CO₂ emissions from electricity generation in ASEAN: An empirical spatial-temporal index decomposition analysis

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Abstract. The Association of Southeast Asian Nations (ASEAN) is a developing region that is poised to be one of the key contributors to rising CO₂ emissions in the future. In particular, the electricity sector’s emissions have risen by 2.4 times since 2000 and may increase by another 2.6 times by 2040, motivated by the burgeoning regional energy demand. If realised, this growth in CO₂ emissions could stall global climate mitigation and sustainability efforts. The electricity sector, however, has a large potential for decarbonization. To reveal the driving factors of historical trends, spatial-temporal index decomposition analyses (ST-IDA) based on the logarithmic mean Divisia index (LMDI) is applied to analyse ASEAN’s aggregate carbon intensity (ACI) of electricity from 2000 to 2015. The technique combines temporal and spatial data to reveal the factors influencing regional trends and allow for comparisons across countries. The results show that in the face of rapidly rising electricity demands, many ASEAN countries have failed to maintain consistent improvements in the ACI through the adoption of renewable energy or improvement in generation mix. While some countries have switched to cleaner forms of generation such as natural gas, varying energy resource endowments, national circumstances and energy demand trends are challenges to the adoption of renewable energy. Pressures from energy demand and technological challenges also prevent some countries from sustaining overall improvements in generation efficiencies of fossil fuel plants. Improving energy planning, demand management and greater regional cooperation are key to the decarbonisation of the electricity system.

Keywords: ASEAN; Electricity production; Carbon emission intensity; Index decomposition analysis; LMDI

1. Introduction

One of the key sources of rising CO₂ emissions worldwide is the increase in CO₂ emissions from fuel combustion in developing regions. The share of energy-related CO₂ emissions from non-OECD countries increased from 42% of the global total in 2000 to 60% in 2015 [1]. The ten member countries forming the Association of Southeast Asian Nations (ASEAN) is one such regional economy that is set to become a key contributor to global energy consumption and CO₂ emissions in the near future. Energy-related CO₂ emissions are likely to grow more rapidly as countries in the region develop and seek to provide electricity to 65 million people who currently do not have access to electricity. IEA estimates that the region will consume 10% of total global energy demand by 2040, with electricity accounting for the largest share of the rise in final energy consumption [2].
Fuelled by rapid economic development and electrification, CO₂ emissions from the electricity sector in ASEAN increased by 2.4 times between 2000 and 2015, much faster than total energy-related CO₂ emissions which rose by 1.8 times in the same period. Presently, many ASEAN countries depend heavily on fossil fuels. Together with the large potential for growth in the region, CO₂ emissions from the electricity sector may increase by another 2.6 times by 2040 if unabated [2].

A key indicator for the electricity generation sector is the aggregate carbon intensity (ACI) of electricity [3] which is the average level of CO₂ emissions per unit of electricity produced, measured in kilograms of CO₂ emissions per kilowatt-hours (kgCO₂/kWh). A lower ACI is preferred as it indicates that a country emits less CO₂ per kWh of electricity produced, a key goal for decarbonisation. As the ACI is not scale-dependent it is often used in benchmarking studies as comparisons can be made easily across countries even when there is great diversity among them, as is the case for ASEAN.

CO₂ emissions from electricity generation in ASEAN increased from 213 million tonnes of CO₂ (MTCO₂) in 2000 to 515 MTCO₂ in 2015. In the same period, electricity output increased from 370 TWh to 873 TWh.¹ This resulted in a slight increase in the ASEAN ACI from 0.576 kgCO₂/kWh to 0.590 kgCO₂/kWh. ASEAN’s ACI is higher than the world average of 0.506 kgCO₂/kWh in 2015 [1]. This means that the region contributes to a worsening of the global ACI and can do more for global climate mitigation and environmental sustainability efforts. A better understanding of the factors driving changes across ASEAN countries over time can provide insights into current and future challenges. Index decomposition analysis (IDA) is a technique that can be used to analyse trends in the ACI. In this study, a spatial-temporal IDA (ST-IDA) [4] is applied to analyse past trends in the ASEAN ACI.

### 2. ST-IDA methodology

ST-IDA integrates temporal and spatial IDA in a single framework. Previous studies have conducted decompositions for each country over time [3,6] or benchmarked countries against each other for a particular point in time [7]. However, comparisons of changes within a group of countries, in this case ASEAN countries, over time, cannot be carried out easily as there is no common benchmark. To overcome this limitation, Ang et al. [4] developed the integrated ST-IDA framework to allow for a two-dimensional analysis over time and space. Based on this ST-IDA framework, the ACI of a country, denoted by V, can be defined by two driving factors according to the following formula,

$$
V = \frac{C}{G} = \sum_i \frac{Q_i C_i}{G_i} = \sum_i m_i u_i
$$

(1)

where C and G are the total CO₂ emissions from electricity generation and the total electricity generation respectively, Qᵢ is the electricity generation from fossil fuel i and Cᵢ is the associated CO₂ emissions. mᵢ = Qᵢ / Q is the share of electricity output from fossil fuel i in total electricity output and uᵢ = Cᵢ / Qᵢ is the real emission intensity of electricity generation by fossil fuel i. To obtain the effects, the arithmetic change in the aggregate emission intensity ∆Vₜₒₜ between an ASEAN country c in a particular year t, and the reference region, Ru, is given by

$$
\Delta V_{t o t} = V_{c, t} - V_{R u} = \Delta V_m + \Delta V_u
$$

(2)

∆Vₘ is the generation mix effect and ∆Vᵤ is the emission intensity effect. They measure the impacts of differences in the electricity generation mix and generation efficiency of fossil fuel plants respectively.

ST-IDA has several advantages in comparison to the conventional temporal or spatial IDA. A comparison of the three methods is shown in Table 1. For ease of explanation, examples of decomposition results from a temporal study of ASEAN between 2000 and 2015, and a spatial analysis of ASEAN in 2015, are shown in Fig. 1 and 2 respectively. The results can be compared with the ST-IDA results shown in Fig. 3. All three decomposition analyses use the same identity shown in Eq. (1). The additive logarithmic mean Divisia index (LMDI) decomposition method [9] is used to obtain the two effects shown in Eq. (2) and the detailed formulae are given in the Appendix. Constant emission

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¹ Due to a lack of data, Laos is excluded from this study. Laos relies mainly on hydropower and does not contribute significantly to current CO₂ emissions in ASEAN.
factors of 3.99 for coal, 3.08 for oil and 2.33 for natural gas in tonnes of CO₂ per tonne of oil equivalent are used. Energy data was obtained from the IEA world energy statistics database [8]. For temporal analysis, the arithmetic change in the aggregate emission intensity $\Delta V_{\text{tot}}$ is the difference in the ACI of a country between 2015 and 2000 while in spatial analysis, $\Delta V_{\text{tot}}$ is defined as the difference in the ACI between an ASEAN country and the ASEAN average in 2015. The size of the circle in the spatial plot indicates the size of the CO₂ emissions of that country. For ST-IDA, the reference region, $R_u$, is also defined as the average of ASEAN in 2015. This reference region was selected to provide consistency between the ST-IDA study and future scenarios which utilise 2015 as the base year [2].

| Table 1. Comparison of temporal, spatial and spatial-temporal index decomposition analyses |
|-----------------------------------------------|---------------------------------------------------------------|
| **Method**                              | **Description**                  | **Conclusions**                               | **Example**                                                                 | **Pros**                                                                 | **Cons**                                                                 |
| Temporal                                 | Quantify drivers of change in ACI over time by country | Impact of different factors on change in ACI of individual countries over time | Switching to natural gas generation in Singapore led to improvements in the ACI | Detailed study with many factors and levels of disaggregation is possible | Unable to benchmark across countries | Absolute ACI at each point in time is not presented | Hard to visualize annual changes |
| Spatial                                   | Benchmark performance of a country against regional average in a particular year on contour plot | General trends in the distribution of countries across the spatial plot | Convergence in generation efficiencies of power plants across ASEAN over time | Regional benchmarking at a point in time | Maximum of 2 factors | Intensity indicator is preferred | Difficult to analyse annual changes |
| ST-IDA                                   | Changes in the ACI and drivers over time and across countries are displayed on contour plot | Consistency of progress of each country as well as potential for future improvements, challenges and barriers | Consistent progress in gains in generation efficiency in Brunei, highly irregular path in the Philippines | Regional benchmarking with detailed temporal pathways of each country shown on a single plot | Maximum of two factors | Intensity indicator is preferred | More complex |

Other reference regions may be constructed depending on the purpose of the study. For example, Ang et al. [4] use the weighted average of a group of countries over three years as the reference region. Note that different reference regions result in different decomposition results.

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Figure 1. Temporal decomposition results for ASEAN countries (2000-2015)
Figure 2. Spatial decomposition results for ASEAN countries in 2000 and 2015

In ST-IDA, all decomposition results can be combined within a single two-dimensional contour plot as shown in Fig. 3. The generation mix effect is shown on the horizontal axis while the emission intensity effect is shown on the vertical axis. The intersection of the two axes is the average ACI of ASEAN in 2015 ($V_{Ru}$). The diagonal dotted lines are contour lines that join points in the plot with the same ACI. Annual data between 2000 and 2015 for each ASEAN country is used to obtain a detailed
path taken by each ASEAN country over time. The path is mapped by joining points from 2000 to 2015 in chronological order and the direction is indicated by an arrow. These paths provide insights into the source and extent of changes each country experiences over time in comparison to other countries. Key characteristics of each country’s path such as U-turns or fluctuations in a particular effect can be easily visualised. As such, ST-IDA is well-suited for analysing ASEAN’s current progress and future outlook.

3. Understanding the drivers of ACI over time and across countries

The ST-IDA results for countries with more consistent performance are shown in Fig. 3a while results for countries with large fluctuations are shown in Fig. 3b. Key features of each country’s trajectory in the ST-IDA plots are summarised in Table A.1 in the Appendix.

3.1 Consistency of progress

The paths taken by Brunei and Singapore exhibit very consistent progress. This was led by steady improvements in the efficiencies of natural gas plants in Brunei which contributed to reductions in the intensity effect and the substitution of oil with natural gas in Singapore which led to reductions in the generation mix effect. Both countries also recorded the slowest growth in electricity demand across ASEAN and have electricity systems which depend mainly on one type of fuel. Consistent trajectories which largely moved in the horizontal direction were also observed in Cambodia and Myanmar. This was largely due to increases in the share of hydropower which caused a decrease in the generation mix effect. However, Cambodia experienced a U-turn after 2013 while Myanmar and Vietnam saw fluctuations in the generation mix effect after 2009 and 2010 respectively. The three countries also experienced large increases in electricity output between 2000 and 2015, ranging from a tripling of output in Myanmar to an almost ten-fold increase in Cambodia. The U-turns and fluctuations in the generation mix effect highlight the difficulties emerging economies face in maintaining or increasing the share of renewables in the face of burgeoning electricity demand. While output from renewables has generally increased over time, they were unable to maintain their share in the electricity mix. This trend stands in contrast to the consistent paths taken by countries with more stable electricity demand and less diverse, largely fossil-based electricity systems such as Singapore and Brunei.

On the other hand, the trajectories of Malaysia and Indonesia fluctuate largely in the vertical direction while in the horizontal direction, there is a trend towards a more carbon-intensive generation mix which is primarily based on coal. Fluctuations in the intensity effect suggest that both countries face difficulties in maintaining efficiency improvements of coal and natural gas power generation. This was especially so during the global financial crisis in 2008 which is likely the key factor that led to the peaking of the intensity effect in 2008 and 2010 in Malaysia, and in 2009 in Indonesia. The Philippines also experienced the peaking of the intensity effect in 2008. Its trajectory fluctuates in all directions, highlighting the perils of a poorly managed energy industry [10] coupled with strong reliance on fuel imports and a relatively more diverse electricity mix. These characteristics makes the Philippines more vulnerable to changes in energy supply and electricity demand.

3.2 Barriers to further improvements

A country’s relative position with respect to the ASEAN average can provide indications of the potential and challenges to further improvements in the ACI. For example, while Myanmar has made significant improvements to its generation mix, its intensity effect remains much higher than the ASEAN average. This means that there is significant potential for reductions in the ACI from efficiency improvements. On the other hand, the potential for efficiency gains in Thailand, Singapore and Brunei are unlikely to be very large as their efficiencies have converged around the ASEAN average. In fact, about three quarters of the natural gas generation capacity in Singapore and Thailand are based on combined cycle gas turbine (CCGT) or combined heat and power plants [11,12]. While there is still some potential for Brunei to replace natural gas open cycle power plants with CCGT [13], reductions in the ACI primarily

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1 Three anomalies in coal efficiencies which were unusually low (i.e. very efficient) were replaced by efficiencies in the preceding year.
through the upgrading of power plants will become increasingly difficult as Brunei’s intensity effect converges towards the ASEAN average. Technological breakthroughs will be necessary to give countries which have already switched to high efficiency plants an option to continue to rely on efficiency gains to reduce their ACI. Countries are also impeded by a lack of easily exploitable renewable resources. The trajectories of countries that face multiple limitations are typically constrained within a small area on the ST-IDA plot. For example, not only is Thailand constrained by a lack of potential for improvements in generation efficiency, its generation mix remained largely unchanged between 2000 and 2015.

4. Conclusion
The ST-IDA results for 2000-2015 paint a picture of fluctuating performance in the Philippines, Vietnam, Malaysia and Indonesia with an observable trend towards more carbon-intensive coal-based systems, U-turns in the generation mix effect in Myanmar and Cambodia and barriers to further improvements in the ACI in Brunei, Singapore and Thailand. The present situation highlights two major problems in ASEAN.

First, the inconsistent performance over time underscores the difficulties countries face in planning for future energy demand while addressing issues such as energy supply, affordability and climate mitigation. In the face of rapidly rising electricity demands, poor energy planning and management has led to fluctuations and U-turns in the generation mix and intensity effects. Better energy planning and forecasting as well as demand management are critical. While new generation capacity holds massive potential for technological leapfrogging and avoids problems of stranded assets, difficulties in planning for future electricity demand can lead to wildly fluctuating performance in generation efficiencies and electricity mixes, especially in countries which have a large share of hydropower.

Second, a number of ASEAN countries are constrained by their limited access to sizeable sources of renewable energy. The difficulty faced by countries in accessing renewable energy resources can be represented by a vertical boundary on the ST-IDA plot. Presently, only Myanmar is in the far left of the plot as 59% of its electricity mix comprises of renewables. Many ASEAN countries such as Singapore and Brunei are unable to traverse this vertical boundary due to a lack of renewable resources. Crossing this boundary will require significant adoption of renewables as a decarbonization wedge [14]. As renewable resources are not evenly distributed across Southeast Asia, greater regional cooperation and the realisation of sub-regional or regional electricity trade through the ASEAN Power Grid [15] can facilitate cross-border power trade with key consumption centres.

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Appendix

The generation mix and emission intensity effects obtained based on a ST-IDA between country \( c \) in time \( t \) and the ASEAN average (\( R_u \)) shown in Eq. (2) can be decomposed based on the additive LMDI decomposition formulae from Ang [9] as follows:

\[
\Delta V_s = \sum_i L (w_i^{c,t}, w_i^{R_u}) \ln \left( \frac{m_i^{c,t}}{m_i^{R_u}} \right)
\]

\[
\Delta V_u = \sum_i L (w_i^{c,t}, w_i^{R_u}) \ln \left( \frac{u_i^{c,t}}{u_i^{R_u}} \right)
\]

where \( w_i^{c,t} = \frac{c_i^{c,t}}{G^{c,t}} \), \( w_i^{R_u} = \frac{c_i^{R_u}}{G^{R_u}} \), \( L(x, y) = \frac{x - y}{\ln x - \ln y} \) for \( x \neq y \), and \( L(x, y) = x \) for \( x = y \).

Table A.1 Key features of trajectories from ST-IDA plot and corresponding electricity system

| Country  | Trajectory                                                                 | Electricity system                                      | Total electricity output in 2015 (TWh) | Change in output between 2015 and 2000 (times) |
|----------|-----------------------------------------------------------------------------|--------------------------------------------------------|---------------------------------------|-----------------------------------------------|
| Brunei   | Consistent policy, straight smooth line of decreasing power generation efficiency | 99% natural gas based generation mix                    | 4.2                                   | 1.7                                           |
| Cambodia | Almost no progress before 2011 and no improvements to generation efficiency Improvement in generation mix effect after 2011 but a U-turn has been observed after 2013 | Largely oil based generation mix until 2012 when fossil fuels decreased to 60% of total generation mix | 4.4                                   | 9.8                                           |
| Singapore| Consistent policy of substitution of oil for natural gas leading to improvements in generation mix effect | Largely oil-based generation mix substituted by natural gas | 50.4                                  | 1.6                                           |
| Thailand | Constrained trajectory Limited changes to electricity mix and power generation efficiency | Relatively stable generation mix primarily dependent on natural gas and coal | 177.8                                 | 1.9                                           |
| Myanmar  | Movement towards cleaner energy mix with variations in the generation mix effect after 2009 Lack of movement in the vertical direction | Largely dependent on renewables and natural gas         | 16.0                                  | 3.1                                           |
| Country   | Description                                                                 | Generation Mix                                                                 | M   | R  |
|-----------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----|----|
| Malaysia  | Lateral movement towards the right shows worsening generation mix            | Diverse generation mix with an active policy to shift away from natural gas towards imported coal | 150.1 | 2.2 |
|           | Fluctuating generation efficiencies, in particular, the two largest fluctuations occurred between 2008 and 2010 due to changes in coal plant generation efficiencies |                                                                                  |     |    |
| Indonesia | Lateral movement towards the right shows worsening generation mix            | Diverse generation mix, mainly reliant on domestic resources, in particular coal | 234.0 | 2.5 |
|           | Fluctuating generation efficiency                                             |                                                                                  |     |    |
| Vietnam   | Worsening generation mix and improvements to generation efficiency between 2000 and 2005. Constrained trajectory after 2005 with fluctuations in the generation mix effect after 2010 | Diverse generation mix, increasing share of coal                                 | 153.3 | 5.8 |
| Philippines | Irregular trajectory signaling fluctuating electricity mix and generation efficiencies | Diverse generation mix, high dependence on imports                              | 82.4  | 1.8 |