Modelling low carbon electricity generation of an integrated ASEAN power grid

Gigih Udi Atmo¹, Takashi Otsuki², Eri Nurcahyanto³

¹Asia Pacific Energy Research Centre, Japan
²Institute of Energy Economics of Japan, Japan
³Asia Pacific Energy Research Centre, Japan

*Corresponding author’s e-mail: eri.nurcahyanto@aperc.or.jp

Abstract. In 1997, 10 economies of the Association of Southeast Asian Nations (ASEAN) established the ASEAN Power Grid (APG), a cross-border interconnection network that effectively uses regional energy resources. This study aims to quantify the effect of ASEAN power grid interconnection on electricity exports-imports between south-east Asia economies and its implications for renewable energy shares and carbon emission in power generation. Three scenarios are assessed in this model. The Base Scenario simulates APG parameters in 2030, considering four existing interconnections and those interconnection projects currently under construction. The second scenario, HAPUA Scenario, includes all the future interconnection projects outlined in the HAPUA report. The carbon tax scenario as the last scenario, aims to evaluate whether carbon pricing policies in Southeast Asia may incentivise cleaner energy and renewable energy development in the region. Under the HAPUA Scenario, Indonesia increases coal and/or gas-fired generation for electricity exports, contributing to a slight increase in CO2 emissions from power generation for the ASEAN region. It appears that carbon price affects the choice of electricity generation and incentivise cross-border electricity trade. Under the carbon tax scenario, emissions will decline to 719 MtCO2 or 22% lower than the base scenario and 24% than the HAPUA scenario.

1. Background

In 1997, 10 economies of the Association of Southeast Asian Nations (ASEAN) established the ASEAN Power Grid (APG), a cross-border interconnection network that aims to effectively use regional energy resources, including fossil fuels and renewables. The group includes seven APEC economies: Brunei Darussalam, Indonesia, Malaysia, the Philippines, Singapore, Thailand and Viet Nam. The other ASEAN economies with substantial hydropower resources, are Myanmar, Cambodia and Lao People's Democratic Republic (Lao PDR). Together, the Heads of ASEAN Power Utilities/Authorities (HAPUA) promotes the APG, which consists of 16 cross-border transmission projects distributed over northern, southern and eastern corridors, totaling 30.75 gigawatts (GW) of capacity (Figure 1) (ACE, 2015). The APG was incorporated into the ASEAN Plan of Action for Energy Cooperation 2016-2025, which received endorsement by the ASEAN Energy Ministers in 2014 (ASEAN Centre for Energy, 2015).
Table 1 summarises the details of cross-border transmission line interconnections, which are divided into five subregions with a total electricity transfer capacity of 5.5 GW.

**Figure 1. ASEAN power grid interconnection master plan**

Table 1. Summary of ASEAN electricity interconnection

| No | ASEAN Power Grid | Existing (MW) | Under Construction (MW) | Future plan | Total Interconnection Capacity |
|----|------------------|---------------|-------------------------|-------------|--------------------------------|
| 1  | Northern System  | 4 442         | 2 179                   | 15 774 - 18 924 | 22 395 - 25 545 |
|    | Thailand - Lao PDR | 3 584         | 1 879                   | 1 865       | 7 328 |
|    | Lao PDR - Vietnam | 538           | -                       | TBC         | 538 |
|    | Thailand - Myanmar | -             | -                       | 11 709 - 14 859 | 11 709 - 14 859 |
|    | Viet Nam - Cambodia | 200           | -                       | TBC         | 200 |
|    | Lao PDR - Cambodia | -             | 300                     | -           | 300 |
|    | Thailand - Cambodia | 120           | -                       | 2 200       | 2 320 |
| 2  | Southern System  | 450           | -                       | 1 800       | 2 250 |
|    | P. Malaysia - Singapore | 450         | -                       | 600         | 1 050 |
|    | P. Malaysia - Sumatera | -             | -                       | 600         | 600 |
|    | Batam - Singapore  | -             | -                       | 600         | 600 |
|    | Singapore - Sumatera | -             | -                       | TBC         | - |
| 3  | Eastern System   | 230           | 30-100                  | 550-800     | 810-1 130 |
|    | Sarawak - W. Kalimantan | 230         | -                       | -           | 230 |
|    | Philippines - Sabah | -             | -                       | 500         | 500 |
|    | Sarawak - Sabah - Brunei | -         | 30-100                  | 50-300      | 80-400 |
|    | E. Sabah - E. Kalimantan | -         | -                       | TBC         | - |
| 4  | Northern - Southern System | 380         | -                       | 400         | 780 |
|    | Thailand - P. Malaysia | 380         | -                       | 400         | 780 |
| 5  | Southern - Eastern System | -           | -                       | 1 600       | 1 600 |
|    | Sarawak - P. Malaysia | -             | -                       | 1 600       | 1 600 |

Notes: E. Kalimantan = East Kalimantan, E. Sabah = Eastern Sabah, Lao PDR = Lao People’s Democratic Republic, P. Malaysia = Peninsular Malaysia, TBC = To be confirmed
2. Study Objective
This study aims to quantify the effect of ASEAN power grid interconnections on electricity exports-imports between south-east Asia economies, and the implications for renewable energy shares and carbon emissions. Specifically, this study aims to evaluate the effectiveness of a carbon tax in increasing the share of renewable energy and electricity fuels in ASEAN's cross-border electricity trade.

The existing ASEAN Power Grid studies (Chang and Li, 2013) studied the ASEAN Power Grid that incorporated the cost of carbon emissions and transmission losses in the cost structure of the least cost of electricity generation and supplies. However, the approach considered too high capacity factor from power generation and did not consider the historical performance of power plant availability factors to determine the amount of electricity generation for future transactions in cross-border electricity trading in ASEAN. This factor is particularly critical to understand the implication of sessional variations on hydropower plants and solar irradiance on the solar PV outputs.

Otsuki et al. (2016) found that regional power grid integration offered opportunities for regions with high electricity production cost (e.g. Japan and Korea) to have access to lower electricity costs from coal power plants in China and hydropower plants in Russia. They developed a multi-region power model based on the least cost linear optimization method to evaluate the economic proposals of electricity grid integration in North-East Asia. This approach can be adopted to evaluate the grid integration plan in South-East Asia.

3. Methodology
To quantitatively assess how integrating power grids could affect electricity trade and CO2 emissions in South-East Asia in 2030, this research applied a multi-region power system model based on linear programming techniques. The model was first introduced in the Asia Pacific Energy Research Centre by Otsuki et al. (2016) to evaluate the economic potential of North-East Asia grid integration. The ASEAN Power Grid study adopts this technique to evaluate grid integration in South-east Asia.

3.1. Multi-region electricity system model for ASEAN power grid study
APERC developed a multi-region electricity system model for Southeast Asia, based on formulations described in a paper published in Otsuki et al (2016). This linear programming model aims to minimize single-year total system cost, consisting of the annualized capital cost, operation and maintenance (O&M) cost, fuel cost, and carbon cost for the whole of Southeast Asia. Figure 2 depicts a schematic diagram of the model. This model formulates electricity transmission as a transport problem, enabling us to keep the optimization problem linear and optimize grid extensions, generation expansion, and operation simultaneously.

The model considers a simplified set of technologies compared with the long-term electricity model that was used in the APEC Energy Outlook 7th edition (APERC 2019). It is intended to ensure consistency with the long-term analysis, techno-economic assumptions and calibrated parameters are harmonised between those that were used in the APEC Energy Outlook 7th edition and those used in ASEAN Power Grid study. The electricity generation in the business-as-usual scenario in the APEC Energy Outlook 7th edition is also used to validate the total amount of electricity generation and fuels in the seven members of APEC ASEAN economies.

The model disaggregates South-East Asia into 12 nodes (Table 2) to improve cross-border electricity trade accuracy in more expansive areas. Thailand is divided into two nodes because of the long distance between electricity demand and supply centres in the north and south region of Thailand. "Thailand-Northern" node represents electricity demand centre of Thailand, which is interconnected to Myanmar and Lao PDR. The “Thailand–Southern” node is assumed to facilitate cross-border connections with Cambodia and the Malaysian Peninsula, although it has smaller demand than “Thailand-Northern” node.

Malaysia electricity system is divided into two nodes, Malaysia Peninsula (MAS-P) represents 60% of total electricity demand while Malaysia Sarawak (MAS-S) accounts for the remaining 40% of total electricity demand in Malaysia. Indonesia, the highest electricity demand in South-East Asia, is divided into two nodes, the Sumatera-Java node and the Kalimantan node. This study assumes that the Sumatera
and Java electricity systems are interconnected, while the Kalimantan grid is not as tightly linked but represents 25% of Indonesia’s total electricity demand.

As for temporal resolution, the model considers hourly load curves for each day. It also considers the load curve characteristics for two types of seasons, namely the dry and wet season, which are typical in South-East Asia. Therefore, one calendar year is decomposed into 48-time segments (24 hours per day for two types of seasons).

**Figure 2.** Schematic diagram of a multi-region power system model

![Schematic diagram of a multi-region power system model](image)

**Table 2.** Modeled regions in the multi-region electricity system model

| Economy | Node abbreviation | Economy | Node abbreviation |
|---------|-------------------|---------|-------------------|
| Brunei  | BD                | Laos    | LAO               |
| Cambodia| KHM               | Myanmar | MMR               |
| Indonesia| INA-K (Kalimantan) | The Philippines | RP |
|         | INA-SI (Rest of Indonesia) |         | SIN               |
| Malaysia| MAS-P (Peninsula Malaysia) | Thailand | THA-N (Thailand North) |
|         | MAS-S (Sarawak and Sabah) |         | THA-S (Thailand South) |
|         |                   | Viet Nam | VET               |

*Source APERC, 2019.*

3.2. Scenarios

Three scenarios are assessed in this model. The Base Scenario includes only four existing interconnections and those that will be completed by 2030 based on government plans: between Brunei Darussalam and Sabah (Malaysia); West Kalimantan (Indonesia) and Sarawak (Malaysia); Cambodia and Thailand; and Laos PDR and Thailand. Assumptions from the Base Scenario are harmonized with the BAU Scenario of APEC’s 7th Edition Outlook. As an alternative, the HAPUA Scenario includes all the future projects described in Figure 1, except for the connections between peninsular Malaysia and Sarawak, and between the Philippines and Malaysia.

For supplemental assessment, low and high carbon prices cases are examined under the HAPUA Scenario. The simulated year is 2030. The Base case, which only includes existing and under construction interconnectors, works as the baseline of this assessment. The HAPUA case aims to quantify the impacts of the interconnection projects outlined in HAPUA (HAPUA Working Group 2 [HWG2], 2017) and the Integrated case to discuss the potential costs and benefits of accelerated interconnections in South-East Asia. The supplemental analysis of carbon prices aims to evaluate whether carbon pricing policies in South-East Asia may incentivise cleaner energy and renewable energy development in the region.

The Base Scenario simulates APG parameters in 2030, considering four existing interconnections, and those interconnection projects that are currently under construction in Table 1 and will be operating by 2030. Assumptions for the Base Scenario are harmonised with the BAU Scenario of APEC’s 7th
Edition Outlook. The four modelled existing interconnections considered in this scenario are Brunei Darussalam and Sabah (Malaysia); West Kalimantan (Indonesia) and Sarawak (Malaysia); Cambodia and Thailand; and Laos PDR and Thailand.

The simulations of the Base Scenario target the year 2030. This study assumes that by 2030, five more cross-border interconnection projects will succeed in the APG: two in the Northern System, one in the Southern System, one extension in the Eastern System, and one in the Northern–Southern System (Table 3). These are listed in a report by HAPUA (HAPUA, 2018), and the total capacity reaches 7 243 MW in 2030. The connection between Sarawak-Sabah-Brunei is expected to reach a maximum capacity of 100 MW.

Table 3. Cross-border interconnection within ASEAN by 2030

| No | ASEAN Power Grid         | Total Existing Interconnection in 2018 (MW) | Total Interconnection in 2030 (MW) |
|----|--------------------------|--------------------------------------------|-----------------------------------|
| 1  | Northern System          |                                            |                                   |
|    | Thailand - Lao PDR       | 4 442                                      | 6 083                            |
|    | Vietnam - Cambodia       | 3 584                                      | 5 463                            |
|    | Lao PDR - Cambodia       | 200                                        | 200                              |
|    | Thailand - Cambodia      | -                                          | 300                              |
| 2  | Southern System          |                                            |                                   |
|    | P. Malaysia - Singapore  | 450                                        | 450                              |
| 3  | Eastern System           |                                            |                                   |
|    | Sarawak - W.Kalimantan   | 230                                        | 260-330                          |
|    | Sarawak - Sabah - Brunei | 230                                        | 230                              |
|    | -                        | 30-100                                     |
| 4  | Northern - Southern System|                                           |                                   |
|    | Thailand - P. Malaysia   | 380                                        | 380                              |

Source: HAPUA (2018)

The HAPUA Scenario includes all the future interconnection projects outlined in the HAPUA report (HAPUA, 2018), except for two (between peninsular Malaysia and Sarawak, and between the Philippines and Malaysia). These two interconnections represent the most extended transmission lines in the HAPUA plan. The interconnection within Malaysia, between the peninsula and Sarawak Island via submarine cable, is excluded from this analysis. One key consideration is that the route crosses over Indonesian territory, including a giant gas reserve in East Natuna, which Indonesia plans to develop in the future. The gas pipelines installed for this development may prompt the interconnection project to reroute outside Indonesian territory, which would only be economically justified beyond 2030.

3.3. Key assumptions
Cross-border transmission capacity is given exogenously under the Base and HAPUA cases, and the last case allows capacity additions through cost-optimisation. The Base case includes existing interconnection plus on-going projects, totalling 8.5 GW in the ASEAN region (HAPUA, 2015). Assumptions for the HAPUA case rely on the projects outlined in HAPUA reports, as shown in Table 4 (HAPUA Working Group 2 [HWG2], 2017).
The 800 km Malaysia Peninsula that is interconnected to Malaysia Sarawak in the HAPUA interconnection plan is crossing the Indonesian territory is excluded from this study. Both economies have not discussed about this interconnection and does not exist in Indonesia's energy plan.

Source: HAPUA, 2018.

Initial capacity settings for power generation and storage technologies are based on the BAU Scenario in APEC’s 7th Edition Outlook. It must be noted that the Base case does not allow any capacity additions for power generation and storage technologies, and annual CO$_2$ emissions in each case are constrained to the level in the BAU of the 7th Edition Outlook. Tables 5 summarises other techno-economic assumptions for power generation technologies, which have been harmonised with the long-term electricity model of the 7th Edition Outlook. Some assumptions on power generation technologies, such as capital cost, maximum availability and efficiency, are expressed in ranges to describe variations among the economies. Other assumptions are assumed to be the same across south-east Asia. Capital cost is annualised using an assumed discount rate of 5% and assumed lifetimes of each technology. Energy prices in 2030 and carbon content of fossil fuels are also in line with 7th Edition assumptions; for every tonne of oil equivalent (toe), 113-127 USD and 3.82 tonnes of CO$_2$ (tCO$_2$) for coal, 338-422 USD and 2.2 tCO$_2$ for natural gas, and 756 USD and 2.52 tCO$_2$ for oil.

Table 4. International interconnection outlined by HAPUA

| No | Region  | Capacity [MW] | No | Region  | Capacity [MW] |
|----|---------|---------------|----|---------|---------------|
| 1  | MAS-P   | SIN           | 7  | PHI     | MAS-S         | 600 |
| 2  | MAS-P   | THA           | 8  | MAS-S   | BD            | 380*|
| 3  | MAS-S   | MAS-P         | 9  | THA     | LAO           | 0** |
| 4  | MAS-P   | INA-S         | 10 | LAO     | VIET          | 500 |
| 5  | INA-S   | SIN           | 11 | THA     | MYA           | 600 |
| 6  | MAS-S   | INA-K         | 12 | VIET    | CAM           | 230*|

Notes: *Existing cross-border lines interconnection.
**The 800 km Malaysia Peninsula that is interconnected to Malaysia Sarawak in the HAPUA interconnection plan is crossing the Indonesian territory is excluded from this study. Both economies have not discussed about this interconnection and does not exist in Indonesia's energy plan.

Source: HAPUA, 2018.

Table 5. Key assumptions for the multi-region electricity system model

|            | Nuclear | Coal | Gas  | Oil  | Hydro | Geothermal | Biomass |
|------------|---------|------|------|------|-------|------------|---------|
| Capital cost [USD/kW] | 4 500  | 1 600 | 950  | 950  | 2 000 | 4 848      | 2 574   |
| Fixed O&M cost rate [USD/kW] | 0.045 | 0.035 | 0.02 | 0.03 | 0.012 | 0.020      | 0.035   |
| Lifetime [year] | 40     | 40   | 40   | 40   | 60    | 30         | 30      |
| Max. availability [%] | 65-80  | 20-85.5 | 70-83.5 | 90-95 | 22-39 | 80         | 24-60   |
| Efficiency [%] | 33     | 34-38 | 51-53 | 51   | 100   | 10         | 28-42   |
| Max. ramp-up/down rate [%/hour] | 0      | 30   | 50   | 100  | 30    | 50         | 50      |
| Share of DSS | 0      | 0    | 40   | 70   | --    | --         | 40      |
| Minimum output level [%] | 100    | 30   | 30   | 0    | 100   | 30         |         |

Note: DSS=Daily Start and Stop.
Source: APERC Energy Outlook 7th edition

4. Result and Discussion
The analysis of simulation results focuses on cross-border electricity trade in South-east Asia between three Scenarios. It firstly simulates cross-border electricity transactions under the business-as-usual in Scenario 1 where the interconnections only come from the existing cross-border transmission lines. The next section compares electricity trade between the BAU scenario and HAPUA Interconnection scenario. This paper then presents an investigation on the implication of carbon pricing on the cross-border electricity trade in the HAPUA Interconnection scenario. Figure 3 and Figure 4 depicts cross-border electricity trade between 10 ASEAN economies under the HAPUA interconnection plan and under carbon tax scenario.
4.1. Northern System interconnection

The Northern system interconnects five economies in South-east Asia: Cambodia, Laos PDR, Myanmar, Thailand, and Viet Nam. Under the HAPUA Scenario, total electricity trade expands to 41 TWh per year. Thanks to low-cost hydropower resources and geographical location close to demand centres, Cambodia, Lao PDR and Myanmar become the top three electricity exporters. The annual revenues for exporters amount to USD 862 million in 2030. This estimation is obtained by utilising the reference price for the multi-lateral electricity trade among Laos PDR, Malaysia and Thailand.

Under Scenario 2, coal power generation in Lao PDR increases to 6.4 TWh/year from a negligible amount of generation in Scenario 1. Accordingly, Lao PDR is projected to produce 6.7 Mt-CO₂ emissions which are emitted from the electricity generation from coal-fired power plants. Thailand has the highest share of electricity imports in the northern region of interconnection. Under the Scenario 2 of the HAPUA interconnection, it is found to be least costly to import electricity while the economy reduces electricity use from gas power generation. While gas-fired power generation decreases in Thailand, coal-fired power generation is almost unchanged, proving that it is the most competitive fuel for generating electricity. Thailand utilises the maximum allowable cross-border electricity capacity (15% of the domestic reserve margin) to import electricity from Lao PDR and Myanmar.

Cross-border interconnection enables Thailand to find a lower cost alternative than generating electricity from gas fired power plants. Interestingly, biomass electricity generation increases as...
domestic gas utilisation decreases. It appears that maximum constraints on gas generation have reduced its output and leave the remaining portion of electricity demand to be filled through combined domestic generation from coal, electricity import, biomass, and other renewable energy sources. Biomass power generation increases 12%. Interestingly, biomass power generation in Thailand is more competitive than electricity produced by solar PV and wind power.

Electricity generation from variable renewable energy (VRE) is almost unchanged in Thailand under Scenario 3. This indicates that cross-border electricity interconnection in the northern interconnection region does not sufficiently facilitate higher generation from variable renewable energy sources when other low-cost electricity sources from coal and large hydropower plants are available. Other policy or pricing instruments may be required if electricity generation from variable renewable energy is expected to increase in the northern interconnection region.

In addition to Thailand, Viet Nam is also benefiting from access to competitive electricity sources through the cross-border electricity imports in the northern region. Under Scenario 2, Viet Nam imports 3.2 TWh from Cambodia. Cross-border grid expansion between Lao PDR and Viet Nam has been utilised to its maximum transfer capacity (85% of transmission line utilisation) to transmit 2.1 TWh of electricity from Lao PDR to Cambodia. It shows that Lao PDR offers competitive electricity prices to Thailand and Cambodia. Interestingly, the cross-border interconnection also provides electricity export opportunities from Viet Nam to Cambodia. The HAPUA interconnection has given Viet Nam a strategic position from which to access low cost electricity generation from Lao PDR to meet its growing electricity demand. Simultaneously, transmission interconnection from Viet Nam and Cambodia enables the economy to export electricity to Cambodia. The limited fossil fuel resources in Cambodia have made electricity generation from the economy relatively more expensive than in Viet Nam. Accordingly, it is found to be more economic to import electricity from Viet Nam.

4.2. Southern System interconnection
The Southern System interconnects the electricity systems of Singapore, Indonesia (Sumatera and Java), Malaysia (Peninsula), and Thailand South. Under the HAPUA interconnection plan in Scenario 2, Singapore is expected to become a net importer of electricity from Indonesia (4.1 TWh) and Malaysia (4.2 TWh). The total amount of electricity imports represents 15% of the total annual electricity consumption in Singapore. The Southern System interconnects Singapore to Indonesia (Sumatera) and Malaysia (Peninsula) via cross-border transmission lines with a transfer capacity of 600 MW.

The multi-region power model results show that these two interconnection lines are fully utilised at an upper limit of 80%, indicating the average generation costs in Indonesia (Sumatera) and Malaysia (Peninsula) are lower than in Singapore. Accordingly, it is more cost efficient to import electricity from its neighbouring economies (e.g. Indonesia and Malaysia).

Peninsular Malaysia is the largest electricity exporter in the Southern System interconnection, sending 6.8 TWh of electricity to Indonesia (1.8TWh), Thailand (0.8 TWh) and Singapore (4.2 TWh). The grid integration model assumes that the Laos-Thailand-Malaysia (LTM) line, the first multilateral electricity transaction in south-east Asia, is continued. Accordingly, peninsular Malaysia exports 0.8 TWh of electricity to Thailand (South). The electricity exports are carried through the existing cross-border interconnection between Malaysia (Peninsula) and Thailand (South), which has a transfer capacity of 380 MW.

The multilateral Laos-Thailand-Malaysia pilot project is an example of where the initiative for multilateral trade is not always motivated by finding the lowest cost of electricity generation; it is rather about finding electricity which comes from renewables. This could be the case when a carbon price is applied to south-east Asia and coal fired power generation becomes less competitive. In contrast to the cross-border interconnection between Indonesia (Sumatera)-Malaysia (Peninsula)-Singapore, the interconnection between Malaysia (Peninsula) and Thailand (South) is rather underutilised. At a transfer capacity of 380 MW, line utilisation factor is at 8.8%, which indicates the economics of electricity transfer from Thailand to Malaysia (Peninsula) are less attractive.
Malaysia (Peninsula) purchases electricity at a 300 MW transfer capacity interconnecting Malaysia and Thailand (South), and a total of 0.23 0.8TWh is exported annually from Thailand (South) to Malaysia (Peninsula). As the model assumes optimum cost integration of the integrated Northern System and Southern System, specific regional cooperation such as the Laos-Thailand-Malaysia interconnection needs to be modeled separately, which is beyond this study's scope.

The Southern System interconnection will enable Singapore to import 8.3 TWh (15% of total electricity demand) from Indonesia (4.1 TWh) and Malaysia (4.2 TWh). Singapore's electricity generation is predominantly from gas-fired power plants with higher electricity production costs than in Indonesia and Malaysia respectively. These two economies have electricity generation mix from fossil fuels and renewable energy sources.

The interconnected Sumatera and Java grid of Indonesia is projected to export 4.1 TWh electricity to Singapore while it imports 1.7 TWh from Malaysia (Peninsula). It appears that electricity load profile differences has enabled electricity exports from Malaysia (Peninsula) to meet peak electricity demand in Indonesia although the average cost of electricity generation between the two economies are only marginally different.

4.3. Eastern System Interconnection
On the Eastern system interconnection in the Base Scenario, interconnection occurs only between Indonesia and Malaysia. At a moderate size of 230 MW transmission line capacity, the interconnection between Indonesia-Kalimantan and Malaysia Sarawak provides opportunities for Malaysia-Sarawak electricity producers to export 1.6 TWh annually to Indonesia Kalimantan. A bilateral electricity trade agreement between Indonesia and Malaysia was signed in 2015, which allows for electricity trade between the two economies.

Malaysia – Sarawak is the primary electricity producer for the Eastern System Interconnection. Sarawak Energy is the state-owned electric company in Sarawak. The company has a total installed capacity of 5 307 MW of combined hydro, thermal and small-scale renewable energy generation. Sarawak Energy has electricity generation from large hydro power with a total installed capacity of 3 452 MW, including the Bakun Hydroelectric Power with a total installed capacity of 2 400 MW. With limited demand growth in the Sarawak region, electricity generation from Sarawak Energy may be exported to meet regional electricity demand from Indonesia – Kalimantan and Brunei.

4.4. Indonesia-Kalimantan and Malaysia–Sarawak
Electricity interconnection between Sarawak and Kalimantan started in 2016, a significant milestone as the first cross-border electricity interconnection in the eastern system interconnection of ASEAN Power Grid. A 275 kV transmission interconnection was established between Sarawak and Kalimantan. With a total transmission length of 208 km and transfer capacity of 230 MW, the cross-border interconnection enables bidirectional power trade between Sarawak and Kalimantan.

Electricity demand in Sarawak is predominantly from aluminium smelting and the petroleum industry which reach peak demand during the day. On the other hand, residential demand has the highest share of electricity demand in Kalimantan and reaches peak demand in the evening. Electricity generation and trade can be coordinated allowing low-cost electricity generation from Kalimantan to meet peak demand in Sarawak during the day. Electricity from the Sarawak utility company can meet residential peak demand in Kalimantan at night.

Based on the simulation of power trade between the two regions, Indonesia–Kalimantan is projected to import 1.6 TWh from Malaysia–Sarawak in 2030. This amount of electricity is 43% higher than the imports in 2017, when Indonesia imported 1 120 GWh (MEMR 2018). Under the carbon tax scenarios, the amount of electricity trade between Sarawak and Kalimantan is steady between the HAPUA plan and the low carbon price scenario at USD 3.7/ton-CO\textsubscript{2} at 1.6 TWh per year. Electricity imports from Sarawak are almost six times higher than the low carbon price scenario or 11.7 TWh in 2030.
Table 6. CO₂ Emissions from power generation under the base, HAPUA and carbon tax scenarios, selected ASEAN economies

| Scenario          | Brunei | Indonesia | Malaysia | Singapore | Thailand | Viet Nam |
|-------------------|--------|-----------|----------|-----------|----------|----------|
| Base Emissions [MtCO₂] | 2.6    | 462       | 121      | 30        | 166      | 138      |
| HAPUA Emissions [MtCO₂] | 2.6    | 479       | 124      | 26        | 160      | 138      |
| Carbon Tax Emissions [MtCO₂] | 3.9    | 218       | 201      | 46        | 106      | 145      |
| Base Intensity [kgCO₂/kWh] | 0.67   | 1.7       | 1.4      | 0.55      | 0.95     | 0.59     |
| HAPUA Intensity [kgCO₂/kWh] | 0.67   | 1.8       | 1.4      | 0.47      | 0.88     | 0.59     |
| Carbon Tax Intensity [kgCO₂/kWh] | 0.76   | 1.1       | 1.7      | 0.7       | 0.63     | 0.63     |

Source: APERC analysis.

Under the higher carbon price scenario, the least cost solution for electricity supply in Kalimantan is increasing electricity imports from Sarawak, while reducing electricity generation from gas-fired power plants. Gas-fired generation decreases by 60% while coal-fired power plants maintain a similar level of outputs at 71.4 TWh in 2030. Electricity generation from solar PV is almost three times higher than in the HAPUA Scenario, reaching 2.0 TWh while hydro power and other renewable power generation only marginally change under the higher carbon price scenario.

It appears that carbon price affects the choice of electricity generation and incentivise cross-border electricity trade between Sarawak and Kalimantan. At a carbon price up to USD 30/ton-CO₂, electricity generation from coal-fired power plants remains competitive enough to provide low-cost electricity supply in Kalimantan. At an assumed gas-fired power production price between USD 0.029-0.037/kWh, gas-fired power plants are subject to reduced power generation and are less competitive than coal-fired power plants.

4.5. Indonesia–Kalimantan and Malaysia–Sarawak

The eastern interconnection of the ASEAN Power Grid includes a cross-border interconnection between Sarawak, Sabah and Brunei. In addition to the existing interconnection between Sarawak and Kalimantan, future cross-border trade from Sarawak may be extended to cover electricity export to Brunei through Sabah in Malaysia. Unlike the electric grid interconnection between Sarawak and Kalimantan, Sarawak, Sabah and Brunei have three independent grids which are not interconnected. Integrating the electric grid between Sarawak and Sabah is the first stage for developing electricity export to Brunei. The Borneo Grid is expected to be extended to cover 275 kV transmission lines between these three regions.

In Scenario 2 of HAPUA plan, cross-border electricity trade increases to 2.0 TWh per year because of electricity interconnection between Sabah and Brunei. Based on the HAPUA plan, the Eastern System interconnection is extended to interconnect between Sarawak-Sabah-Brunei with a transfer capacity of between 30 to 100 MW. This study assumes that 30 MW is the minimum power transfer between Sarawak–Sabah–Brunei, while 100 MW is the power transfer upper limit. Accordingly, Brunei imports 0.1 TWh annually from Sabah–Malaysia. In Brunei, electricity demand is projected to reach 3.88 TWh in 2030, mostly driven by the industry and residential sectors (APEC, 2019). Based on the multi-region power model, under the HAPUA plan, Brunei would import 0.1 TWh, representing 8.6% of total electricity generation in Brunei in 2030. Further imports may be possible if the transmission transfer capacity increases and Brunei allows the share of electricity imports to exceed their electricity reserve margin, which is set at 10% of the total electricity generation.

Under the carbon tax scenarios, the amount of electricity imported from Sarawak remains unchanged at 0.1 TWh when a low carbon price at USD 3.7/ton-CO₂ is applied. The amount of electricity imported increases by 54% to 0.7 TWh when a high carbon price scenario of USD 30/ton-CO₂ is applied in the South-east Asia region. At a higher carbon price, coal-fired power plants are not economical to generate electricity in Brunei. As such it has no electricity output, a step decline from 1.25 TWh under the low carbon tax and HAPUA plan scenarios.
Electricity generation from gas-fired power plants increases by 29% from 3.4 TWh/year under the HAPUA and low carbon tax scenarios to 4.4 TWh/year under the higher carbon tax scenario. With higher operating efficiency and less carbon content, gas fired power plants are more economical than coal-fired power plants. The cross-border electricity interconnection helps Brunei reach a new equilibrium in its electricity supply system when a higher carbon price of USD 30/ton-CO$_2$ is applied. It helps the economy access more cost competitive electricity from Malaysia-Sarawak and suppresses electricity generation from its own coal-fired power plants.

5. Conclusions
The ASEAN Power Grid's primary goal is improving the energy security of the region by collectively sharing energy resources among ASEAN member economies. The co-benefits from cross-border electricity interconnection occur between the economies that are interconnected.

Interconnections in the region encourage hydropower development in Lao PDR and Myanmar. However, this scenario analysis also suggests that grid integration could contribute to expanding the capacity factor of fossil fuel-powered plants. Under the HAPUA Scenario, Indonesia increases coal- and/or gas-fired generation for electricity exports, contributing to a slight increase in CO$_2$ emissions from power generation for the ASEAN region as a whole. Overall, the region sees a 2.3% increase in emissions, from 920 MtCO$_2$ per year to 941 MtCO$_2$ per year in the Base case. To avoid such ‘adverse effects,’ region-wide environmental policies will be important. Under the carbon tax scenario, power trade from renewable sources, Indonesia (Kalimantan) increases imports from Sarawak, while reducing electricity generation from gas-fired power plants. It appears that carbon price affects the choice of electricity generation and incentivise cross-border electricity trade. Under the carbon tax scenario, emissions will decline to 719 MtCO$_2$ or 22% lower than base scenario and 24% than HAPUA scenario.

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