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Research article

Emission growth and drivers in Mainland Southeast Asian countries

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A R T I C L E I N F O

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A B S T R A C T

Mainland Southeast Asian (MSEA) countries (Cambodia, Laos, Thailand, Myanmar, and Vietnam) are likely to become one of the next hotspots for emission reduction, since CO_2 emissions in this area will have a two-thirds increase by 2040 due to rapid economy growth and associated energy consumption. As one of the most vulnerable areas to climate change, MSEA countries need to develop low-carbon roadmaps based on accurate emission data. This study provides emission inventories for MSEA countries for 2010-2019, based on the IPCC territorial emission accounting approach , including emissions from five types of fuels (i.e., coal, crude oil, oil products, natural gas, and biofuels & waste) used in 47 economic sectors. The results show that the emissions in MSEA countries are on the rise, with average annual growth rates ranging from 2.5% in Thailand to 19.3% in Laos. Biomass is one of the most important sources of carbon emissions, contributing between 11.8% and 76.7% of total carbon emissions, but its share has been declining in most countries, whereas the share of emissions from coal has risen sharply in Laos, Vietnam, and Cambodia. We further examine the drivers behind the changes in emissions using index decomposition analysis. Economic growth was the strongest driver of growth in emissions, while population growth has only had a small effect on emission growth. Energy intensity varies widely across nations, but only significantly reduced CO_2 emission growth in Thailand. The secondary sector considerable contributed to an increase in CO_2 emissions in Laos and Vietnam, while the tertiary sector only moderately contributed to emissions in Thailand. Our study provides a better understanding of the composition and underlying factors of emission growth in MSEA countries, this could shape their low-carbon development pathway. Our results could also inform other emerging economies, which may become emission hotspots in the next decades, to develop low-carbon roadmaps, thereby contributing to the achievement of global climate change targets.

1. Introduction

Carbon mitigation actions should be based on accurate emission accounting, providing a comprehensive understanding of CO_2 emission patterns (Li et al., 2017). Discussions on how to mitigate climate change and reduce CO_2 emissions have historically focused on larger economies, such as the U.S., China, and the EU (Dai et al., 2017; Guan et al., 2018; Xiao et al., 2022). While carbon emissions in a growing number of developed countries are already falling or are about to fall (Le Quéré et al., 2019), emissions in developing countries are likely to continue to rise as their economic growth still highly depends on fossil fuels (Jackson et al., 2018). There is no doubt that the next combat zone of emission reduction will shift to developing countries such as the Mainland Southeast Asian (MSEA) countries. On one hand, like many other emerging economies, MSEA countries are benefiting from cheap labor costs and weak environmental regulations, supporting fast-growing manufacturing activities (Sumabat et al., 2016). Consequently, emissions from MSEA countries have increased by 60.0% from 2008 to 2018 according to the International Energy Agency (IEA) (IEA, 2020a). On the other hand, due to the fact that Myanmar, Laos, and Cambodia are still among the least developed countries and have large coastal areas in Thailand, Vietnam, and Myanmar, MSEA countries are among the most vulnerable areas to climate change. Considering these trends, exploring a low-carbon roadmap that satisfies economic development, and meanwhile lowers the environmental burden seems to be the best option, which is in line with national interests, and meets low-carbon

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efforts globally.

However, there is limited knowledge about national level emissions in MSEA countries. Theres is some research on a few specific sectors on the Indochinese peninsula, such as the power sector in Thailand and Vietnam (Huy and Kim Oanh, 2017; Limmeechokchai and Suksuntornsiri, 2007), the transport sector in Cambodia and Thailand (Hak et al., 2017; Ratanavaraha and Jomnonkwao, 2015), the residential sector (Huy et al., 2021; Thuy and Limmeechokchai, 2015), or on a specific fuel type such as biomass emissions (Lasko et al., 2017; Luukkanen et al., 2015), but a comprehensive overview of emissions by sector and energy type and comparison between countries is still lacking.

There are a number of global datasets such as the ones provided by the IEA (2020a), Carbon Dioxide Information Analysis Centre (CDIAC) (Boden et al., 2017), and Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2020), which include national-level emission inventories for these countries, but there are still huge inconsistencies between their estimates. For example, for Myanmar, the total CO_2 emission estimate by the IEA (30.40 Mt) (IEA, 2020a) is 41.7% lower than EDGAR (43.07 Mt) (Crippa et al., 2020) for 2017. Furthermore, the data from these sources lack transparency as the underlying activity data is not publicly available and provide less detailed classification (Shan et al., 2020), making it hard to verify the accuracy of these inventories, which further leads to obstacles for research using these emission data (Chontanawat, 2018, 2019; Lopez et al., 2021; Zhang et al., 2020).

Similar geographic location and resource endowment have led to many similarities in these Indochinese countries, whereas differences in driving forces may lead to different emission patterns and thus require potentially different mitigation strategies in each country. Even though previous studies have investigated the driving forces in this region, they are more focused on the whole group of ASEAN countries (Khan and Majeed, 2020; Lisaba and Lopez, 2021), which include MSEA countries. These studies lack detailed information on the drivers of each MSEA country separately and make it difficult to assess national characteristics. Meanwhile, even though some analyses include some information related to MSEA countries, it is also important to compare the results over time and in different countries to develop carbon mitigation strategies based on the best available data.

To fill these research gaps, we provide territorial emission accounts for five Indochinese countries from 2010 to 2019, for five fuels (i.e., coal, crude oil, oil products, natural gas, and biofuels & waste) used in 47 economic sectors. We further examine the drivers behind emission changes for each country employing index decomposition analysis (IDA). The findings will help Indochinese countries to have a better understanding of their emission pattern and driving forces and barriers of emission change and thus improve the evidence base for carbon emission reduction plans. In addition, our results could provide a reference for other ASEAN countries and emerging economies, who are at a fast-developing stage and face similar challenges of climate change mitigation.

2. Methods and data

2.1. Emission accounts

Territorial emissions refer to emissions that occur within national territories and offshore areas under national jurisdiction while excluding emissions from international aviation or shipping (IPCC, 1996). The majority of territorial emissions are caused by fossil fuel combustion (Nataly Echevarria Huaman and Jun, 2014), that is, energy-related emissions. Considering this, this work focused on energy-related CO_2 emissions. According to the IPCC inventory guidelines (IPCC, 2006), energy-related CO_2 emissions can be calculated as Equation (1):

$$CE = \Sigma_j \Sigma_i CE_{ij} = \Sigma_j \Sigma_i AD_{ij} \times NCV_i \times CC_i \times O_i \quad (1)$$

where CE refers to total CO_2 emissions; CE_{ij} indicates CO_2 emissions in sector j caused by combustion of fuel type i (e.g., CO_2 emissions from coal in manufacturing); AD_{ij} refers to the activity data. More specifically, it displays the number of fuels by type i consumed in the sector j. Our inventories include emissions from both final energy consumption and transformation processes (e.g., emissions from coal combustion for thermal power conversion in power plants). NCV_i stands for the net calorific value of fuel i, i.e., the heat produced by burning one unit of fuel i. CC_i is the carbon content of fuel type i, which refers to the amount of carbon emitted per unit of heat value of fuel type i. O_i indicates the oxidation factor of fuel i during combustion, meaning the percentage of the carbon that is oxidized to CO_2 during combustion. The emission factors were collected from the IPCC default value.

2.2. Activity data and data sources

Energy consumption data and emission factors are used to estimate the emissions. Energy data used in this study are from national and regional sources. Since the definition of sectors differs between countries, we reallocate sectoral energy consumption data into 47 sectors (shown in Supplemental Information Table S1) according to the International Standard Industrial Classification of All Economic Activities (United Nations, 2008). We estimated the CO_2 emissions from five fuels (i.e., coal, crude oil, oil products, natural gas, and biofuels & waste) (shown in Supplemental Information Table S2). The time period for the emission inventory is 2010–2019 but varies for different countries due to data availability. Detailed data sources are listed by country in Table 1 and Supplemental Information Table S3.

Table 1
Data sources: energy statistics and CO_2 emissions.

Country	Data type	Source
Lao PDR	Energy balance table	Economic Research Institute for ASEAN and East Asia (Lao PDR Ministry of Energy and Mines, 2020)
	Emission factor	IPCC (IPCC, 2021)
	Reallocation indicator (GDP)	Laos Statistical Information Service (Laos Statistical Information Service, 2022)
Cambodia	Energy balance table	Economic Research Institute for ASEAN and East Asia (ERIA&Cambodia Ministry of Mines and Energy, 2019)
	Emission factor	IPCC (IPCC, 2021)
	Reallocation indicator (IO)	Asian Development Bank (Asian Development Bank, 2021a)
Vietnam	Energy balance table	Vietnam General Statistics Office (Vietnam General Statistics Office, 2019)
	Emission factor	IPCC (IPCC, 2021)
	Reallocation indicator (Turnover)	Vietnam General Statistics Office (Vietnam General Statistics Office, 2019)
Thailand	Energy balance table	Ministry of Energy of Thailand (Ministry of Energy of Thailand, 2021)
	Emission factor	IPCC (IPCC, 2021)
	Reallocation indicator (GDP)	Asian Development Bank (Asian Development Bank, 2021c)
Myanmar	Energy balance table	Economic Research Institute for ASEAN and East Asia (ERIA & Myanmar Ministry of Electricity and Energy, 2020)
	Emission factor	IPCC (IPCC, 2021)
	Reallocation indicator (GDP, State-Owned Economic Enterprises)	Asian Development Bank (Asian Development Bank, 2021b) Myanmar Statistical Information Service (Myanmar Statistical Information Service, 2021)

Note: Reallocation indicator refers to the indicator to map the energy consumption of the sector provided by the country to the 47 standardized sectors in this work.

2.3. Index decomposition analysis

There are two widely used decomposition analysis approaches, namely, structural decomposition analysis (SDA) and index decomposition analysis (IDA) (Dong et al., 2018). SDA is usually used in combination with input-output models (Rose and Casler, 1996). Compared with SDA, IDA has lower data requirements and is widely used in the area of energy-related emissions analysis (Ang and Zhang, 2000; Dong et al., 2018; Shan et al., 2019). Among many IDA approaches, the logarithmic mean Divisia index (LMDI) decomposition method is commonly applied in the field of energy and environment (Ang, 2015). This is mainly due to its advantages, such as easy-to-interpret results and no residuals (Akyürek, 2020; Ang, 2015; Ang and Choi, 1997; Ang et al., 1998). The IPCC frequently uses the Kaya identity to analyze the drivers of emissions (Dhakal et al., 2022). Following previous studies (Guan et al., 2018; Jung et al., 2012; Štreimikienė and Balezentis, 2016; Zheng et al., 2018), we use the Kaya identity to decompose emissions into five drivers. Similar to previous studies, we only decompose the emissions from economic sectors and excluded the emissions from the household. This could make the value of energy intensity as a driver in the decomposition analysis lower than the national energy intensity calculated as the total energy consumption divided by GDP. The Kaya identity can be expressed as follows:

$$CO_2 = int_C \times str_{en} \times int_{en} \times Eco \times Pop = \Sigma_j \frac{C_j}{E_j} \times \frac{E_j}{E} \times \frac{E}{GDP} \times \frac{GDP}{Pop} \times Pop \tag{2}$$

Where $int_C = \frac{C_j}{E_j}$ refers to carbon intensity in sector j (i.e., emissions per unit of energy consumption); $str_{en} = \frac{E_j}{E}$ refers to the energy consumption structure, which is the proportion of the energy consumption in total energy use in sector j; $int_{en} = \frac{E}{GDP}$ refers to energy intensity, which is quantified as energy consumption per GDP; $Eco = \frac{GDP}{Pop}$ indicates the GDP per capita which measures the economic growth effect; Pop is the population of each country. Supplemental Information Table S1

Based on Ang (2005), we adopt the additive approach to decompose the total CO_2 emission change between year 0 and year t in each country as follows:

$$\Delta CO_2 = CO_2^T - CO_2^0 = \Delta C_{int-carbon} + \Delta C_{str-energy} + \Delta C_{int-energy} + \Delta C_{economy} + \Delta C_{population} \tag{3}$$

in which, $\Delta C_{int-carbon}, \Delta C_{str-energy}, \Delta C_{int-energy}, \Delta C_{economy}, \Delta C_{population}$ are the quantified contributions from each driver to the emissions.

3. Results

3.1. Emission trends

Fig. 1 shows that 684.37 Mt CO_2 were emitted on the Indochinese peninsula in 2017, i.e., 2.1% of global emissions (IEA, 2020a), and the emissions kept increasing over the entire period. Thailand contributed the most, followed by Vietnam. These two countries account for more than 80.0% of the region's total emissions. Laos had the least emissions until 2016 after which it surpassed Cambodia's emissions, mainly due to the huge emissions from the Hongsa coal fire plant. After Hongsa started to operate, the annual emission in Laos surged from 9.62 Mt in 2014 to 24.30 Mt in 2017, with an average annual growth rate of 36.2%. Vietnam's CO_2 emissions also increased rapidly, with an annual rate of 17.9%. Thailand has the slowest growth rate with 2.5% from 2013 to 2019. In terms of per capita emissions Supplemental Information Fig. S1, Thailand had the highest number in 2017 (4.94 tons), followed by Laos (3.49 tons). Even though Laos has almost the lowest emissions among Indochinese countries, its per capita emissions are significantly higher than in the other countries, especially Cambodia and Myanmar (1.18

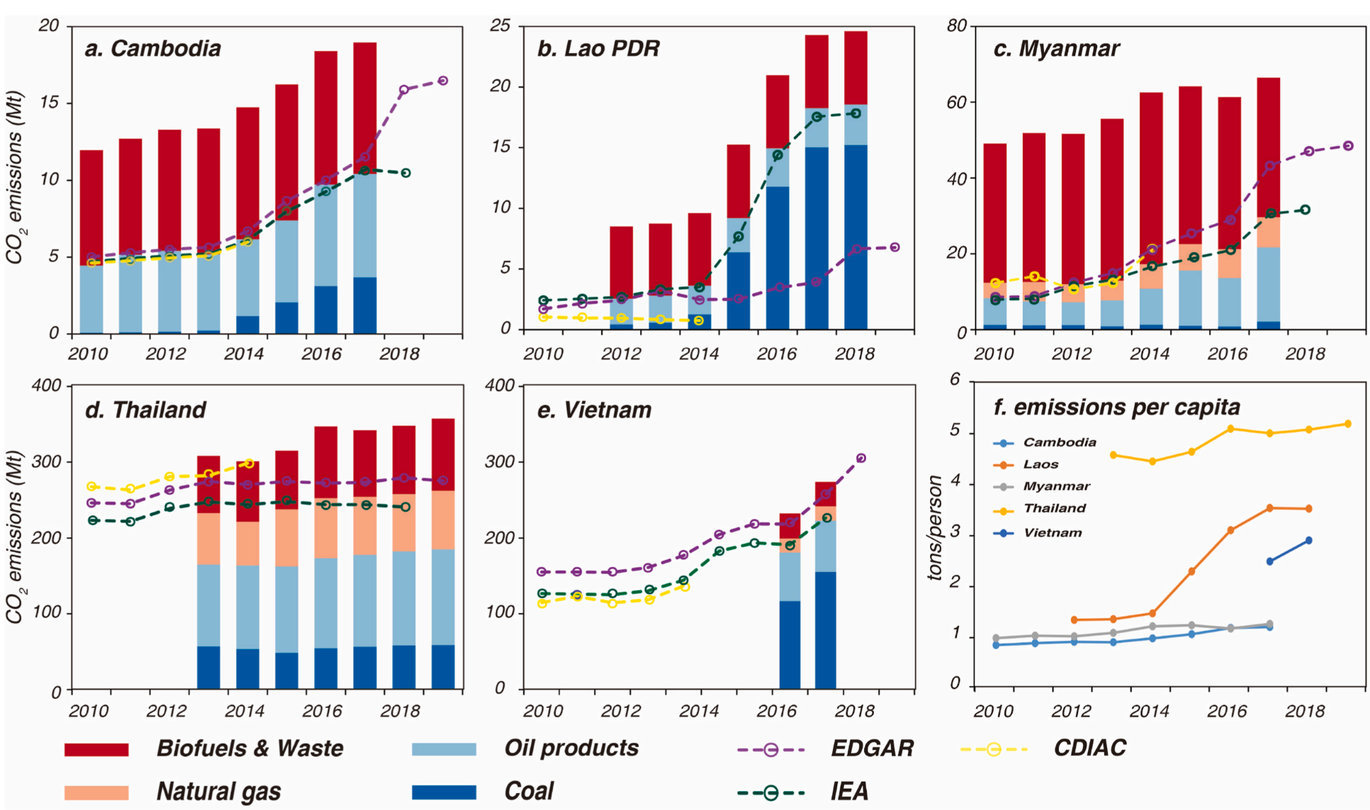

Fig. 1. Aggregate CO_2 emission trends, emissions by fuel type, and emissions per capita. Note that, a-e refer to aggregate CO_2 emission trends and emissions by fuel type by country, and f indicates emissions per capita.

tons and 1.24 tons, respectively).

Urbanization is still at an early stage on the Indochinese peninsula. For example, Thailand has the highest percentage of the urban population with 50.0% in 2018, compared to 23.4% in Cambodia (World Bank, 2019). Given the large share of the rural agricultural population, biomass combustion is an important source for CO_2 emissions among Indochinese countries contributing between 11.8% (Vietnam 2018 data) and 76.7% (Myanmar 2013 data) of carbon emissions. Crop residues are the dominant fuel in rural areas and are a convenient and cheap source, mainly used for cooking and heating (MEM&ERIA, 2020; MME&ERIA, 2019; Tun and Juchelková, 2019), especially in Myanmar and Cambodia. In 2010, biomass contributed 74.8% (or 36.68 Mt) and 62.8% (or 7.51 Mt) of emissions in these two countries respectively. However, the share of biomass emissions experienced a decrease in most Indochinese countries. For example, in Myanmar and Cambodia, emissions dropped to 55.3% (or 36.76 Mt) and 45.0% (or 8.53 Mt) in 2017, respectively. In Laos, this phenomenon is even more pronounced, where the biomass emission share dropped from 70.1% (or 5.97 Mt) in 2012 to 24.6% (or 6.05 Mt) in 2018. While, with the advancement of industrialization, the share of fossil fuels in these countries has been increasing, the energy efficiency of biomass is improving, due to the promotion of high-efficiency stoves by the government in rural areas (ERIA & Myanmar Ministry of Electricity and Energy, 2020; MEM&ERIA, 2020; MME&ERIA, 2019). The only exception is Thailand, where biomass emissions and its share increased from 24.4% (or 75.36 Mt) in 2013 to 26.6% (or 95.07 Mt) in 2019. This growth is mainly due to the increased consumption of bagasse, a fibrous material that remains after crushing sugarcane or sorghum stalks, which is mainly consumed in the power sector to generate electricity, this could be seen from the energy balance table in Thailand. As a result, bagasse-related emissions increased from 23.68 Mt in 2013 to 38.52 Mt in 2019.

The share of fossil fuel emissions has been increasing among Indochinese countries. In Laos, Vietnam, and Cambodia, coal emissions have risen sharply. In Cambodia, the emission share of coal increased from 0.7% (or 0.09 Mt) in 2010 to 19.4% (or 3.68 Mt) in 2017. In Vietnam, its emission share increased from 50.2% (or 116.63 Mt) to 56.7% (or 155.38 Mt) between 2017 and 2018. Laos has seen the largest growth, the coal emission share increased from 5.2% (or 0.44 Mt) in 2012 to 61.8% (or 15.22 Mt). In these countries, coal is mainly consumed in power generation to meet the growing electricity demand. In comparison, in Myanmar, oil products emissions have doubled with an increase from 14.4% (or 7.08 Mt) in 2010 to 29.4% (or 19.56 Mt) in 2017. This growth mainly comes from the transport sector. Different from other Indochinese countries, the fossil fuel emission structure in Thailand is relatively stable and its total fossil fuel emission share even displayed a slight downward trend overall, from 75.6% (or 232.91 Mt) in 2013 to 73.4% (or 262.09 Mt) in 2019.

3.2. *Characteristics of sectoral emissions*

We further consolidate 47 sectors into 9 main sectors in Fig. 2. The result shows that Power & Heat sector accounts for the majority of the total emissions in most Indochinese countries (except for Myanmar). This is mainly due to the strong electricity demand, due to industrialization, urbanization, and electrification in these countries. The emission share of the Power & Heat sector in Myanmar is smaller compared to the other countries, due to its lower electrification rate. More than 30.0% of the population in Myanmar has no access to electricity, whereas in Cambodia, the second-lowest performer, this number is only 7.0% (World Bank, 2019). The emission share of the Power & Heat sector has risen most significantly in Laos. After the Hongsa coal-fired power plant was put into use in 2015, its power sector emission was 35.9 times that of 2014, and the emission share increased from 1.7% (or 0.16 Mt) to 38.1% (or 5.81 Mt). After 2015, the emission share of the power sector continues to rise and gradually stabilized in 2018, which contributed 61.4% (or 15.10 Mt) of the total emissions. Thailand experienced a huge leap in the Power sector's emission share between 2015 and 2016, which increased from 34.4% (or 108.28 Mt) to 39.9% (or 138.53 Mt) and then gradually dropped to 36.8% (or 131.51 Mt) in 2019, due to the economic recession in Thailand from 2013 to 2015. The economic downturn suppressed the electricity demand, further curbing the growth of emissions from this sector. Starting from 2016, the economy started to recover, contributing to a sharp rise in 2016. However, renewable energy as a share of the total primary energy supply increased by 6.9% between 2013 and 2018 (International Renewable Energy Agency, 2021), and in addition, electricity generated by the Hongsa power plant

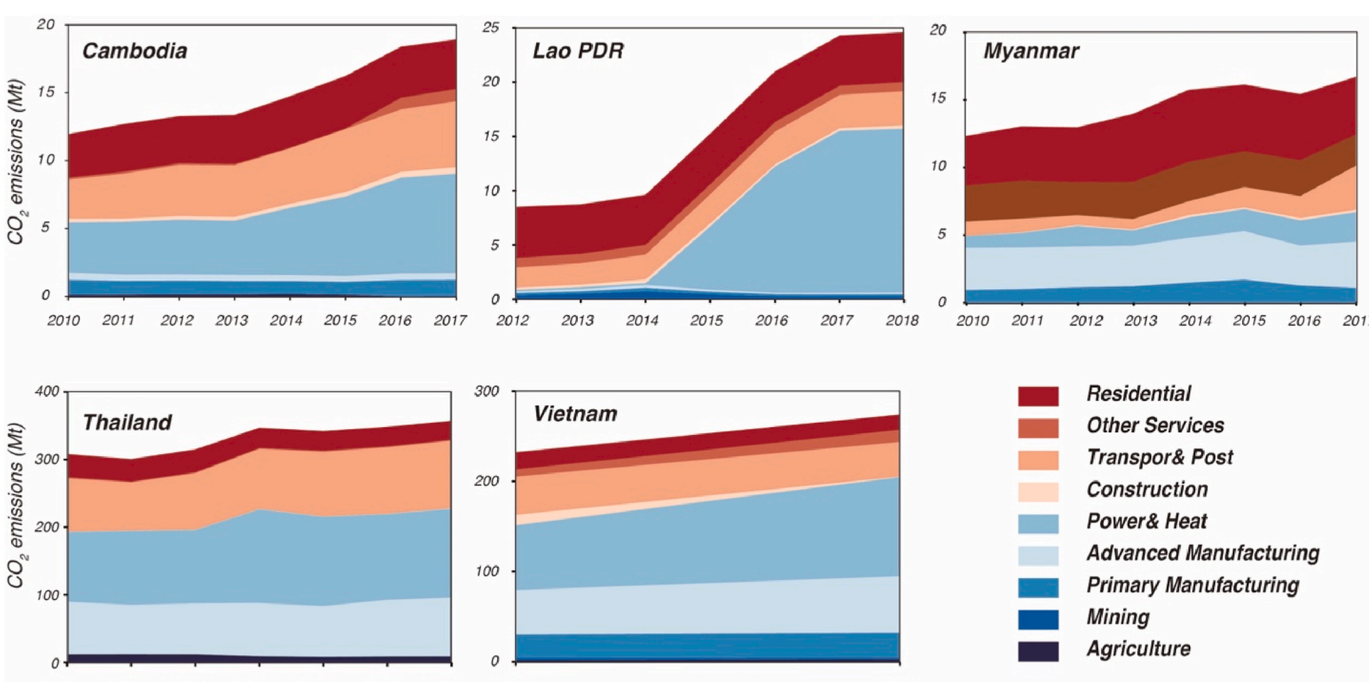

Fig. 2. Sectoral emissions of Indochinese countries.

is exported to Thailand, which reduced emissions from the Power & Heat sector emissions in Thailand after 2016 (MEM&ERIA, 2020).

Transport & postal services is another hotpot sector in Indochinese countries. In Thailand, Cambodia, and Myanmar, the share of transport emissions fluctuated but show an increase overall. Especially in Myanmar, there is a huge leap from 10.6% (or 6.50 Mt) in 2016 to 19.6% (or 13.00 Mt) in 2017. Aiming for improving the poor transport infrastructure, the Myanmar government has put forward a series of plans to upgrade the transport infrastructure and improve traffic availability, such as the National Transport Master Plan, The Urban Transport Development Plan of the Greater Yangon, and the National Strategy for Rural Roads and Access (Htike, 2017). In Laos, the sector's emissions kept increasing, from 1.87 Mt in 2012 to 3.14 Mt in 2018, however, the emission share of this sector has decreased from 21.9% to 12.8%. Even though research shows that carbon intensity in the transport sector in most Indochinese countries displayed a decrease (Wang et al., 2020), this reduction in intensity has not offset the increase in emissions brought by the growing traffic volume. The only exception is Vietnam's transportation sector, where both emissions and emission share showed a decline, from 18.2% (or 42.33 Mt) in 2017 to 14.0% (or 38.36 Mt) in 2018. Gasoline-powered motorcycles are the most important means of transportation for Vietnamese residents, especially in cities. But recently, the number of electric two-wheelers in Vietnam has been growing rapidly, with an annual growth rate of 30–40% (Huu and Ngoc, 2021). This could be seen as a sign of the clean energy transition in the transport sector and explain the emission reduction from the Vietnam transport sector.

In contrast, the emission share of the residential sector decreased in all countries, for example, in Laos, it dropped from 55.5% (or 4.72 Mt) in 2012 to 18.7% (or 4.61 Mt) in 2018. The Residential sector emission share in Thailand decreased from 11.1% (or 34.22 Mt) in 2013 to 7.8% (or 27.90 Mt) in 2019. The reduction in emissions is mainly seen in rural areas. Indochinese countries have a large number of rural population. The dominant fuel used in rural areas is biomass due to the cheap price and availability coupled with a low electrification rate in remote rural areas. However, this biomass is usually burned in a very inefficient way and causes unnecessary carbon emissions, mainly because of a lack of efficient combustion devices. To solve this situation, governments from Indochinese countries have issued energy plans, such as the 20-year Energy Efficiency Development Plan and Alternative Energy Development Plan in Thailand and the Energy Efficiency and Conservation plan in Laos.

In general, energy consumption in the residential sector is diversifying especially in rural areas. More efficient energy is replacing traditional low efficient energy, such as using LPG to replace traditional biomass (ERIA & Myanmar Ministry of Electricity and Energy, 2020). In addition, the efficiency of energy use has been gradually improving. For example, Thailand is promoting energy-efficient household appliances (Meangbua et al., 2019). In Laos, Cambodia, and Myanmar, high-efficiency stoves are being deployed in rural areas (Asian Development Bank, 2016; ERIA & Myanmar Ministry of Electricity and Energy, 2020; MEM&ERIA, 2020; MME&ERIA, 2019), and the increasing electrification rate, especially in Laos, Myanmar, and Cambodia further led to a decline in the direct emissions from the residential sector (World Bank, 2019).

3.3. Drivers of emissions

The decomposition analysis (Fig. 3) shows that economic growth was the major driver for increased CO_2 emissions in all countries. This effect contributed 139.3% (or 76.93 Mt) of the CO_2 emission increase in Thailand, which is the highest among all Indochinese countries. Compared with other Indochinese countries, the economic growth effect in Laos is relatively weak, only contributing 26.2% (or 4.25 Mt) for the

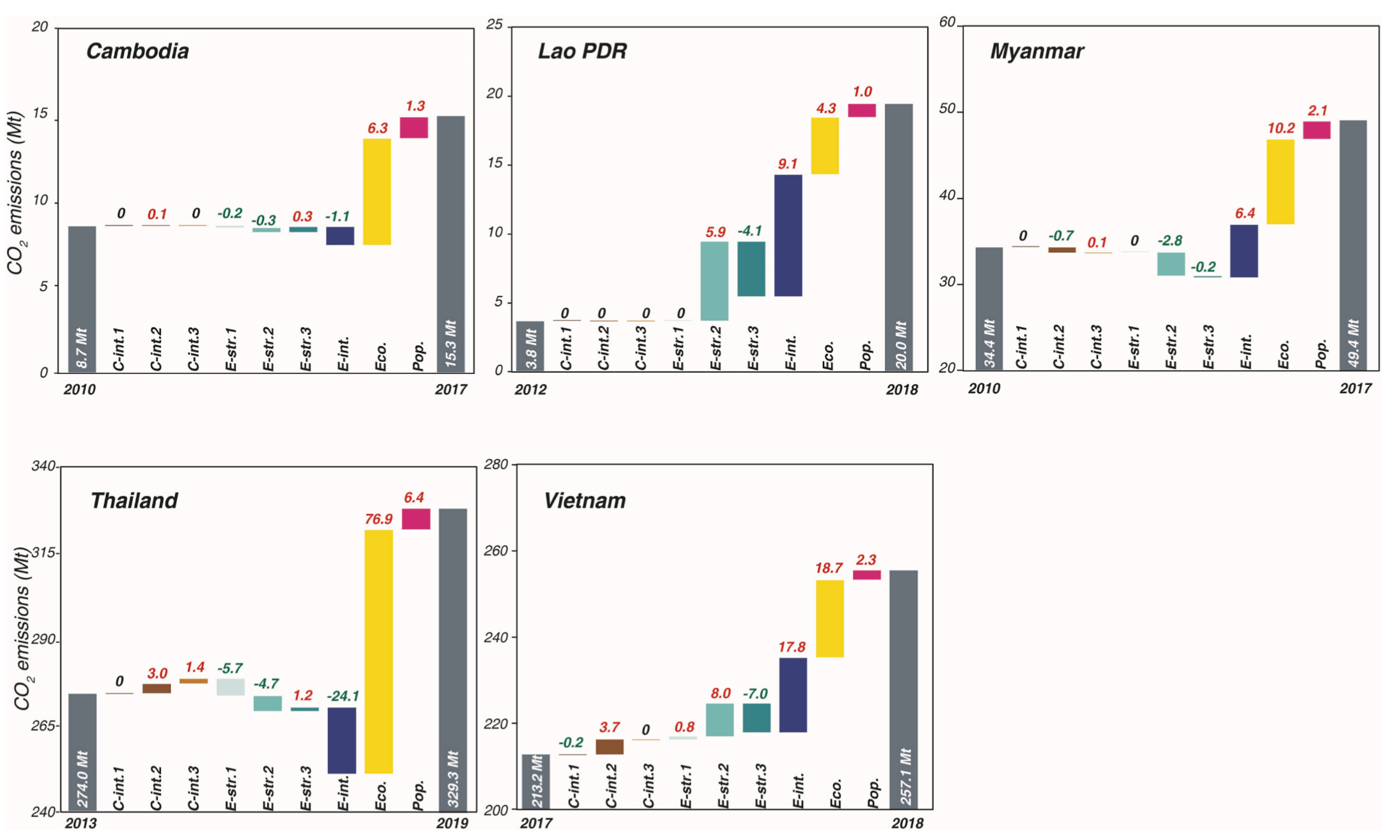

Fig. 3. Emission drivers of Indochinese countries. Note: C-int.1-3 and E-str.1-3 indicate the carbon intensity and energy structure from primary sector, secondary sector, and tertiary sector, separately.

entire time period. The population effect also increased CO_2 emissions in all countries, ranging from 5.2% (or 2.28 Mt) in Vietnam to 19.1% (or 1.25 Mt) in Cambodia.

The energy intensity effect decreased CO_2 emissions in Cambodia and Thailand. Especially in Thailand, this effect contributed to a significant (but not sufficient) decline to offset the previously discussed emission drivers . Its contribution offset 43.5% (or 24.05 Mt) CO_2 emissions in 2019 compared with the base year 2013. This is due to the increasing deployment of low-carbon technologies. For example, a total of 4 hydropower stations were put into operation between 2010 and 2017, with a total installed capacity of 722 MW in Cambodia (Asian Development Bank, 2018). Such progress lowers the energy intensity and slows the country's growth in CO_2 emissions. However, the continuous expansion of clean energy did not stop the growing demand for carbon-intensive fuels, especially in the power sector and the transport sector. For example, in Cambodia, the Sihanoukville CIIDG coal-fired power plant was put into use in 2014, with a power capacity of 135 MW, and this number gradually increased to 405 MW in 2017 (ERIA, 2019). This explains the energy intensity effect increase of 1.57 Mt CO_2 emissions over this period. For the other countries, the energy intensity effect increased emissions, due to the growing share of non-renewables in the total primary energy supply. For instance, in Laos, after the Hongsa coal-fired power plants were put into operation in 2015, the energy intensity effect contributed 69.2% (or 3.87 Mt) to the change in annual emissions. We found that the energy structure varies widely across countries, ranging from −20.5% (or −3.06 Mt) in Myanmar to 4.0% (or 1.78 Mt) in Vietnam. Specifically, the contribution from the primary sector is small, only in Thailand, its contribution offset 9.2% (or 5.07 Mt) emissions. The secondary sector significantly increased CO_2 emissions in Laos and Vietnam, mainly due to the increase of coal consumption in the Power & Heat sector, contributing 36.4% (or 5.90 Mt) and 18.2% (or 7.98 Mt), respectively. The tertiary sector moderately increased emissions in Thailand, contributing 2.2% (or 1.23 Mt), as emissions from the transport sector increased. Generally speaking, the contribution from the carbon intensity effect was small. This shows that during the study period, there was no major change in the fossil fuel mix for MSEA industries. It only moderately increased CO_2 emissions in Thailand and Vietnam, contributing 8.1% (or 4.45 Mt) and 7.8% (or 3.43 Mt), respectively, mainly coming from the secondary sector.

3.4. Comparisons with other estimates and uncertainties

Compared with inventories provided by other international institutions, our accounts cover emissions caused by both fossil fuels and biomass, this explains why our results are higher. If only considering emissions caused by fossil fuel combustion, there are still huge differences between the data sources (Fig. 1), ranging from −94.9% to 45.1%.

Theres are a number of reasons for these differences: First, we adopted different data sources based on regional data providers. Our activity data mainly come from Economic Research Institute for ASEAN and East Asia (ERIA) (Myanmar, Laos, and Cambodia), and the National Bureau of Statistics (Thailand and Vietnam). IEA employed energy consumption data from its database, with multiple and adjusted data sources (IEA, 2020b). The activity data used by EDGAR before 2018 mainly comes from the energy balance statistic from IEA (Crippa et al., 2020). While CDIAC used energy statistics published by the United Nations (Boden et al., 2017). Different data sources lead to different activity data. For example, in 2014, the final consumption of coal in Laos was 309 ktoe, collected by this study, whereas, the numbers are 273 ktoe, and 571 TJ (around 13.64 ktoe) provided by IEA and CDIAC, respectively (IEA, 2022; Boden et al., 2017). Similarly, in 2017, oil products used in Cambodia's transport sector adopted by IEA were 1.74 Mtoe, but our data show that the oil products consumed in transport were 1.61 Mtoe (ERIA&Cambodia Ministry of Mines and Energy, 2019). Second, we adopted more detailed emission factors. This is mainly due to the statistical classifications of energy varieties being different between sources. For example, in this study, oil products are further divided into motor gasoline, diesel oil, fuel oil, LPG, jet fuel, kerosene, and other petroleum products, each of which with a corresponding emission factor derived from the IPCC default value, while the energy balance table published by IEA uniformly displayed these as petroleum products. This could lead to inconsistencies in selecting emission factors in the calculation process. Third, different institutes employed different accounting methods, which also affects emission estimates. This situation mainly refers to CDIAC, which used the method given by Marland and Rotty (1984).

Even though all institutes state the data source, detailed activity data are not provided. EDGAR and IEA state that they adopted the same activity data, emission factors, and methods (IEA, 2022; Gilfillan and Marland, 2021). However, as can be seen in Fig. 1, their results differ considerably. One reason could lie in the account scope of EDGAR which is wider than the scope of IEA, by also including emissions from gas flaring, and carbonate decomposition (including cement manufacture), which are excluded by the IEA (Gilfillan and Marland, 2021). However, the inconsistency in the accounting scope does not sufficiently explain the difference in the estimates between them (see the emissions of Laos in Fig. 1). To rectify this problem, our study provides transparent data to facilitate future studies. We adopted activity data from regional institutes and local governments, these agencies are dedicated to serving these countries and therefore could provide more precise data. For example, the energy type classification is more detailed, providing more accurate results. Furthermore, emissions from biomass, one of the most important fuels in this region, are included in our study but are excluded from the emission estimates by EDGAR, IEA, and CDIAC.

This study has some limitations, mainly owing to the low data quality in some countries. For example, the Vietnamese government has only published bi-annual energy balance tables during the period of this study, making the analysis of its change pattern less accurate. Our estimates for Myanmar employed GDP published by the Asian Development Bank as the reallocation indicator. However, the data only provides GDP for the whole manufacturing industry, whereas our study further divides the manufacturing industry into finer sectors (e.g., machinery, metal products). To match the gap, we employed the number of economic enterprises from each sector to downscale the GDP data, which could impact the results. Thus, this study still can be improved with higher quality data in the future.

4. Discussion

Indochinese countries have achieved remarkable economic progress. For example, Cambodia has transformed from a low-income country to lower-middle-income status and is expected to attain upper-middle-income status by 2030 (World Bank, 2019). In Vietnam, the poverty rate dropped from 70.0% to below 6.0% (World Bank, 2019). On the other hand, the population is expected to further increase in the next decade. Thus, it is predicted that the economic growth effect and population effect will keep increasing CO_2 emissions in this region. To reduce CO_2 emissions, actions need to focus on decreasing energy intensity and key sectors' emissions.

Similar to other ASEAN countries, such as Indonesia, Malaysia, and Singapore, whose energy intensity has remarkably decreased in some of the years (Lisaba and Lopez, 2021), our results show that all MSEA countries show some decline in some of the years, however, only Thailand achieved a significant decline for the entire time period. In countries like Vietnam and Laos, energy intensity is one of the major drivers of emission increase, due to a significant increase in coal consumption. Meanwhile, renewable energy supply decreased, for example, in Laos, renewable energy supply dropped from 912.19 PJ (99.5%) in 2013 to 726.98 PJ (41.9%) in 2018, since biomass from the residential sector is replaced by electricity, generated by non-renewable energy (International Renewable Energy Agency, 2021). In contrast, Cambodia's renewable energy increased from 178.47 PJ (43.7%) in 2013 to 210.81 PJ (61.8%) in 2018 (International Renewable Energy Agency, 2021). In Cambodia, improvements in energy intensity could only reduce the overall emission growth due to the rapid increase in coal consumption. This highlights an increasing need for developing renewable energy as alternatives to the current highly coal-dependent mode of development. Noteworthy is also that the over-dependency on coal is not only a problem Vietnam and Laos face; it also applies to a much broader range of developing countries, such as China and India, and developed countries, like Australia and the US, as well as the Netherlands and Germany. In these countries, coal either dominates their energy mix or plays an important role in the country's economy. However, harmful subsidies for the coal industry are still existing, for example, in Vietnam, domestic coal prices are artificially low because of government subsidies (Fuentes and Chapman, 2021). This creates a hindrance to phasing out coal and achieving decarbonization.

One common problem among Indochinese countries is that their economic growth is increasingly coupled with fossil fuels, especially in Vietnam (Le, 2019). The increasing reliance on fossil fuels, not only increased CO_2 emissions but also reduced the country's energy security, making it more difficult to maintain energy supply at an affordable price (IEA, 2019). But abundant renewable energy endowment, especially for hydropower, solar, and biomass, provides the possibility of an energy transition for Indochinese countries. Currently, hydropower plays a significant role in this region. For example, Thailand already has 3.0 GW of hydropower in 2000 (International Renewable Energy Agency, 2017), while large hydropower accounted for 52.0% of Cambodia's total electricity capacity in 2017 (Asian Development Bank, 2018). Even so, there is a large remaining development potential. Predictions show that there is 15.2 GW of theoretical hydropower potential in Thailand, and 39.6 GW in Myanmar (Tang et al., 2019). Compared to hydropower, the development of other renewables is still at an early stage in most Indochinese countries (except for Thailand, and Vietnam). In Laos, the potential for solar power generation is 8.8 GW but only 32.0 MW was developed in 2017 (Asian Development Bank, 2019), while in Myanmar, the potential is 30.0 GW, but the installed solar energy capacity was only 84 MW in 2020 (Asian Development Bank, 2019; International Renewable Energy Agency, 2021). Compared to hydropower, the previously high cost of solar energy was the main reason limiting the development of solar energy (International Renewable Energy Agency, 2020). But the fast decreasing cost of solar PV provides another opportunity to contribute to a low carbon roadmap, as much criticism has been raised on hydropower's negative impact on ecosystems and biodiversity (Siala et al., 2021). Meanwhile, the government could gradually shift subsidies for coal to these renewable energies. Biomass is widely used in rural areas; however, efficiency is low. More efficient use, such as refining biofuels, should also be the focus of attention in the future.

As for emissions from key sectors, the secondary sector dominated by the power sector contributed most of their emissions in most countries (except for Myanmar), due to increasing electricity demand. For example, Vietnam consumed only 70 kWh of electricity per person in 1986, but this number increased to almost 2000 kWh in 2019 (Le, 2019). This is driven by strong economic growth, the rate of industrialization in the region, and electrification. For example, the electrification rate, increased in Laos from 76.4% in 2012 to 100.0% in 2019 (World Bank, 2019). Given these drivers, the increase in power consumption, not only in MSEA countries but also in other developing countries with late industrialization and rapid economic development, seems inevitable. The energy transition can be seen as a major solution, however, the transition cost for less developed countries with lower levels of income is even higher, compared with developed countries, as they need to import expensive technologies (Taghizadeh-Hesary et al., 2021). Higher electricity costs will affect electricity consumption and will impact economic development. Thus, it is necessary for policymakers to diversify roadmaps (Chen et al., 2019) and employ different policy instruments (Li and Taeihagh, 2020), to develop short-term and long-term energy transition plans, covering any side effects on electricity usage patterns of economic actors (Taghizadeh-Hesary et al., 2021).

In Laos, Vietnam, and Thailand, total emissions of the residential sector exhibited a decline, while the population kept growing. We found that in these countries, the share of primary energy (mainly biomass) has been decreasing while the share of secondary energy (for example, LPG and electricity) has been increasing. These can be seen as a result of the ongoing energy transition in the residential sector in Indochinese countries, where the government is trying to improve this sector's energy efficiency through promoting those more efficient energy sources and high-efficiency stoves in rural areas. It is worth mentioning that, when discussing emission reduction achieved by replacing primary biomass with electricity, we also need to pay attention to the energy mix and efficiency rates in the power sector. For countries, such as Vietnam and Laos, electricity is replacing primary biomass in rural areas, however, due to the fact that the main fuel for power generation is coal, this replacement is futile in achieving nationwide emission reduction. But in Thailand, a large part of the emission increase from the power sector comes from biomass (mainly bagasse and agriculture waste) and it can be used more efficiently than in the residential sector.

In general, the tertiary sector shows a decrease in emissions, whereas in Thailand we observe an increase, mainly due to the transport sector. The improvement of the transportation infrastructure has increased the highway capacity, meeting the urgent needs of the increase in transportation volume, but also facilitating further emission growth. Even though the carbon intensity from the transport sector shows a decrease with technological improvement (Wang et al., 2020), but was unable to fully offset the CO_2 increase caused by the larger traffic volume. In contrast, the transport sector from Vietnam has substantially decreased the emissions. This is due to the increasing share of electric vehicles in Vietnam, especially in cities (Huu and Ngoc, 2021).

5. Conclusions

This study presents the emission inventories for five main types of fuels (i.e., coal, crude oil, oil products, natural gas, and biofuels & waste) used in 47 economic sectors in five Indochinese countries for the years 2010–2019. We further examine the drivers behind the changes in emission for each country using iIndex decomposition analysis.

Our results show that the total emissions of countries vary greatly. Even though CO_2 emissions in all Indochinese countries are on the rise, average annual growth rates are also very different between countries, ranging from 2.5% in Thailand to 19.3% in Laos. Our results of the driving analysis show that economic development and population growth cause emissions increase in all countries. Energy intensity varies widely across nations, but only significantly decreased CO_2 emission growth in Thailand. The secondary sector significantly increased CO_2 emissions in Laos and Vietnam, due to the increase of coal consumption in the power & heat sector, the tertiary industry only moderately increased emissions in Thailand, due to the rising share of fossil fuels in the transport sector.

Based on our analysis, one approach for Indochinese countries to achieve emission reduction targets is to accelerate the energy transition, which is to reduce dependence on fossil resources and develop renewable energy. This is especially urgent for Vietnam and Laos, as the share of renewable energy keeps decreasing. Indochinese countries are rich in renewable energy, however, many renewable energy sources have not been properly planned and utilized. Developing renewable energy and optimizing energy structures can lower carbon intensity. This is critical, especially for the power sector, which is the key sector to achieve the national emission reduction target. The ongoing energy transition in the residential sector decreased emissions in all countries and emissions from the residential sector are expected to continue decreasing, since primary biomass is still the dominant fuel used in rural areas in many MSEA countries. Our study not only provides an understanding of the emission patterns and mitigation barriers in Indochinese countries but also informs other emerging economies at the same development stages to develop their mitigation roadmaps, thereby contributing to the achievement of global climate change targets.

Credit author statement

Binyuan Liu: Methodology; Software; Formal analysis; Investigation; Data curation; Writing – original draft; Visualization; Funding acquisition, Yuru Guan: Validation; Writing – review & editing; Visualization; Funding acquisition, Yuli Shan: Conceptualization; Methodology; Investigation; Resources; Writing – review & editing; Supervision; Project administration; Funding acquisition, Cui Can: Methodology; Software; Validation, Klaus Hubacek: Conceptualization; Methodology; Investigation; Resources; Writing – review & editing; Supervision; Project administration; Funding acquisition

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.

Data availability

Data will be made available on request.

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All the data and results have been uploaded to Carbon Emission Accounts and Datasets for emerging economies (CEADs.net) for free download. This work was supported by the China Scholarship Council Ph.D. program (B. Liu and Y. Guan).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.117034.

References

Akyürek, Z., 2020. LMDI decomposition analysis of energy consumption of Turkish manufacturing industry: 2005–2014. Energy Efficiency 13, 649–663. https://doi.org/10.1007/s12053-020-09846-8.
Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33, 867–871. https://doi.org/10.1016/j.enpol.2003.10.010.
Ang, B.W., 2015. LMDI decomposition approach: A guide for implementation. Energy Policy 86, 233–238. https://doi.org/10.1016/j.enpol.2015.07.007.
Ang, B.W., Choi, K.-H., 1997. Decomposition of aggregate energy and gas emission intensities for industry: a refined Divisia index method. The Energy Journal 18. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol18-No3-3.
Ang, B.W., Zhang, F.Q., 2000. A survey of index decomposition analysis in energy and environmental studies. Energy 25, 1149–1176. https://doi.org/10.1016/S0360-5442(00)00039-6.
Ang, B.W., Zhang, F.Q., Choi, K.-H., 1998. Factorizing changes in energy and environmental indicators through decomposition. Energy 23, 489–495. https://doi.org/10.1016/S0360-5442(98)00016-4.
Asian Development Bank, 2016. Myanmar Energy Sector Assessment, Strategy, and Road Map. Asian Development Bank, Manila, Philippines. URL https://www.adb.org/sites/default/files/institutional-document/218286/mya-energy-sector-assessment.pdf.
Asian Development Bank, 2018. Cambodia: Energy Sector Assessment, Strategy, and Road Map. Asian Development Bank, Manila, Philippines. URL https://doi.org/10.22617/TCS189801.
Asian Development Bank, 2019. LAO People's Democratic Republic Energy Sector Assessment, Strategy, and Road Map. Asian Development Bank, Manila, Philippines. URL https://doi.org/10.22617/TCS190567.
Asian Development Bank, 2021a. Cambodia: Input-Output Economic Indicators. ADB.
Asian Development Bank, 2021b. Key Indicators, Myanmar.
Asian Development Bank, 2021c. Thailand. Key Indicators.
Boden, T., Marland, G., Andres, R., 2017. Global, Regional, and National Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory. US Department of Energy, Oak Ridge, Tenn., USA. https://doi.org/10.3334/CDIAC1, 2009.
Chen, C., Xue, B., Cai, G., Thomas, H., Stückrad, S., 2019. Comparing the energy transitions in Germany and China: Synergies and recommendations. Energy Reports 5, 1249–1260. https://doi.org/10.1016/j.egyr.2019.08.087.
Chontanawat, J., 2018. Decomposition analysis of CO2 emission in ASEAN: an extended IPAT model 153, 186–190. https://doi.org/10.1016/j.egypro.2018.10.057.
Chontanawat, J., 2019. Driving Forces of Energy-Related CO2 Emissions Based on Expanded IPAT Decomposition Analysis: Evidence from ASEAN and Four Selected Countries. Energies 12, 764. https://doi.org/10.3390/en12040764.
Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Solazzo, E., M.-F., F., O., J.G.J., , ignati, E., 2020. Fossil CO2 Emissions of All World Countries, 2020 Report, EUR 30358 EN. Publications Office of the European Union, Luxembourg.
Dai, H.-C., Zhang, H.-B., Wang, W.-T., 2017. The impacts of U.S. withdrawal from the Paris Agreement on the carbon emission space and mitigation cost of China, EU, and Japan under the constraints of the global carbon emission space. Advances in Climate Change Research, Including special topic on U.S. withdraw from the Paris Agreement and its. impacts 8, 226–234. https://doi.org/10.1016/j.accre.2017.09.003.
Dong, F., Li, J., Zhang, Y.-J., Wang, Y., 2018. Drivers Analysis of CO2 Emissions from the Perspective of Carbon Density: The Case of Shandong Province, China. International Journal of Environmental Research and Public Health 15, 1762. https://doi.org/10.3390/ijerph15081762.
Dhakal, S., Minx, J.C., Toth, F.L., Abdel-Aziz, A., Figueroa, M.J., Hubacek, K., Jonckheere, I.G.C., Yong-gun, K., Nemet, G., Pachauri, S., Tan, X., Wiedmann, T., Amon, B., Diga, G.M.. Emissions Trends and Drivers. In Climate Change 2022: Mitigation of Climate Change IPCC: Intergovernmental Panel on Climate Change. https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf.
ERIA & Myanmar Ministry of Electricity and Energy, 2020. Energy Demand and Supply of the Republic of the Union of Myanmar 2010-2017. ERIA , Myanmar Ministry of Electricity and Energy.
Gilfillan, D., Marland, G., 2021. CDIAC-FF: global and national CO 2 emissions from fossil fuel combustion and cement manufacture: 1751–2017. Earth Syst. Sci. Data 13, 1667–1680. https://doi.org/10.5194/essd-13-1667-2021.
Guan, D., Meng, J., Reiner, D.M., Zhang, N., Shan, Y., Mi, Z., Shao, S., Liu, Z., Zhang, Q., Davis, S.J., 2018. Structural decline in China's CO2 emissions through transitions in industry and energy systems. Nature Geosci 11, 551–555. https://doi.org/10.1038/s41561-018-0161-1.
Hak, M., Matsuoka, Y., Gomi, K., 2017. A qualitative and quantitative design of low-carbon development in Cambodia. Energy policy. Energy Policy 100, 237–251. https://doi.org/10.1016/j.enpol.2016.10.017.
Htike, H., 2017. Status and Future Plan for National Logistics Master Plan. Ministry of Transport and Communications Myanmar, Myanmar. URL https://www.unescap.org/sites/default/files/Myanmar%20-%20Logistics.pdf.
Huu, D.N., Ngoc, V.N., 2021. Analysis Study of Current Transportation Status in Vietnam's Urban Traffic and the Transition to Electric Two-Wheelers Mobility. Sustainability 13, 5577. https://doi.org/10.3390/su13105577.
Huy, L.N., Kim Oanh, N.T., 2017. Assessment of national emissions of air pollutants and climate forcers from thermal power plants and industrial activities in Vietnam. Atmospheric Pollution Research 8, 503–513. https://doi.org/10.1016/j.apr.2016.12.007.
Huy, L.N., Winijkul, E., Kim Oanh, N.T., 2021. Assessment of emissions from residential combustion in Southeast Asia and implications for climate forcing potential. Science of The Total Environment 785, 147311. https://doi.org/10.1016/j.scitotenv.2021.147311.
IEA, 2019. Energy security Ensuring the uninterrupted availability of energy sources at an affordable price. URL https://www.iea.org/areas-of-work/ensuring-energy-security.
IEA, 2020a. Greenhouse Gas Emissions from Energy Highlights. IEA.
IEA, 2020b. WORLD ENERGY BALANCES 2020 EDITION DATABASE DOCUMENTATION. IEA.
International Renewable Energy Agency, 2017. Renewable Energy Outlook: Thailand. International Renewable Energy Agency, Abu Dhabi. URL https://www.irena.org/-/media/files/irena/agency/publication/2017/nov/irena_outlook_thailand_2017.pdf.
International Renewable Energy Agency, 2020. Renewable Power Generation Costs in 2019. International Renewable Energy Agency, Abu Dhabi. URL https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf.
International Renewable Energy Agency, 2021. Statistical Profiles. International Renewable Energy Agency. URL https://www.irena.org/Statistics/Statistical-Profiles.
Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, 5, 1996. Overview Of The IPCC Guidlines Vol.1 Reporting Instructions.
IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories 2006.
IPCC, 2021. IPCC Emission Factor Database. IPCC.
Jackson, R.B., Le Quéré, C., Andrew, R., Canadell, J.G., Korsbakken, J.I., Liu, Z., Peters, G.P., Zheng, B., 2018. Global energy growth is outpacing decarbonization. Environ. Res. Lett. 13, 120401. https://doi.org/10.1088/1748-9326/aaf303.
Jung, S., An, K.-J., Dodbiba, G., Fujita, T., 2012. Regional energy-related carbon emission characteristics and potential mitigation in eco-industrial parks in South Korea: logarithmic mean Divisia index analysis based on the Kaya identity. Energy, Energy and Exergy Modelling of Advance Energy Systems 46, 231–241. https://doi.org/10.1016/j.energy.2012.08.028.
Khan, S., Majeed, M.T., 2020. Drivers of decoupling economic growth from carbon emission: empirical analysis of ASEAN countries using decoupling and

decomposition model. Pakistan Journal of Commerce and Social Sciences (PJCSS) 14, 450–483.
Lasko, K., Vadrevu, K.P., Tran, V.T., Ellicott, E., Nguyen, T.T., Bui, H.Q., Justice, C., 2017. Satellites may underestimate rice residue and associated burning emissions in Vietnam. Environ. Res. Lett. 12, 085006 https://doi.org/10.1088/1748-9326/aa751d.
Le, P.V., 2019. Energy demand and factor substitution in Vietnam: evidence from two recent enterprise surveys. Journal of Economic Structures 8, 35. https://doi.org/10.1186/s40008-019-0168-9.
Le Quéré, C., Korsbakken, J.I., Wilson, C., Tosun, J., Andrew, R., Andres, R.J., Canadell, J.G., Jordan, A., Peters, G.P., van Vuuren, D.P., 2019. Drivers of declining CO2 emissions in 18 developed economies. Nat. Clim. Chang. 9, 213–217. https://doi.org/10.1038/s41558-019-0419-7.
Li, L., Taeihagh, A., 2020. An in-depth analysis of the evolution of the policy mix for the sustainable energy transition in China from 1981 to 2020. Applied Energy 263, 114611. https://doi.org/10.1016/j.apenergy.2020.114611.
Li, Y., Du, W., Huisingh, D., 2017. Challenges in developing an inventory of greenhouse gas emissions of Chinese cities: A case study of Beijing. Journal of Cleaner Production 161, 1051–1063. https://doi.org/10.1016/j.jclepro.2017.06.072.
Limmeechokchai, B., Suksuntornsiri, P., 2007. Embedded energy and total greenhouse gas emissions in final consumptions within Thailand. Renewable and Sustainable Energy Reviews 11, 259–281. https://doi.org/10.1016/j.rser.2005.01.005.
Lisaba, E.B., Lopez, N.S., 2021. Using Logarithmic Mean Divisia Index method (LMDI) to estimate drivers to final energy consumption and emissions in ASEAN. In: IOP Conf. Ser.: Mater. Sci. Eng., 1109, 012070. https://doi.org/10.1088/1757-899X/1109/1/012070.
Lopez, N.S., Moreau, V., Yu, K.D., Chiu, A.S.F., Xu, M., 2021. Production- and consumption-based energy use in the ASEAN: Lessons from the Tiger and the cubs. Journal of Cleaner Production 304, 126986. https://doi.org/10.1016/j.jclepro.2021.126986.
Luukkanen, J., Akgün, O., Kaivo-oja, J., Korkeakoski, M., Pasanen, T., Panula-Ontto, J., Vehmas, J., 2015. Long-run energy scenarios for Cambodia and Laos: Building an integrated techno-economic and environmental modelling framework for scenario analyses. Energy 91, 866–881. https://doi.org/10.1016/j.energy.2015.08.091.
Marland, G., Rotty, R.M., 1984. Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1982. Tellus B: Chemical and Physical Meteorology 36, 232–261. https://doi.org/10.3402/tellusb.v36i4.14907.
Meangbua, O., Dhakal, S., Kuwornu, J.K.M., 2019. Factors influencing energy requirements and CO2 emissions of households in Thailand: A panel data analysis. Energy Policy 129, 521–531. https://doi.org/10.1016/j.enpol.2019.02.050.
IEA, 2022. World Energy Balances. IEA. URL https://www.iea.org/data-and-statistics/data-product/world-energy-balances.
Lao PDR Ministry of Energy and Mines & ERIA, 2020. Energy Demand and Supply of the Lao People's Democratic Republic 2010-2018. ERIA. URL https://www.eria.org/publications/energy-demand-and-supply-of-the-lao-peoples-democratic-republic-2010-2018/.
Fuentes, U., Chapman, A., 2021. Shifting investment away from fossil fuels in Southeast Asia. URL https://climateanalytics.org/publications/2021/shifting-investment-away-from-fossil-fuels-in-southeast-asia/.
MEM&ERIA, 2020. Lao PDR Energy Outlook 2020. ERIA. URL https://www.eria.org/publications/lao-pdr-energy-outlook-2020/.
Ministry of Energy of Thailand, 2021. Energy Balance of Thailand. URL https://webkc.dede.go.th/testmax/search/node/energy%20balance.
ERIA&Cambodia Ministry of Mines and Energy, 2019. Energy Demand and Supply of Cambodia 2010-2018. URL https://www.eria.org/publications/energy-demand-and-supply-of-cambodia-2010-2018/.
MME&ERIA, 2019. Cambodia Basic Energy Plan. Economic Research Institute for ASEAN and East Asia (ERIA), Indonesia. URL https://www.eria.org/publications/cambodia-basic-energy-plan/.
Myanmar Statistical Information Service, 2021. Statistical Yearbook. URL https://www.mmsis.gov.mm/sub_menu/statistics/fileDb.jsp?code_code=001.
Ratanavaraha, V., Jomnonkwao, S., 2015. Trends in Thailand CO2 emissions in the transportation sector and Policy Mitigation. Transport Policy 41, 136–146. https://doi.org/10.1016/j.tranpol.2015.01.007.
Rose, A., Casler, S., 1996. Input–Output Structural Decomposition Analysis: A Critical Appraisal. Economic Systems Research 8, 33–62. https://doi.org/10.1080/09535319600000003.
Shan, Y., Huang, Q., Guan, D., Hubacek, K., 2020. China CO2 emission accounts 2016–2017. Sci Data 7, 54. https://doi.org/10.1038/s41597-020-0393-y.
Shan, Y., Zhou, Y., Meng, J., Mi, Z., Liu, J., Guan, D., 2019. Peak cement-related CO2 emissions and the changes in drivers in China. Journal of Industrial Ecology 23, 959–971. https://doi.org/10.1111/jiec.12839.
Siala, K., Chowdhury, A.K., Dang, T.D., Galelli, S., 2021. Solar energy and regional coordination as a feasible alternative to large hydropower in Southeast Asia. Nat Commun 12, 4159. https://doi.org/10.1038/s41467-021-24437-6.
Štreimikienė, D., Balezentis, T., 2016. Kaya identity for analysis of the main drivers of GHG emissions and feasibility to implement EU "20–20–20" targets in the Baltic States. Renewable and Sustainable Energy Reviews 58, 1108–1113. https://doi.org/10.1016/j.rser.2015.12.311.
Sumabat, A.K., Lopez, N.S., Yu, K.D., Hao, H., Li, R., Geng, Y., Chiu, A.S.F., 2016. Decomposition analysis of Philippine CO2 emissions from fuel combustion and electricity generation. Applied Energy 164, 795–804. https://doi.org/10.1016/j.apenergy.2015.12.023.
Taghizadeh-Hesary, F., Rasoulinezhad, E., Shahbaz, M., Vinh Vo, X., 2021. How energy transition and power consumption are related in Asian economies with different income levels? Energy 237, 121595. https://doi.org/10.1016/j.energy.2021.121595.
Tang, S., Chen, J., Sun, P., Li, Y., Yu, P., Chen, E., 2019. Current and future hydropower development in Southeast Asia countries (Malaysia, Indonesia, Thailand and Myanmar). Energy Policy 129, 239–249. https://doi.org/10.1016/j.enpol.2019.02.036.
Thuy, V.T.H., Limmeechokchai, B., 2015. Analyses of Energy use and CO2 Emission in Residential Sector: Case Studies in Thailand and Vietnam. Energy Procedia, 2015 International Conference on Alternative Energy in Developing Countries and Emerging Economies 79, 290–295. https://doi.org/10.1016/j.egypro.2015.11.488.
Tun, M.M., Juchelková, D., 2019. Biomass Sources and Energy Potential for Energy Sector in Myanmar. An Outlook. Resources 8, 102. https://doi.org/10.3390/resources8020102.
Nataly Echevarria Huaman, R., Xiu Jun, T., 2014. Energy related CO2 emissions and the progress on CCS projects: A review. Renewable and Sustainable Energy Reviews 31, 368–385. https://doi.org/10.1016/j.rser.2013.12.002.
ERIA, 2019. Overview of the Energy and Power Situation in ASEAN, Study on the Biomass and Coal Co-combustion in the ASEAN Region. ERIA Research Project Report FY2018 no.17, Jakarta: ERIA, pp.4-38. URL https://www.eria.org/uploads/media/Study-Biomass-and-Coal-Co-Combustion/6.RPR_FY2018_17_Chapter-2.pdf.
Vietnam General Statistics Office, 2019. Statistical Yearbook 2019. Vietnam General Statistics Office. URL https://www.gso.gov.vn/en/data-and-statistics/2020/09/statistical-yearbook-2019/.
United Nations, 2008. International Standard Industrial Classification of All Economic Activities. United Nations.
Wang, C., Wood, J., Wang, Y., Geng, X., Long, X., 2020. CO2 emission in transportation sector across 51 countries along the Belt and Road from 2000 to 2014. Journal of Cleaner Production 266, 122000. https://doi.org/10.1016/j.jclepro.2020.122000.
World Bank, 2019. World Development Indicators. World Bank, Washington, DC.
Xiao, L., Guan, Y., Guo, Y., Xue, R., Li, J., Shan, Y., 2022. Emission accounting and drivers in 2004 EU accession countries. Applied Energy 314, 118964. https://doi.org/10.1016/j.apenergy.2022.118964.
Zhang, J., Fan, Z., Chen, Y., Gao, J., Liu, W., 2020. Decomposition and decoupling analysis of carbon dioxide emissions from economic growth in the context of China and the ASEAN countries. Science of The Total Environment 714, 136649. https://doi.org/10.1016/j.scitotenv.2020.136649.
Zheng, H., Shan, Y., Mi, Z., Meng, J., Ou, J., Schroeder, H., Guan, D., 2018. How modifications of China's energy data affect carbon mitigation targets. Energy Policy 116, 337–343. https://doi.org/10.1016/j.enpol.2018.02.031.
Laos Statistical Information Service, 2022. Statistical Data. URL https://laosis.lsb.gov.la/tblInfo/TblInfoList.do.