904	END	1.1399	EC	0.9024	EC	1.6344	END

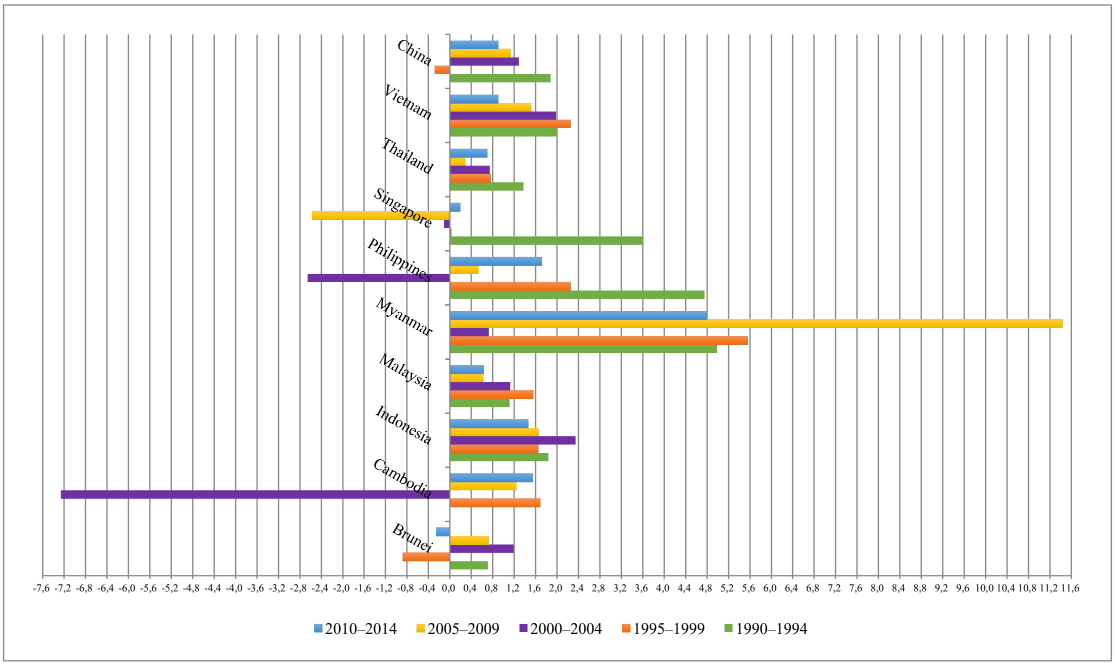

Figure 8 The decoupling of CO_2 from energy consumption from 1990 to 2014 in China and the ASEAN countries

The GDP decoupling elasticity of energy consumption from 1990 to 2014 in China and the ASEAN countries is presented in Table 4 and illustrated in Figure 9. Most countries experienced an era of an alternative change of weak decoupling and strong decoupling or a change of only one of them for decades, such as Cambodia, Indonesia, Myanmar, the Philippines, Singapore, Vietnam and China. The other three countries, Brunei, Malaysia and Thailand, have undergone a period of changing between expansive negative decoupling and expansive coupling during the past decades. Compared with the diversified decoupling status of the ten countries in the 1990s and 2000s, weak decoupling and expansive coupling could be distinguished in most countries from 2010 to 2014, with the decoupling elasticity value being mainly between 0.4 and 1.2, except in Brunei (Figure 9).

Table 4 The GDP decoupling elasticity of energy consumption from 1990 to 2014 in China and the ASEAN countries

	1990–1994		1995–1999		2000–2004		2005–2009		2010–2014		1990–2014	
Brunei	3.2132	END	2.0419	END	0.9051	EC	103.7897	END	53.1459	END	7.1656	END
Cambodia	-	-	0.5712	WD	-0.0766	SD	1.7154	END	0.6429	WD	-	-
Indonesia	0.5246	WD	-13.1290	SND	0.5270	WD	0.3596	WD	0.4361	WD	0.4988	WD
Malaysia	0.9813	EC	1.3446	END	1.2370	END	0.9024	EC	1.0943	EC	0.9959	EC
Myanmar	0.3272	WD	0.1573	WD	0.1743	WD	-0.0772	SD	0.9192	EC	0.1322	WD
Philippines	0.8117	EC	0.5404	WD	-0.0682	SD	-0.0048	SD	0.5481	WD	0.2277	WD
Singapore	0.2091	WD	1.0663	EC	3.0684	END	-0.1263	SD	0.6792	WD	0.7876	WD
Thailand	1.0352	EC	-14.5537	SND	1.4626	END	1.0457	EC	1.0582	EC	1.3638	END
Vietnam	0.4878	WD	0.6659	WD	1.1188	EC	0.9806	EC	0.6051	WD	0.6275	WD
China	0.2267	WD	-0.0693	SD	0.9849	EC	0.5223	WD	0.5598	WD	0.2503	WD

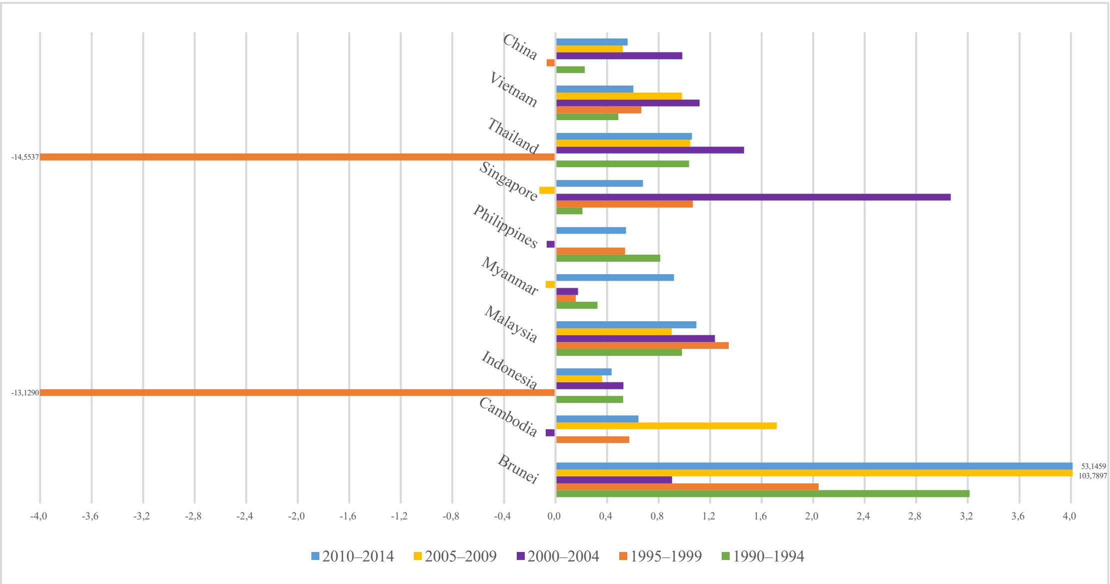

Figure 9 The decoupling of energy consumption from the GDP from 1990 to 2014 in China and the ASEAN countries

3.3 Decomposition analysis of CO_2 emissions

Based on the LMDI model in section 2.2, the contribution of the four factors, namely the carbon density effect, energy intensity effect, per capita GDP effect and population effect, to the total CO_2 emissions in China and the ASEAN countries from 1990 to 2014 is provided in Table 5 and depicted in Figure 10 as percentage values.

The carbon intensity effect (ΔC_{ce}) mainly played a positive role in increasing CO_2 emissions in China and most ASEAN countries, except Brunei, Singapore and Thailand, from 1990 to 2014. The accumulated effect was largest in China, with an increase of 1699.46 Mt, followed by Indonesia and Vietnam, with an increase of 116.48 Mt and 51.87 Mt, respectively, between 1990 and 2014. The carbon intensity effect contributed 65.38% of the total carbon emission change in the Philippines, which ranked number one in the ten countries, followed by Myanmar (63.30%) and Vietnam (41.19%), while it contributed to the decrease in CO_2 emissions in Malaysia from 2005 to 2014, in Myanmar from 2000 to 2004, in the Philippines from 2005 to 2009, in Singapore in the second half of the 1990s and the first half of 2010s and in Thailand from 1995 to 2014.

The energy intensity effect (ΔC_{eg}) was the key factor for decreasing CO_2 emissions in China and the ASEAN countries from 1990 to 2014. Taking China as an example, the energy intensity effect accounted for a decrease of 776.66 Mt, 989.01 Mt, 17.12 Mt, 1106.62 Mt and 1030.07 Mt of the total change in CO_2 emissions in the five research periods from 1990 to 2014, respectively, with the biggest decrease occurring during the first decade of the 2000s. The energy intensity effect contributed a total decrease of 5281.4 Mt, which is 75.17% of the CO_2 emissions in the 25 years in China, followed by Myanmar and the Philippines accounting for an 85.01% and 71.13% decrease in the total CO_2 emissions, respectively. The opposite applies to Thailand, where the energy intensity effect contributed 18.72% of the increase in CO_2 emissions on average between 1990 and 2014. The contribution of the energy intensity effect to the increase in CO_2 emissions was even greater in Brunei, with 145.89% on average from 1990 to 2014.

Compared with the other three factors, the per capita GDP effect (ΔC_{gp}) was the major driving force behind the increase in CO_2 emissions in China and most ASEAN countries. The accumulated effect was largest in China, with an increase of 9725.15 Mt, followed by Indonesia and Thailand, with an increase of 206.63 Mt and 120.13 Mt, respectively, between 1990 and 2014. The contribution of the per capita GDP effect to the increase in CO_2 emissions was significant in China throughout the whole research period, accounting for 184.9% of the total change from 1990 to 1994, 3839.35% from 1995 to 1999, 75.74% from 2000 to 2004, 147.48% from 2005 to 2009 and 172.23% from 2010 to 2014. The contribution of the per capita GDP effect to the increase in CO_2 emissions was also obvious in Brunei, Singapore and Vietnam between 2010 and 2014, in Indonesia and Thailand between 2005 and 2014, in Myanmar between 2000 and 2004 and in Singapore between 1995 and 1999. Exceptionally, the story was different in the Philippines from 2005 to 2009: the per capita GDP played a dominant role in decreasing the CO_2 emissions, as it did in Singapore from 2000 to 2004.

In general, the population effect (ΔC_p) was the main driving force behind the increase in CO_2 emissions in China and the ASEAN countries from 1990 to 2014. The accumulated effect was greatest in China, with an increase of 882.44 Mt, followed by Indonesia and Malaysia, with an increase of 86.61 Mt and 56.80 Mt, respectively, between 1990 and 2014. The contribution of the population effect to the CO_2 emissions was extremely apparent in the Philippines from 2000 to 2004, China and Singapore in the second half of the 1990s and Singapore from 2005 to 2009 and from 2010 to 2014, accounting for 237.53%, 551.76%, 1882.43%, 246.52% and 318.65%, respectively. An exceptional case occurred in Brunei from 1995 to 1999 and from 2010 to 2014 and in the Philippines from 2005 to 2009, during which the population effect played a role in decreasing the CO_2 emissions.

Table 5 Decomposition of CO_2 emissions in China and the ASEAN countries (1990–2014)

		ΔC_{ce} (Mt)	$\Delta C_{ce}/\Delta C$ (%)	ΔC_{eg} (Mt)	$\Delta C_{eg}/\Delta C$ (%)	ΔC_{gp} (Mt)	$\Delta C_{gp}/\Delta C$ (%)	ΔC_p (Mt)	$\Delta C_p/\Delta C$ (%)	ΔC (Mt)
Brunei	1990–1994	-0.30	-34.72	0.77	87.98	0.0039	0.45	0.41	46.29	0.88
	1995–1999	-0.64	205.43	0.17	-52.79	-0.24	77.47	0.41	-130.10	-0.31
	2000–2004	0.08	15.28	-0.04	-8.46	0.12	24.45	0.34	68.72	0.49
	2005–2009	-0.75	-28.78	3.32	127.13	-0.36	-13.78	0.40	15.44	2.61
	2010–2014	-0.78	471.57	0.60	-364.26	-0.39	236.58	0.40	-243.89	-0.16
	1990–2014	-3.29	-95.72	5.01	145.89	-0.60	-17.42	2.31	67.24	3.44
Cambodia	1990–1994	-	-	-	-	-	-	-	-	-
	1995–1999	0.16	37.51	-0.18	-41.04	0.27	61.48	0.18	42.04	0.44
	2000–2004	0.48	115.41	-0.76	-183.46	0.54	130.35	0.16	37.69	0.41
	2005-2009	0.27	15.67	0.53	30.99	0.70	41.26	0.21	12.07	1.71
	2010–2014	0.48	32.27	-0.48	-32.76	1.14	77.08	0.35	23.40	1.48
	1990–2014	-	-	-	-	-	-	-	-	-
Indonesia	1990–1994	18.83	42.03	-20.28	-45.29	35.90	80.16	10.34	23.09	44.79
	1995–1999	21.22	36.43	40.11	68.85	-16.45	-28.25	13.38	22.96	58.25
	2000–2004	33.20	54.77	-22.54	-37.19	34.61	57.09	15.36	25.33	60.62
	2005–2009	17.70	38.10	-45.88	-98.78	56.70	122.06	17.93	38.61	46.45
	2010–2014	18.05	30.20	-48.28	-80.76	68.98	115.40	21.02	35.16	59.78
	1990–2014	116.48	38.49	-107.08	-35.38	206.63	68.28	86.61	28.62	302.64
Malaysia	1990–1994	2.01	8.60	-0.34	-1.46	15.42	65.95	6.29	26.91	23.39
	1995–1999	8.68	32.45	4.30	16.09	4.56	17.04	9.21	34.42	26.75
	2000–2004	3.16	10.04	4.97	15.79	13.16	41.77	10.21	32.40	31.51
	2005–2009	-7.82	-55.97	-2.19	-15.68	12.62	90.34	11.36	81.31	13.97
	2010–2014	-15.75	-51.33	3.61	11.77	30.24	98.56	12.58	41.00	30.69
	1990–2014	17.08	9.99	-0.35	-0.2	97.40	56.98	56.80	33.23	170.93
Myanmar	1990–1994	1.19	77.10	-0.65	-42.24	0.77	50.07	0.23	15.08	1.54
	1995–1999	1.51	80.10	-1.75	-92.61	1.72	91.40	0.40	21.11	1.89
	2000–2004	-0.26	-35.65	-3.63	-503.16	4.23	586.22	0.38	52.59	0.72
	2005–2009	-3.28	92.71	-3.05	86.12	2.55	-72.13	0.24	-6.70	-3.54
	2010–2014	8.20	70.39	-0.26	-2.26	3.30	28.29	0.42	3.58	11.65
	1990–2014	9.90	63.30	-13.30	-85.01	16.70	106.75	2.34	14.96	15.64
Philippines	1990–1994	7.17	77.08	-0.48	-5.16	-1.50	-16.13	4.11	44.20	9.31
	1995–1999	5.29	53.71	-3.63	-36.86	2.71	27.48	5.48	55.67	9.84
	2000–2004	3.32	138.62	-13.24	-553.00	6.63	276.84	5.69	237.53	2.39
	2005–2009	0.03	-87.72	-12.02	35953.10	7.53	-22529.74	4.42	-13235.64	-0.03
	2010–2014	7.28	39.12	-8.33	-44.79	14.19	76.28	5.47	29.39	18.60
	1990–2014	37.70	65.38	-41.02	-71.13	31.60	54.79	29.39	50.96	57.67
Singapore	1990–1994	6.25	69.37	-8.75	-97.18	7.68	85.27	3.83	42.54	9.01
	1995-1999	-7.32	-3147.01	0.43	183.98	2.74	1180.61	4.38	1882.43	0.23
	2000–2004	-20.54	822.64	11.25	-450.49	5.41	-216.62	1.39	-55.52	-2.50
	2005–2009	3.49	140.70	-8.19	-330.42	1.07	43.20	6.11	246.52	2.48

	2010–2014	-4.14	-394.55	-2.25	-215.06	4.10	390.96	3.34	318.65	1.05
	1990–2014	-29.04	-177.40	-6.41	-39.18	30.44	185.98	21.38	130.60	16.37
Thailand	1990–1994	9.85	23.11	0.95	2.24	28.09	65.89	3.74	8.77	42.64
	1995–1999	-3.53	-29.94	16.42	139.39	-7.63	-64.73	6.51	55.28	11.78
	2000–2004	-12.33	-29.70	15.28	36.81	31.27	75.32	7.29	17.56	41.52
	2005–2009	-16.61	-237.21	0.98	13.94	20.53	293.22	2.10	30.06	7.00
	2010–2014	-8.26	-41.06	1.47	7.32	23.31	115.89	3.59	17.84	20.12
	1990–2014	-14.47	-8.90	30.44	18.72	120.13	73.87	26.53	16.31	162.63
Vietnam	1990–1994	2.80	46.49	-2.91	-48.29	4.72	78.19	1.42	23.60	6.03
	1995–1999	6.53	50.95	-2.76	-21.52	6.97	54.40	2.07	16.17	12.81
	2000–2004	12.65	43.29	1.55	5.30	12.26	41.97	2.76	9.43	29.22
	2005–2009	9.87	30.37	-0.40	-1.22	18.96	58.32	4.07	12.53	32.51
	2010–2014	-1.68	-9.77	-11.04	-64.12	24.19	140.50	5.75	33.40	17.22
	1990–2014	51.87	41.19	-21.01	-16.68	76.09	60.42	18.98	15.07	125.93
China	1990–1994	226.39	44.14	-776.66	-151.43	948.31	184.90	114.84	22.39	512.88
	1995–1999	96.05	461.59	-989.01	-4752.70	798.94	3839.35	114.82	551.76	20.81
	2000–2004	313.21	19.11	-17.12	-1.05	1241.07	75.74	101.44	6.19	1638.59
	2005–2009	182.63	10.92	-1106.62	-66.14	2467.38	147.48	129.65	7.75	1673.04
	2010–2014	-137.10	-9.89	-1030.07	-74.33	2386.91	172.23	166.11	11.99	1385.86
	1990–2014	1699.46	24.19	-5281.40	-75.17	9725.15	138.42	882.44	12.56	7025.66

3.4 Discussion

Both China and the ASEAN countries have committed to reducing their carbon emissions in compliance with the Paris Agreement. China aims to lower its CO_2 emissions per unit of GDP by 60 to 65% from the 2015 level by 2030 and to increase its non-fossil fuel energy to 20% of its energy mix. As a country dominated by coal consumption, CO_2 emission reduction has been written into its 13th Five-Year Plan for 2016 to 2020 to stipulate a maximum 58% share of coal in the national consumption by 2020 (Lin 2017). Relative policies also include an emission trading system and a mandatory renewable energy certificate scheme. Similarly, a carbon-intensive energy structure with a fossil fuel-dominated energy mix is common in the ASEAN region, mainly due to fossil fuel's relative abundance and low cost. The IEA statistics (2019) show that China is the world's biggest coal producer, with 45.4% of the world total. Indonesia ranks as the world's fourth-largest coal producer, with 7.0% of the world total, and as the top net exporter, while China, Malaysia and

Thailand are the first, eighth- and ninth-largest importers. Fossil fuels (coal, gas and oil) will account for 78% of South-East Asia's primary energy demand, driven by coal consumption tripling by 2040 (The Economist Corporate Network 2016). Following China's use of coal-dominated energy in the past few decades is certainly not the best option for the ASEAN region. Countries like Indonesia, Malaysia, the Philippines and Vietnam have other decarbonized options, such as natural gas, to lower the carbon intensity and substitute their coal generation. The impact of energy choice and replacement could be inspiring. It is predicted hypothetically that replacing all the coal generation from the electricity mix with wind could displace 764 $MtCO_2$, which is sufficient to meet the ASEAN region's unconditional target (a reduction of 415 $MtCO_2$) but insufficient to achieve its conditional target (a reduction of 899 $MtCO_2$) (Paltsev et al. 2018). A single option is hardly sufficient to achieve the emission reduction targets. As illustrated earlier, the carbon intensity effect is one of the major factors driving the increase in CO_2 emissions, and the region's high dependence on carbon-intensive energy makes it a great challenge to undertake the transition from a carbon-intensive to a low-carbon economy. The potential to develop renewable energy is vast in the region. For example, Indonesia is abundant in hydropower, biomass and geothermal, and most ASEAN countries are supplied with wind power, hydropower and solar energy (ACE 2016). Solar and wind generation in the ASEAN region are projected to grow fivefold between 2015 and 2030 (Paltsev et al. 2018). An ameliorated energy structure adapting to lower carbon energy and new clean technologies is the wise path to follow.

It can be seen from the decomposition analysis that energy intensity is the major driving factor behind the decrease in CO_2 emissions. The finding is in line with the study of Chontanawat (2018) and Pani and Mukhopadhyay(2013). The ASEAN has committed to reducing its energy intensity by 20% from the 2005 levels by 2020 and by 30% by 2025 and to increase renewable energy to 23% of its energy mix by 2025, as stated in the ASEAN Plan of Action for Energy Cooperation (APAEC) 2016–2025 (ACE 2015). Even though it is not binding, it demands that the ASEAN makes substantial efforts to facilitate policy implementation, diversify the energy mix and cut emissions by guaranteeing the broader incorporation of renewable energy and greater energy efficiency. None of the above could be realized without strong political willingness, administrative capacities, specific mandates, financial resources and public awareness of low carbon lifestyle to implement a tailor-made policy framework for each country in the region.

The per capita GDP has been identified as one of the major driving factors for the increase in carbon emissions. It is in line with the study of Chontanawat (2019), Pani and Mukhopadhyay (2011), Yao et al.(2015) and many others. The GDP is projected to grow steadily in the ASEAN region, with the lowest growth rate of 2.39% in Brunei and the highest growth rate of 7.87% in Myanmar (Paltsev et al. 2018). From the economic point of view, only Singapore and Brunei are classified as high-income economies, China, Thailand and Malaysia are grouped into the upper-middle-income economies and the remaining six countries are in the group of lower-middle-income economies (The World Bank 2019). This means that there is huge potential for the region to achieve continued economic growth and raise living standards with increasing energy consumption. It is predicted that the energy consumption of the ASEAN region will grow by about 80% while electricity will grow by about 115% from 2015 to 2030 (Paltsev et al. 2018). It seems overly demanding to conduct decarburization in the region, as no decoupling of economic growth from CO_2 emissions can be found in the aggregate region's data in the past two decades.

Population growth, identified as the major driving factor for the increase in carbon emissions, is projected to be steady by 2030 in all nine ASEAN countries, with the lowest average annual growth rate of 0.1% in Thailand and the highest average annual growth rate of 1.4% in the Philippines (Paltsev et al. 2018). The positive relationship between population and CO_2 emission is supported by many of the studies (Chontanawat, 2019; Pani and Mukhopadhyay, 2011; Rahman 2017; Salman et al.2019; Yao et al., 2015; Zhu et al., 2016). The role of the population as an up-pulling determinant on CO_2 could be understood from different perspectives. The population growth causes increased consumption of resources such as energy, leading to increased CO_2 emission. Population as a determinant factor to the increase of CO_2 emission is not only simply affected by its number but also by its affluence (Pani and Mukhopadhyay, 2013). Furthermore, urbanization as a variable linearly related with the population in most countries, has found to have a significant positive relationship with CO_2 emission (Al-Mulali et al., 2015; Ali et al., 2019; Akram et al., 2019; Mamun et al., 2014; Phong, 2019; Yao et al., 2015). While scholars argue the extent of influence varied in terms of the level of emission and income in different countries (Akram et al., 2019). It indicates the complexity of the causation behind CO_2 emission with regard to population growth. Therefore, whether optimum population growth or deurbanization should be employed depends on the different contexts.

At the country level, the energy intensity effect has negative values during all the five sub-research periods in China, indicating there has been a continuous amelioration of energy structure, so does it in the Philippines and Myanmar. The emission intensity effect has negative values in Brunei and

Thailand for four of the five sub-research periods, meaning a steady shifting towards less emitting energy. Singapore set a good example to follow as both carbon intensity effect and energy intensity effect contributed to the decrease of CO_2 emission, which means its continuous stepping to low carbon energy usage and less energy - intensive economic development. Since the four selected decomposed effects were set as the predefined factors of interest, their role of positively or negatively affecting the decrease of CO_2 emission is relatively determined, as adding new factors or a different combination of factors of interest could result in a different conclusion. While the result of this study is in accordance with many of the conclusions in current literature as referred above.

It is worthy to mention that the GDP decoupling elasticity of CO_2 performed gradually improvement in Indonesia, Vietnam, and China from 2000 to 2014 at different levels. The steady progress also presented in Myanmar and the Philippines during the two decades from 1990 to 2009. In Singapore, this period is relatively shorter from 1990 to 2004. Malaysia experienced a continuously improving stage from 1995 to 2009 with regard to the GDP decoupling elasticity of CO_2. While Brunei, Cambodia, and Thailand fluctuated dramatically and changed irregularly. The trend of the continuously improved decoupling status could be interrupted by negative numbers of GDP, as indicated in Indonesia and Thailand from 1995 to 1999 with strong negative decoupling presented. Singapore performed the best decoupling status during the whole research period, with weak decoupling of 0.18, followed by China of 0.409 and Myanmar of 0.657. Comparing the two sub-decoupling elasticity, the GDP decoupling elasticity of energy consumption performed much better than the energy consumption decoupling elasticity of CO_2, with six countries presented a weak decoupling in the former and six countries presented expansive negative decoupling in the latter (see Table 2 and 3).

Considering China and ASEAN region as a whole, the decoupling result should be critically interpreted. As argued by Ward et al. (2016), if the trade between China and ASEAN countries embodied in monetary flow is not accompanied by material usage and energy consumption, this part of the contribution will also be calculated into GDP growth. Furthermore, separating production from consumption could also cause the export of CO_2 to other regions. Moreover, transboundary CO_2 emission brings environmental externalities, which is not considered in decoupling research, meriting further understanding.

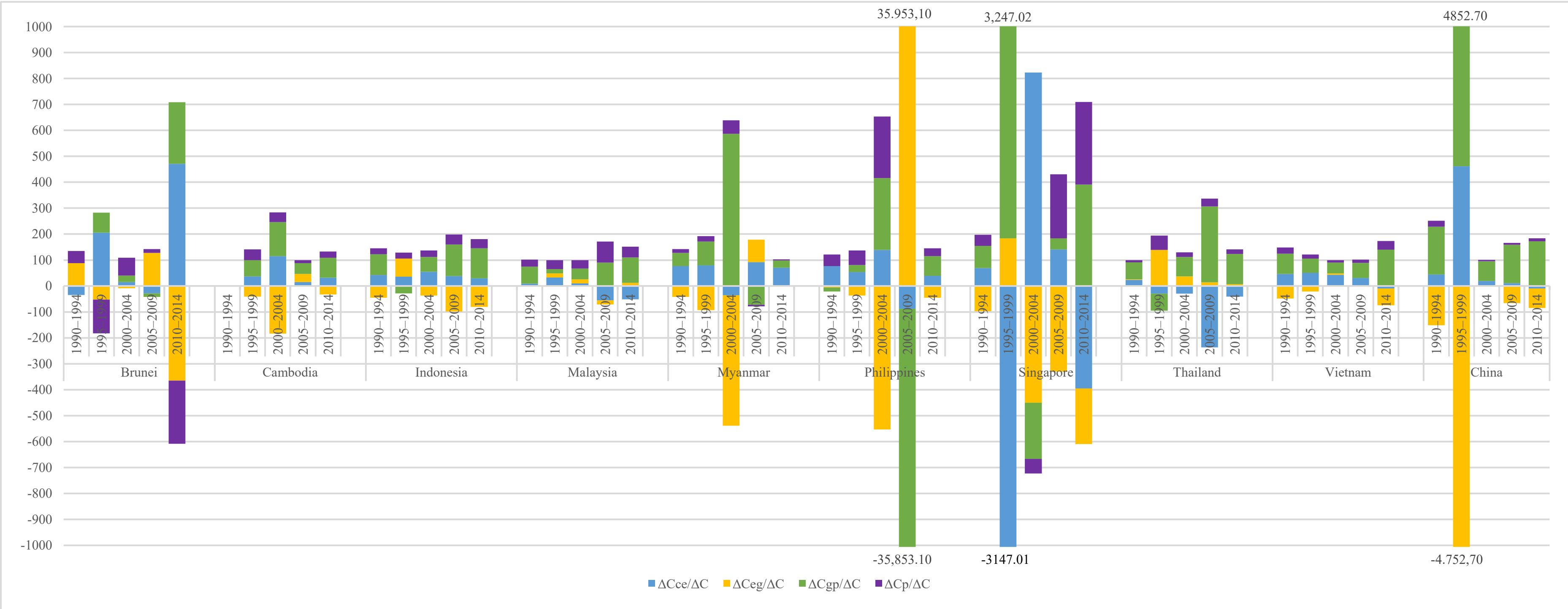

Figure 10 Decomposition of CO_2 emission changes in percentages (1990–2014) (unit: %)

4. Conclusions

The combination of decoupling and decomposition analysis provides insights into the relationship between economic growth and carbon emissions by investigating the decoupling statuses occurring and their driving forces. This paper studied the different statuses of decoupling indicators in China and the ASEAN countries during the period 1990–2014 and the factors driving the changes in CO_2 emissions. While no decoupling of economic growth from CO_2 emissions can be found in the aggregate region's data in the past two decades, over the study period, only three decoupling statuses occurred in the GDP decoupling elasticity of CO_2: namely weak decoupling, expansive coupling and expansive negative decoupling. China, Singapore and Myanmar performed weak decoupling during the period 1990–2014. Thailand, the Philippines and Indonesia presented expansive coupling, while Vietnam, Malaysia and Brunei performed expansive negative decoupling. To decompose the driving forces behind CO_2 emissions, the carbon density effect (ΔC_{ce}), the per capita GDP effect (ΔC_{gp}) and the population effect (ΔC_p) mainly played a role in increasing CO_2 emissions in China and most ASEAN countries from 1990 to 2014, while the energy intensity effect (ΔC_{eg}) was the key factor for decreasing CO_2 emissions in China and the ASEAN countries from 1990 to 2014.

Though China and the ASEAN countries are experiencing different stages of economic development, they are facing the same challenge regarding the balance between the environment and economic growth. Strong decoupling of economic growth from carbon emissions has rarely happened in the region. Optimistically speaking, the energy intensity effect has played a role in decreasing CO_2 emissions in China and most ASEAN countries, demonstrating environmentally friendly changes in the energy structure. This is far from enough, as the other three effects, namely the carbon density effect (ΔC_{ce}), the per capita GDP effect (ΔC_{gp}) and the population effect (ΔC_{p}), are outweighing the effect of energy intensity. Thus, both China and the ASEAN countries need to scale up the share of renewable energy, increase the efficiency of energy use and implement green development as long-term targets in the region.

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